DOCTORAL DISSERTATION

Uniwersytet Rolniczy im. Hugona Kołłątaja w Krakowie

Wydział Leśny

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Hydrological response of urban soil to changes in anthropogenic factors

Reakcja hydrologiczna gleb miejskich na zmiany czynników antropogenicznych

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Summary

Urban soils play a key role in ecosystem functioning; they support water retention, vegetation growth, and help mitigate the effects of climate change. However, urbanization and human interventions, such as soil amendments and vegetation management, change soil properties, reducing retention capacity, disrupting water cycles, and increasing the urban heat island effect.

This dissertation aimed to assess the impact of selected anthropogenic factors, including soil amendments (spent coffee grounds, road salt, sand), vegetation management (mowed and unmowed lawns, flower meadows), and climatic variables, on the hydrological response of urban soils. The research combined three complementary approaches: field experiments, statistical modelling (ARDL), and a bibliometric analysis of scientific literature on nature-based solutions (NBS). This integrative design allowed for capturing both local-scale processes and broader scientific context.

Field experiments showed that spent coffee grounds (SCG) at 2 t/ha improved soil water retention (VWC, Sa, capillary water) and reduced water drop penetration time (WDPT), though slightly lowered pH and nitrogen levels. In contrast, road salt increased electrical conductivity (EC), negatively affecting soil health. Unmowed lawns and flower meadows enhanced water retention and helped cool the microclimate, while frequently mowed lawns increased surface drying and heat accumulation.

Modeling based on climate data from Kraków and Warsaw revealed that precipitation, relative humidity, and minimum temperatures positively influenced soil moisture. In contrast, high maximum temperatures, wind speed, and surface temperature had a negative impact. This confirmed the high sensitivity of urban soils to climate variability.

The dissertation demonstrates the potential of organic soil amendments and nature-based solutions, such as flower meadows and reduced mowing, for improving soil hydrology and mitigating climate impacts. It also emphasizes the need for adaptive strategies, including drought-tolerant vegetation, water conservation practices, and proper green space management. The findings contribute valuable knowledge and offer practical recommendations for sustainable urban planning.

Keywords: soil amendments, vegetation management, climate change, soil water retention properties, urban soil

Streszczenie

Gleby miejskie odgrywają istotną rolę w funkcjonowaniu ekosystemów – wspierają retencję wody, rozwój roślinności i łagodzenie skutków zmian klimatu. Jednak urbanizacja i działalność człowieka wpływa na ich właściwości, prowadząc do spadku retencji, zaburzeń w obiegu wody i nasilania efektu miejskiej wyspy ciepła.

Celem niniejszej rozprawy było określenie wpływu czynników antropogenicznych – takich jak dodatki do gleby (fusy po kawie, sól drogowa, piasek), sposoby zarządzania zielenią miejską (trawniki koszone i niekoszone, łąki kwietne) oraz wybrane parametry klimatyczne – na hydrologiczną odpowiedź gleby miejskiej. W badaniach zastosowano trzy komplementarne podejścia: eksperymentalne (badania terenowe), modelowe (analiza danych klimatycznych z użyciem modelu ARDL) oraz przeglądowe (bibliometryczna analiza literatury dotyczącej rozwiązań opartych na przyrodzie – NBS). Takie zintegrowane podejście pozwoliło uchwycić zarówno lokalne mechanizmy retencji wody w glebie, jak i ich szerszy kontekst środowiskowy i naukowy.

W części eksperymentalnej wykazano, że organiczna poprawka w postaci fusów z kawy (SCG) w dawce 2 t/ha znacząco zwiększa zdolność gleby do zatrzymywania wody (VWC, Sa, woda kapilarna) i skraca czas infiltracji (WDPT), choć jednocześnie obniża pH i zawartość azotu. Dodatek soli drogowej prowadził do wzrostu przewodnictwa elektrycznego (EC), co wskazuje na pogorszenie zdrowia gleby. W zakresie roślinności stwierdzono, że niekoszone trawniki i łąki kwietne poprawiały bilans wodny gleby i łagodziły warunki mikroklimatyczne (niższa temperatura powietrza i gleby), natomiast trawniki intensywnie koszone sprzyjały przesuszeniu gleby i wzmacniały efekt miejskiej wyspy ciepła.

Modelowanie oparte na danych z Krakowa i Warszawy wykazało, że opady, wilgotność powietrza i minimalne temperatury mają pozytywny wpływ na wilgotność gleby, natomiast wysoka temperatura maksymalna, prędkość wiatru i temperatura powierzchni ziemi – wpływ negatywny. Potwierdzono także dużą wrażliwość gleb miejskich na zmiany klimatyczne.

Rozprawa podkreśla znaczenie rozwiązań opartych na przyrodzie oraz prostych zabiegów (takich jak ograniczenie koszenia czy stosowanie poprawek organicznych) jako realnych sposobów poprawy funkcjonowania gleb miejskich i zwiększania ich odporności na zmiany klimatyczne. Wyniki mają nie tylko wartość poznawczą, lecz także praktyczne zastosowanie w planowaniu zielonej infrastruktury i adaptacji miast do współczesnych wyzwań środowiskowych.

Słowa kluczowe: poprawa jakości gleby, zarządzanie roślinnością, zmiana klimatu, właściwości retencji wody w glebie, gleba miejska

List of Research Manuscripts Included in this Doctoral Dissertation

The doctoral dissertation is based on the four published manuscripts in the scientific research journals, titled as follows:

Publication 1: Khan, M. O., D. Keesstra, S., Słowik-Opoka, E., Klamerus-Iwan, A., & Liaqat, W. (2025). Determining the Role of Urban Greenery in Soil Hydrology: A Bibliometric Analysis of Nature-Based Solutions in Urban Ecosystem. *Water*, *17*(3), 322. https://doi.org/10.3390/w17030322

(IF: 3, MNiSW: 100)

Publication 2: Khan, M. O., Klamerus-Iwan, A., Kupka, D., & Słowik-Opoka, E. (2023). Short-term impact of different doses of spent coffee grounds, salt, and sand on soil chemical and hydrological properties in an urban soil. *Environmental Science and Pollution Research*, *30*(36), 86218-86231. https://doi.org/10.1007/s11356-023-28386-z

(IF: 5.8, MNiSW: 100)

Publication 3: Khan, M. O., & Klamerus-Iwan, A. (2025). Impact of the management of the lower level of urban greenery on water retention in urban ecosystems. *Urban Forestry & Urban Greening*, 128886. https://doi.org/10.1016/j.ufug.2025.128886

(IF: 6.7, MNiSW: 100)

Publication 4: Khan, M. O., Marcinek, T., & Iwan, A. K. (2024). Impact of climate change on root zone soil moisture in two Polish cities. *sylwan*, *168*(10), 717-735. https://doi.org/10.26202/sylwan.2024021

(IF: 0.6, MNiSW: 70)

Total Ministry Points According to the Publication Year: 370
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1. Introduction

Urbanization is a defining global trend of the 21st century, increasingly shaping the structure, function, and sustainability of ecosystems. Today, more than half of the world's population lives in urban areas, with projections suggesting that nearly 70% will do so by 2050 (United Nations, 2014; 2019). This shift, while connected with economic development (Al-Zahrani, 2018; Tripathi, 2021), has profound environmental consequences, including altered land use, increased surface sealing, and rising exposure to extreme weather events linked to climate change (IPCC, 2014; de Moraes et al., 2018).

One of the most visible influences of these changes is the intensification of the urban heat island (UHI) effect, which increases energy demand, worsens outdoor thermal comfort, and challenges the stability of urban ecosystems (Li & Bou-Zeid, 2013; Jochner et al., 2013; Mora et al., 2017). Simultaneously, converting vegetated areas into impervious surfaces has significantly altered hydrological processes, decreasing infiltration, increasing surface runoff, and modifying soil–water dynamics (Kastridis et al., 2020; Zhao et al., 2021).

Besides these transformations, urban soils are essential in regulating ecosystem health. Although often overlooked, they provide crucial services such as water retention, nutrient cycling, vegetation support, contaminant removal, and carbon sequestration (Garcia et al., 2023; Ozdemir et al., 2019; Ziter & Turner, 2018). However, urban soils are also among the most degraded, marked by reduced organic matter, increased salinity and compaction, and disrupted microbial communities (Weissert et al., 2016; Liu et al., 2023). In cold climates, the widespread use of sodium chloride as a de-icing agent further deteriorates soil quality and threatens urban vegetation (Fay & Shi, 2012; Cekstere & Osvalde, 2013).

The decline in soil health poses a serious challenge to the maintenance of urban greenery, especially under shifting climate regimes. Increasingly irregular rainfall, prolonged droughts, and higher average temperatures reduce soil moisture availability, limit plant growth, and intensify ecological stress (Knox et al., 2012; Solomon et al., 2007). Dry, compacted soils become more hydrophobic, further reducing their capacity to absorb water and increasing the risk of localized flooding after heavy rainfall (Zscheischler et al., 2018). These processes compromise not only the resilience of green spaces, but also the broader functionality of urban ecosystems (Gillner et al., 2014; Mullaney et al., 2015).

In response, nature-based solutions (NBS) have gained recognition as practical strategies to improve the performance of urban landscapes. Practices such as introducing flower meadows, reducing mowing intensity, or increasing ground cover have been shown to mitigate the UHI effect, enhance stormwater retention, and support soil recovery (Lim & Lu, 2016; Berland et al., 2017; Valois et al., 2023). Complementary to these are soil amendments, specifically organic materials derived from urban food waste, which can restore degraded soils while promoting circular waste management (Brown et al., 2011; Martinez-Blanco et al., 2009).

One such amendment is spent coffee grounds (SCG), a readily available by-product with demonstrated potential to enhance water retention, nutrient availability, soil porosity, and carbon sequestration in soils (Stylianou et al., 2018; Cervera-Mata et al., 2021, 2022; Comino, 2020). While some phytotoxic concerns have been raised, research suggests that, when properly applied, SCG can improve both physicochemical and biological soil functions, particularly in deficit organic matter urban soils.

Despite this promising context, there remains a lack of comprehensive, interdisciplinary studies that evaluate how urban soils respond hydrologically to the combined effects of organic amendments, vegetation management, and changing climate conditions. Especially underrepresented are studies that link field-scale interventions with long-term environmental factors and embed them within the current global discourse on nature-based and climate-resilient solutions.

The current dissertation builds on this gap. It investigates how selected anthropogenic factors, such as organic soil amendments and ground-level vegetation practices, affect the water-regulating functions of urban soils. This work is grounded in an integrative research approach, combining field experiments, climatic modeling, and bibliometric analysis, to advance our understanding of sustainable soil and water management in urban environments experiencing dynamic ecological and climatic transitions.

2. Reason for Choosing This Research Problem

The reason for choosing this research problem is the considerable degradation of urban soil's ecological and health functions by anthropogenic activities, specifically when compared to natural forest soils (Weissert et al., 2016; Zhao et al., 2013). Urbanization mainly contributed to this degradation in urban soil. Presently, more than 50% of the world population lives in urban regions, which is expected to increase to 70% by the end of 2050 (United Nations, 2014, 2019). Besides the expansion of urban areas, climate change and land use changes have shown significant impacts on the urban soil's hydrological processes. These alterations disrupt the hydrological water cycle by reducing soil water infiltration, increasing surface runoff, and changing both in groundwater and soil moisture dynamics. The impact of rapid urban development and economic growth on the soil hydrological processes is considerable and cannot be overlooked (Wang et al., 2020).

Climate change further affects these hydrological dynamics, specifically under extreme weather situations (de Moraes et al., 2018). Extreme and continuous droughts are becoming more common, especially in arid and semi-arid regions, due to global warming (Solomon et al., 2007). The increasing global temperatures and unpredictable rainfall patterns are increasingly depleting water and soil resources (Knox et al., 2012). Further, decreased precipitation connected with global warming has increased the intensity and frequency of droughts in urban regions, which seriously threatens ecosystem services offered by green spaces in urban areas (Mullaney et al., 2015; Gillner et al., 2014). These challenges negatively affect the urban soil water retention capacity and damage vegetation, ranging from seasonal grasses to perennial urban trees.

Besides urbanization, different environmental factors adversely influence the growth and life span of urban trees (Nilsson et al., 2001). For example, the widespread usage of chloride de-icing salt in cities with harsh winter conditions, which is used to keep roads and pedestrians passable during snowfall, significantly increases soil salinity (Fay and Shi, 2012). The accumulated salts are absorbed by the trees and vegetation near the roads, which negatively affects their health (Cunningham et al., 2008). According to Cekstere and Osvalde (2013), the trees near the salt-treated roads are susceptible to the stress induced by salt, and the increasing use of de-icing salt agents in recent times for safer transportation demanded by the public has been linked to high tree mortality rates in the urban regions.

In many urban settings where plantation taller vegetation is impractical, lower-growing vegetation, such as grassy lawns, plays an essential role in improving in water retention capacity of the soil. Intensively managed urban grassy lawns among the diverse urban green spaces have become dominant, comprising a considerable element of the city environment globally (Ignatieva et al., 2020; Ignatieva and Hedblom, 2018). These lawns are typically maintained via regular mowing for aesthetic, cultural, and recreational purposes (Kowarik, 2011; Aronson et al., 2017). Nonetheless, routine mowing activities commonly implemented for urban lawns often result in high soil compaction and bulk density, which diminishes soil porosity and limits soil water infiltration capacity (Gregory et al., 2006). As a result, these situations contribute to elevated soil erosion and surface runoff. Furthermore, Lee et al. (2017) emphasized that changing urban grassy lawns into impervious surfaces, rather than transforming them into natural meadows, can intensify urban heat island effects and increase stormwater runoff, thus negatively impacting urban environments.

Therefore, this dissertation was designed to address the hydrological consequences of anthropogenic pressure on urban soils from multiple, complementary perspectives. Given the complexity of urban environments, where biological, climatic, and technical factors interact, the research combines three interconnected approaches:

1) An experimental approach, which tests how soil amendments (e.g., spent coffee grounds, salt, sand) and vegetation management practices (e.g., mowing intensity, meadow establishment) influence key hydrological properties such as water retention, repellency, and infiltration (publications 2 and 3);
2) A modeling approach, which evaluates how climate-related factors (e.g., precipitation, wind, temperature extremes) affect soil moisture over time using long-term meteorological data and econometric modeling (ARDL) in two major Polish cities (publication 4);
3) A bibliometric synthesis, which maps current global research trends in the field of NBS and urban soil hydrology, identifies thematic gaps and underrepresented regions (publication 1).

This tripartite research design was chosen deliberately. It allows not only for the evaluation of immediate, measurable changes in soil functioning (experimental part), but also for broader inference about long-term patterns and potential solutions (modeling and literature analysis). Integrating these approaches enhances the scientific and practical value of the work and supports the development of evidence-based guidelines for sustainable urban land and water management.

3. Objectives

The main objective of this doctoral research was to develop and validate effective techniques for assessing and improving water retention properties in urban soils under the influence of anthropogenic factors and climate variability. This problem becomes increasingly urgent given the increasing frequency of extreme weather events and the alternating periods of drought and flooding affecting urban areas worldwide. To comprehensively address the complexity of the problem, the study combined three complementary methods, as only such an integrative approach enabled both detailed local analysis and broader contextualization within the international scientific discourse.

The specific objectives supporting the main research goal were:

1) To evaluate the impact of various soil amendments (road salt, spent coffee grounds, sand) and various vegetation management approaches (mowed lawns, non-mowed lawns, and flower meadows) on the hydrological and physicochemical properties of urban soil.
2) To investigate how nature-based solutions targeting the lower vegetation layer can influence soil moisture, temperature, infiltration, and other processes regulating urban retention and microclimate.
3) To analyze the long-term variability of soil moisture in selected urban regions (Krakow and Warsaw) in relation to climatic variables using remote sensing data and ARDL dynamic modeling.

To broaden the research within current global trends and challenges by conducting a bibliometric analysis of publications related to nature-based solutions (NBS) and urban soil hydrology (1973–2023), identifying knowledge gaps and practical opportunities for sustainable urban planning.

This research was guided by the following hypotheses:

H1. The addition of spent coffee grounds (SCGs), an organic waste material, to urban soils will not only modify chemical properties (e.g., pH, nitrogen content) but also significantly improve their hydrological functions.

H2. Simple nature-based interventions at the level of lower urban greenery, such as limiting mowing or introducing species-rich flower meadows, can enhance soil water retention and mitigate the urban heat island effect.

H3. In the face of accelerating climate change, traditional field and laboratory assessments must be complemented by modeling techniques to capture long-term trends in soil moisture dynamics using meteorological and remote sensing data.

H4. The hydrological effects of both organic soil amendments and vegetation restructuring are not only measurable in the short term, but may also induce **gradual, long-term transformations** in the water retention potential of urban soils.

4. Materials and Methods

The complexity of the research problem, encompassing hydrological, biological, and climatic aspects, required an interdisciplinary and multi-layered research design. Urban soil functions as a sensitive and dynamic component of anthropogenically altered ecosystems, and thus cannot be fully understood through a single-scale or single-method approach. To capture the full context of how urban soils respond to environmental pressures, the research was structured to include short-term field-based measurements, long-term climate-driven analyses, and a global scientific perspective based on literature trends.

The methodological framework of this dissertation was built upon three complementary pillars:

1) Empirical field experiments were conducted on grassland and meadow plots at the University of Agriculture in Krakow, aimed to assess the effects of soil amendments (spent coffee grounds, salt, sand) and vegetation management strategies (mowed lawns, unmowed lawns, and flower meadows) on key hydrological and physicochemical properties of urban soils. Although limited to a single growing season, the fieldwork was conducted under standardized and controlled conditions, yielding reliable comparative data.
2) Statistical and dynamic modeling (ARDL) based on long-term meteorological data from Krakow and Warsaw allowed for assessing of how climatic variables, such as precipitation, air and surface temperature, humidity, and wind speed, influence root zone soil moisture. The goal was not to reproduce field observations, but to supplement them and explore broader temporal patterns and future scenarios under climate change.
3) A bibliometric analysis of more than 13,000 scientific publications (1973–2023) related to nature-based solutions in the context of urban soil hydrology served as an analytical foundation. This review identified global research hotspots, methodological gaps, and underrepresented regions, further supporting the relevance and originality of the dissertation’s empirical focus.

This integrative research plan was deliberately chosen to reflect the complexity of urban environmental systems and to deliver insights that are both scientifically robust and practically applicable. While the three approaches differ in scope and method, they complement one another by offering a layered understanding of the same problem. Taken together, they allowed for the verification of the research hypotheses and for the development of practical

recommendations in the field of urban soil and greenery management under changing climatic conditions.
Since each component of the study was guided by different methodological assumptions, the following sections present them separately, in line with the structure adopted in the scientific publications on which this dissertation is based.

4.1 Description of Bibliometric Analysis of Nature-Based Solutions in Urban Hydrology

Bibliometric analysis was conducted as part of this dissertation to provide a broader scientific context for the experimental and modeling work. This methodological component allowed for identifying key research trends, collaborative patterns, and knowledge gaps in the field of nature-based solutions (NBS) applied to urban soil hydrology.
The analysis was based on data retrieved from the Scopus database on November 13, 2024. The following keyword string was used in the "Topic" search (title, abstract, and keywords): ("vegetation" OR "trees" OR "blue green infrastructure" OR "greenery" OR "green infrastructure" OR "nature-based solutions") AND ("hydrolog") AND ("city" OR "urban" OR "soil").
The search was limited to publications from 1973 to 2023, written in English, and included research articles, review papers, and conference proceedings. After applying these filters, 13,276 records were selected for further analysis and exported in CSV format.

Data visualization and mapping were done using two open-access bibliometric tools: VOSviewer (v1.6.20) and Biblioshiny (v4.3.0, part of the Bibliometrix R package). These tools enabled the construction of co-authorship and co-keyword networks, a visual representation of thematic clusters, and tracking the evolution of terminology over time. The analysis also included country-level publication productivity and international collaboration networks, further contextualized by plotting the number of publications per country against GDP data (World Bank, accessed November 16, 2024) using Python and Plotly.

The bibliometric approach allowed for the identification of dominant research domains, emerging themes, and the spatial distribution of scholarly activity in this interdisciplinary field. It also highlighted the relative underrepresentation of research focused specifically on soil water retention in urban areas, as well as the fragmented treatment of low vegetation layers and soil amendments within the NBS literature. While bibliometric analysis is increasingly used in environmental sciences, this study contributes a novel application by specifically targeting the intersection of urban soils, hydrology, and nature-based approaches.

In the context of the dissertation, this component helped define the relevance and originality of the research questions posed in the experimental and modeling parts of the study. It also served as a reference framework for positioning the dissertation's findings within the broader scientific discourse.

4.2 Description of Soil Amendments (i.e., SCGs, salt, and sand) Experiment

This field experiment was conducted during winter 2022 on the campus of the University of Agriculture in Kraków, in a less-frequented urban lawn area (Fig. 1). The site, classified as Urbic Technosol (WRB-FAO, 2015), developed on Quaternary sands and characterizes typical urban soil conditions in the Kraków region. The climate during the study period (January–March) was moderately cold, with average monthly precipitation of ~50 mm, mean temperatures between –2°C and 3°C, and average relative humidity of 79%.

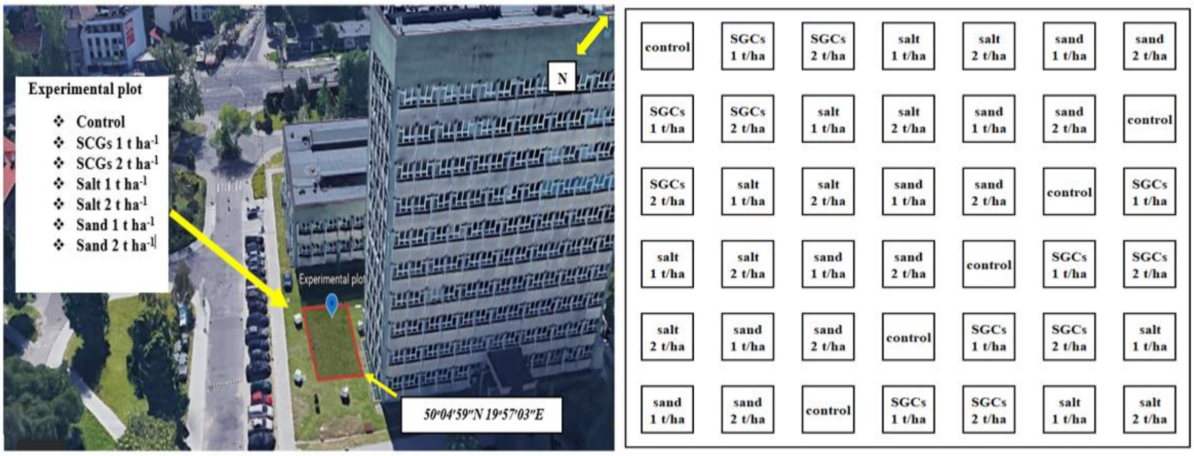

Figure 1. Study site location and experimental layout

This research study employed a completely randomized design (CRD) with 1 × 1 m plots. Four treatments were applied: (1) spent coffee grounds (SCG); (2) road salt (NaCl); (3) sand; (4) control (no amendment).

SCG, salt, and sand were applied at two rates: 1 t ha^{-1} and 2 t ha^{-1}. Each treatment combination was replicated six times, resulting in a robust comparison of amendment effects. Three months after application, soil samples were collected at a 10 cm depth using 100 cm^3 Kopecky cylinders for subsequent analysis of chemical and hydrological properties.

The SCG used in this study was obtained from local coffee shops and characterized by slightly acidic pH, nitrogen content of 0.8–2.3%, and a C/N ratio of 18–22. The road salt, sourced from the Kłodawa Salt Mine, was 90% pure NaCl, with the remainder composed of water-insoluble particles and 20 mg kg^{-1} of potassium ferrocyanide as an anti-caking agent. The sand amendment consisted of fine quartz material (SiO_2, particle size 0–0.5 mm, Grade II) sourced from a regional aggregate supplier.

This controlled field experiment enabled a comparative assessment of how organic (SCG) and inorganic (salt, sand) amendments influence key soil properties relevant to water retention and urban soil health under winter conditions typical of Central European cities.

4.3 Vegetation Management Experiment: Mowed Lawns, Unmowed Lawns, and Flower Meadows

This study was conducted between May and October 2023 on the campus of the University of Agriculture in Kraków, within a representative urban setting. The experiment examined three vegetation types: mowed lawns (A), unmowed lawns (B), and flower meadows (C). Each vegetation type included seven replicate plots, with measurements taken three times per month over the six-month period (Fig. 2).

The lawn areas (A and B) consisted of common grassland species such as *Achillea millefolium, Plantago spp., Bellis perennis, Trifolium repens*, and *Ranunculus acris*, accompanied by grasses like *Festuca spp.*, *Lolium spp.*, *Agrostis spp.*, and *Poa spp.*. Flower meadows (C), was established in 2022 as part of biodiversity initiatives, were sown with a native-adapted "Polish Flower Meadow" seed mix. Species included *Ranunculus spp., Chrysanthemum cinerariifolium, Papaver rhoeas*, and *Vicia spp.*. The turf was removed prior to sowing, and seeds were mixed with sawdust or sand to ensure even distribution (recommended seed rate: 2 g/m^2).

All vegetation plots (5×5 m^2) were maintained under identical conditions: no irrigation, no fertilization, and exposure to the same microclimate, rainfall, and urban pollution. The soil at the site was classified as Urbic Technosol (WRB-FAO, 2015), formed primarily from Quaternary sands, loess, and alluvial deposits. The campus green areas were originally established approximately 40 years ago and maintained by regular mowing until recent years, when selected areas were converted to meadows or left unmanaged for ecological purposes.

This controlled design enabled the assessment of how different vegetation management practices affect soil water retention and microclimatic regulation under real urban conditions.

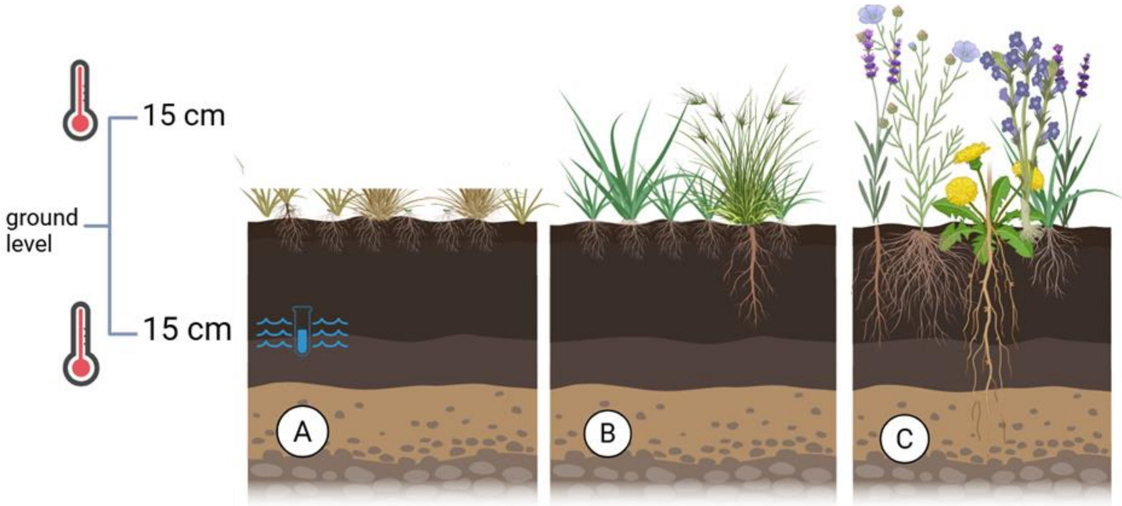

Figure 2. Graphical representation of the different vegetation management strategies; 🌡 Air temperature measured at 15 cm above ground; 🌡 Soil temperature measured up to 15 cm below soil level; 🔵 Soil water content; Infiltration measured at ground surface; A – mowed lawn; B – non-mowed lawn; C – flower meadows

4.4 Climatic Modeling of Root Zone Soil Moisture (RZSM)

This part of the study investigated the long-term impact of selected climatic variables on root zone soil moisture (RZSM) in two Polish cities: Kraków and Warsaw. Kraków (50°03′52.75″N, 19°56′41.93″E), located in southern Poland, covers an area of 327 km² and has a population of approximately 750,000. Its climate is temperate, with a mean annual temperature of ~9 °C and average annual precipitation around 650 mm. Significant sources of CO_2 emissions in Kraków include transportation, natural gas combustion, coal heating, and industrial activities (Jasek-Kamińska et al., 2020). Warsaw (52°13′23.83″N, 21°01′32.27″E), the centrally located capital, exhibits a similar temperate climate, with hotter summers and colder winters. Mean annual temperature ranges between 8–9 °C, and precipitation averages between 500–600 mm yearly. Climatic trends indicate a temperature increase of ~0.4 °C per decade in Warsaw (Kostka & Zając, 2022). While both cities share comparable urbanization levels, soil characteristics differ: Kraków's soils include sandy and clay loam types (Podwika et al., 2020), whereas Warsaw is dominated by sandy soils with better drainage, which influences water retention and urban tree vitality.

Meteorological data were obtained from the NASA POWER database (https://power.larc.nasa.gov) for the period 1985–2023. The analysis focused on six independent climatic variables:

- earth skin temperature (EST, °C),
- relative humidity at 2 m (RH2M, %),
- wind speed at 2 m (WS2M, m/s),
- maximum temperature at 2 m (T2M_MAX, °C),
- minimum temperature at 2 m (T2M_MIN, °C),
- annual precipitation (PCS, mm).

The dependent variable was root zone soil moisture (RZSM) at a depth of 100 cm, serving as a proxy for plant-available water storage. Based on prior studies and the structure of autoregressive distributed lag (ARDL) models, the following time-series regression equation was applied:

$$RZSM_t = \sigma_0 + \sigma_1 EST_t + \sigma_2 RH2M(\%)_t + \sigma_3 WS2M(m/s)_t + \sigma_4 T2M_{MAX(°C)_t} + \sigma_5 T2M_{MIN(°C)_t} + \sigma_6 PCS(mm)_t + \varepsilon_t \quad (1)$$

This formulation enabled the evaluation of short- and long-term relationships between climatic drivers and RZSM, allowing for a better understanding of how ongoing environmental changes may affect soil moisture availability in urban ecosystems.

4.5 Soil Hydrological Properties

The subsequent investigations on soil amendments and urban vegetation management evaluated the given soil hydrological properties:

1. **Water Storage Capacity:** The soil samples were taken from each experimental plot, and their fresh mass (Mf) was recorded immediately. The samples were then fully saturated by immersing them in distilled water at room conditions (approximately 21°C with 30% relative humidity). When the soil samples were saturated entirely in water, the samples were taken out from the water after 24 and 4 hours, to weigh their masses M24 and M4. After this, the soil samples were dried in an oven at 105°C for 24 hours to measure the dry mass (Md). The water storage capacities, such as Sa, S4, and S24, were calculated by using the mass differences as described by Klamerus-Iwan et al. (2020) and Khan et al. (2023) by the given formulas.

$$S4 = \left(M4 - \frac{Md}{Md}\right) \times 100 \quad (2)$$

$$S24 = \left(M24 - \frac{Md}{Md}\right) \times 100 \quad (3)$$

$$Sa = \left(Mf - \frac{Md}{Md}\right) \times 100 \quad (4)$$

2. **Water Drop Penetration Time (WDPT) Test:** The water drops penetration time determines how much a single drop of water takes time to completely absorb within the soil sample (Hallin et al., 2013; Doerr, 1998). In this experiment, a standardized medical dropper was employed to place three uniformly sized water drops onto the surface of each soil sample was timed through a digital stopwatch. The WDPT was measured in two soil samples: fresh soil samples (WDPT_1) and samples dried in laboratory conditions at room temperature for 5 days (WDPT_2). This approach enables evaluating how soil samples, treated with different treatments, respond to the drying process. The WDPT test was also measured on soil samples collected from different vegetation management covers (A, B, and C).
3. **Volumetric Water Content:** A TEROS_12 sensor (Meter n.d.) apparatus was utilized to determine the volumetric water content (VWC%) of the soil. The VWC (θ) was measured by using the following equation:

$$\theta\left(\frac{m^3}{m^3}\right) = 3.879 \times 10^{-4} \times RAW - 0.695 \quad (5)$$

4. **Capillary Capacity (P_k (mm)):** The capillary capacity (P_k) was measured in individual monoliths, which were soaked in water for 7 to 10 days, with initial soaking of monoliths for 2 to 3 days with gradual filling of water (Ilek et al. 2017). The capillary capacity (P_k) was measured by using the following formula:

$$P_k = \left(\frac{v}{V}\right) \times 10 \quad (6)$$

5. Soil Water Infiltration Time: The soil water infiltration duration across different vegetation management strategies (mowed and non-mowed lawns, and flower meadows) was evaluated by mini disk infiltrometer (MDI) (Decagon Devices, Inc., Pullman, WA).

6. Root zone soil moisture: The root zone soil moisture in Krakow and Warsaw was determined by using the regression method (dynamic ARDL model) to predict the impact of different climatic variables on root zone soil moisture.

4.6 Soil Chemical Properties:

The following soil chemical properties were analyzed during this study.

1. **Soil Nitrogen and Carbon Content:** Soil samples were collected in a plastic tube (100 cm3) from each experimental unit for nitrogen and carbon analysis. The soil samples were allowed to dry in the air, and unwanted materials, such as leaves, stones, and other materials, were removed from the soil. The ready cleaned soil samples were then passed through a 2 mm sieve. A 10-gram soil sample was taken from the ready soil samples from each treatment and grounded in a ball mill (Fritsch) for the analysis of nitrogen (N%) and carbon (C%) in a LECO TrueMac Analyser (Leco, St. Joseph, MI, USA).
2. **CO_2 emissions:** The soil carbon dioxide emissions were measured by using the closed chamber incubation method with sodium hydroxide (NaOH) as described by Hopkin (2006). In this procedure, 30 mL of a 1 M NaOH solution was shifted into a beaker and introduced into every soil column. The CO_2 emitted from the soil reacted chemically with NaOH according to the following equation, resulting in the sodium carbonate.

$$2\ NaOH + CO_2 \longrightarrow Na_2Co_3 + H_2O$$

   The barium chloride solution was not used for carbonate precipitation because the soil samples contained no carbonate compounds. To ensure accurate CO_2 measurement and retain soil moisture levels, each soil column with its corresponding beaker was tightly sealed in a plastic bag and placed at 20 °C in an incubator. After a one-week incubation time, the amount of NaOH was quantified by back titration with 0.5 M HCl through potentiometric titration, using an automatic titrator (Mettler Toledo, Inc., Columbus, Ohio). The back-titration was conducted according to the given equation.

$$NaOH + HCl \longrightarrow NaCl + H_2O$$

3. **Soil pH:** To determine soil pH (Buurman et al., 1996), a potentiometric approach, using a combined electrode and a soil suspension (1:5 m/v ratio in distil water), was used.
4. **Total Acidity:** The total acidity of the collected soil samples was determined by the potentiometric titration method (automated titrator Mettler Toledo) (Buurman et al., 1996).
5. **Soil Temperature:** TEROS_12 was used to measure the soil temperature across the different vegetation management covers.

6. **Air Temperature and Air Humidity:** The soil temperature and air humidity across various vegetation covers (A, B, and C) were calculated by using a meteorological apparatus called a thermo-hygrometer (Mutech).

4.7 Statistical Analysis:

The following statistical analysis were used in each study to formulate their specific objectives.

1. **Publication 2:** The statistical analyses of the collected data were primarily performed via Microsoft Excel to carry out analysis of Variance (ANOVA). To recognise statistically significant differences between the various treatments, consisting of control, salt, spent coffee grounds, and sand applied at rates of 1 and 2 t/ha, the test Least Significant Difference (LSD) approach was used using Statistix software (V 8.1). Furthermore, Tukey's Honestly Significant Difference (HSD) test was used in Python to measure the mean differences across treatment groups. The graphic visualizations in the form of boxplots were created using the Python library Seaborn (Waskom et al., 2020). Additionally, statistical calculations, such as principal component analysis (PCA) and regression modeling, were carried out in R via the packages "ggplot2", "Factoextra", and "FactoMiner" (Wickham, 2016; Kassambara, 2017; Le & Husson, 2008). All statistical tests in the research study were evaluated at a 95% confidence interval ($p < 0.05$).
2. **Publication 3:** The Kruskal-Wallis test was performed to evaluate the potential significant variations across the different vegetation management strategies for all parameters examined in the research study. Pairwise post-hoc comparisons were determined using Dunn's test with Bonferroni correction to find which vegetation covers significantly differed. In addition, Spearman's rank correlation analysis was applied to evaluate the relationships between multiple variables.

   Besides these statistical methods, Principal Component Analysis (PCA) was implemented to reduce the dimensionality in the dataset and uncover dominant patterns within the data. This method was particularly valuable due to the several interrelated variables, as it allowed for the identification of the most influential factors without losing essential information.

   The statistical tests and corresponding visualizations were generated using Python libraries, such as NumPy (Harris et al., 2020), pandas (McKinney et al., 2010), Seaborn (Waskom, 2021), matplotlib (Hunter, 2007), SciPy stats (Virtanen et al., 2020), and scikit learn modules for data decomposition and data preprocessing (Pedregosa et al., 2011).

3. Publication 4: This study used the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests to verify the stationarity of time series data utilized (Dickey and Fuller, 1979; Phillips and Perron, 1988). Measuring the stationarity of each series is a crucial requirement before applying the dynamic ARDL simulation model, as the presence of stationarity at I (II) in any variable would compromise the validity of the results. A time series is considered stationary if the ADF or PP test statistic indicates significance at the 5% level. In contrast, the series is considered non-stationary if the p-value exceeds the 5% threshold. The results of the ADF and PP tests show that the studied series are stationary at both the level and first difference, therefore justifying the dynamic ARDL simulation model application. As confirmed by Khan et al. (2020), the dynamic ARDL simulation model addresses several drawbacks of the traditional ARDL model, which has been used repetitively in previous studies. Notably, the dynamic ARDL simulation model has the capability to simulate and predict both positive and negative change graphs compared to the previous ARDL models. The dynamic ARDL simulation model utilized multivariate normal distributions and was based on 5000 vector simulations, as described by Jordan and Philips (2018).

$$\Delta RZSM_{2t} = \sigma_0 RZSM_{2t-1} + \beta_1 EST_t + \sigma_1 \Delta EST_{t-1} + +\beta_2 RH2M_t + \sigma_2 \Delta RH2M_{t-1} + \beta_3 WS2M_t + \sigma_3 \Delta WS2M_{t-1} + \beta_4 T2M\_MAX_t + \sigma_4 \Delta T2M\_MAX_{t-1} + \beta_5 T2M\_MIN_t + \sigma_5 \Delta T2M\_MIN_{t-1} + \beta_6 PCS(mm)_t + \sigma_6 PCS(mm)_{t-1} + \varphi ECT_{t-1} + \varepsilon_t \quad (7)$$

In the above equation (7), the coefficients σ and β represent the short-run and long-run effects of the respective variables. The term ECT_{t-1} (error correction) measures the speed at which the system returns to equilibrium aftershocks, with φ denoting the coefficient of the ECT. This coefficient typically lies within the range of 0 to -1.

5. Main Results

5.1 The influence of urban greenery in urban soil hydrology: A bibliometric literature review

5.1.1 Publications outputs over time

An extensive bibliometric review revealed a total of 13,276 documents related to nature-based solutions (NBS) and urban soil hydrology published between 1973 and 2023 (Figure 3). These included research articles, review papers, and conference proceedings from a wide range of journals, books, and academic sources.

In the early period (1973–1990), the annual number of publications remained relatively low. However, between 1990 and 2000, a steady increase in research output became evident, reflecting a growing academic interest in urban ecological solutions. A particularly sharp rise in the number of publications was observed after 2010, with annual output reaching approximately 900 articles by 2023.

This upward trend likely reflects several contributing factors: increasing global awareness of urban environmental challenges, greater availability of research funding, the growing popularity of NBS frameworks in policy and planning, and enhanced international collaboration. Additionally, advances in data accessibility and analytical tools may have accelerated scientific productivity in this interdisciplinary field. LaPoint et al. (2015) reported the increasing trend in the literature addressing topics in ecology and urban environmental research studies. Similarly, Su et al. (2023) examined the significant volume of publications, demonstrating the researchers' interest in applying nature-based solutions (NBS) to manage stormwater in urban regions.

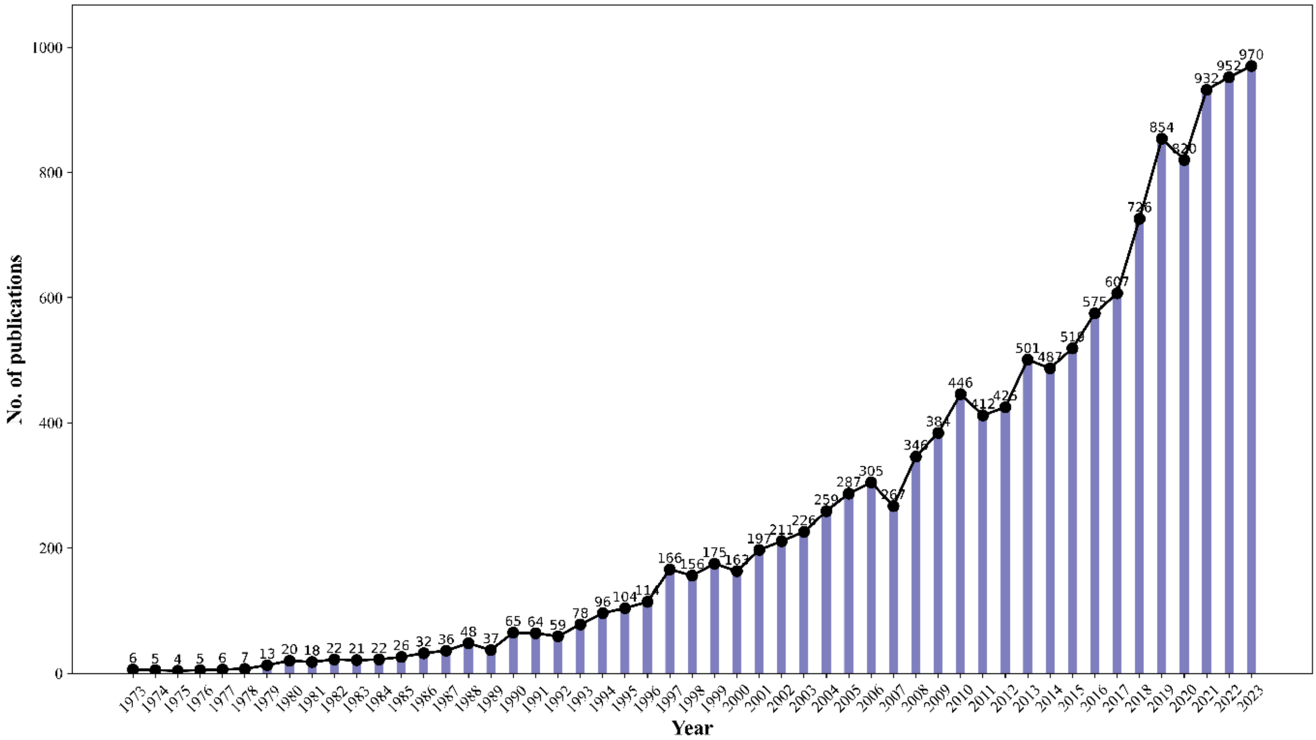

Figure 3. Annual trends in publication output from 1973-2023, showing the increasing research interest in NBS and urban soil hydrology

5.1.2 Global Contribution Map by Countries with their GDP

A global assessment of publications on nature-based solutions (NBS) in urban hydrology revealed contributions from **159 countries**, of which **97 published more than five documents** on this topic. The **United States and China** dominated the field, jointly accounting for **54.6% of the total output**, with the U.S. contributing **36%** and China **18.2%**. Other notable contributors included **Germany (7.6%)**, the **United Kingdom (7.1%)**, **Australia (7%)**, **Canada (5.5%)**, **France (5%)**, **Italy (4.6%)**, and **Spain (4.5%)**.

As shown in **Figure 4**, the countries with the highest scientific output in this field, particularly the U.S., China, and Germany, are also among the world's leading economies. This reflects a broader pattern in global research dynamics, whereby **higher national GDP correlates with increased academic productivity**. Nations with greater economic capacity are typically better positioned to support robust research ecosystems, including investments in education, infrastructure, and international collaboration.

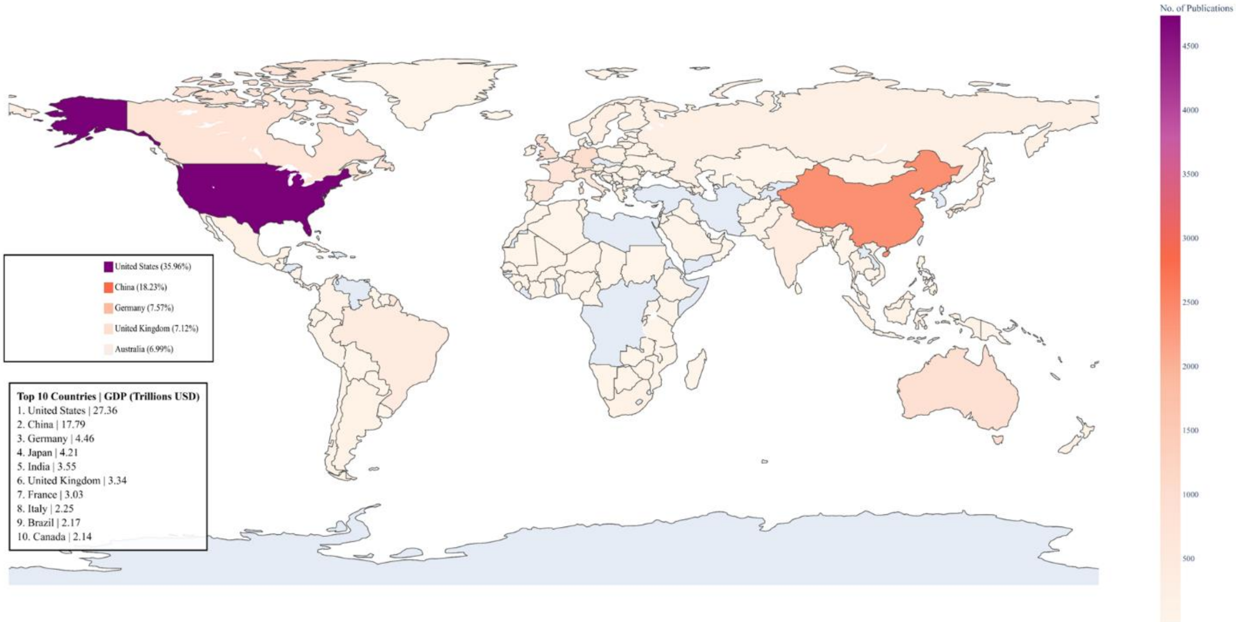

Figure 4. Top 10 leading countries with the maximum publications and GDPs on NBS and urban soil hydrology

5.1.3 Keywords Analysis of Trending Topics

The co-occurrence analysis of author keywords provides essential insights into the conceptual structure of research on nature-based solutions (NBS) in urban hydrology. As shown in Figure 5, the size of each node in the network reflects the frequency with which a given keyword appears in the literature, while the links between nodes indicate co-occurrence within the same publication. The thickness of connecting lines represents the strength of the association between pairs of keywords.

Among the most frequently used terms in this research domain were: hydrology, water quality, soil properties, climate change, restoration, ecosystem services, surface runoff, drainage, evapotranspiration, ecohydrology, soil moisture, forest hydrology, green infrastructure, hydrological modelling, soil water, low impact development (LID), streamflow, throughfall, infiltration, nature-based solutions, and stormwater management. These keywords tend to cluster into distinct thematic groups, each representing a specific subfield or disciplinary focus.

One prominent cluster includes keywords such as “urban hydrology”, “nature-based solutions”, “stormwater management”, “low impact development”, “green infrastructure”, and “urbanization”. This cluster reflects a strong research focus on anthropogenic drivers of hydrological disturbance in urban areas and the application of NBS strategies to mitigate stormwater issues and enhance urban water resilience (Zhang et al., 2023; Dong et al., 2023).

A second major cluster is centred around “hydrology”, “climate change”, “land use change”, “ecosystem services”, “wetlands”, “drainage”, “restoration”, and “surface runoff”. This group highlights the importance of landscape-scale processes and management interventions in shaping hydrological responses. The frequent co-occurrence of terms related to restoration and drainage emphasizes the increasing interest in improving water retention and reducing runoff through ecological and technical measures (Su et al., 2023; Wang et al., 2023). Together, these keyword clusters illustrate the interdisciplinary and applied nature of the field, bridging topics such as soil function, landscape management, and urban sustainability through the lens of hydrology.

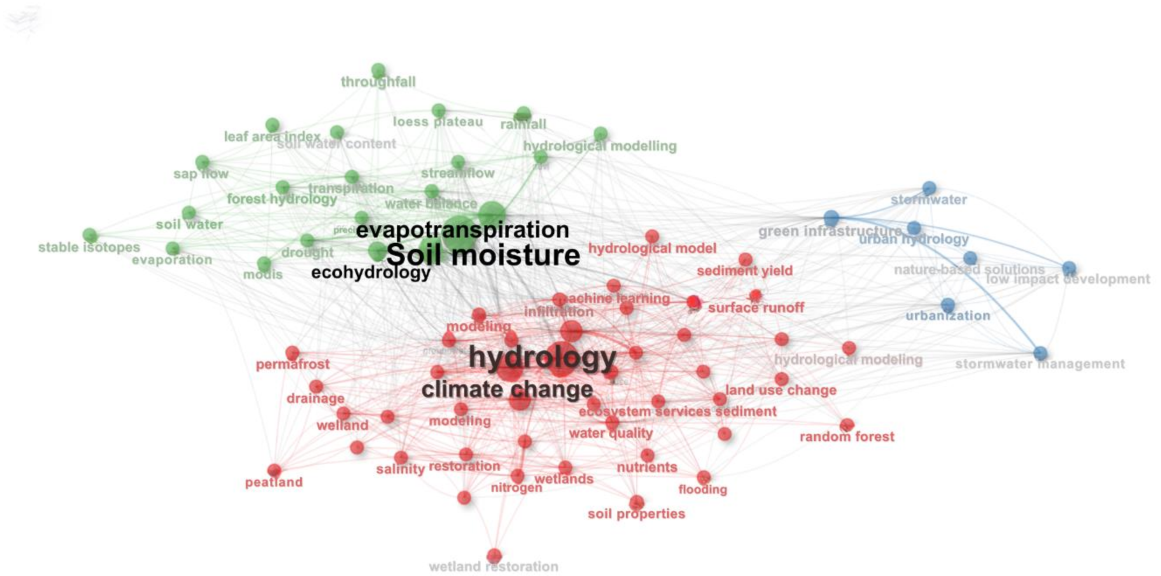

Figure 5. Trending author keyword’s distribution analysis.

5.1.4 Emerging Research Themes in NBS and Urban Soil Hydrology Over Time

Figure 6 illustrates the evolution of research themes related to the application of nature-based solutions (NBS), including vegetation, blue-green infrastructure, urban greenery, green infrastructure, and trees, in urban soil hydrology. The temporal dynamics of keyword usage reflect changing scientific priorities and technological advancements within the field.

Between 2005 and 2015, dominant research themes included nutrient cycling, acidification, hydrological simulation, drainage, species richness, nitrogen dynamics,

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productivity, vegetation, erosion, and evapotranspiration. These topics primarily emphasized fundamental ecological processes and their interaction with soil and water systems under urban pressure.

From 2015 to 2023, the focus shifted noticeably toward more integrative and technology-driven themes. Emerging keywords included remote sensing, climate change, soil moisture, green infrastructure, drought, machine learning, and nature-based solutions. This shift indicates a growing interest in data-driven approaches, climate adaptation, and the strategic implementation of NBS to improve urban resilience and soil-water interactions.

The increased use of terms such as “urban greenery”, “urban hydrology”, and “nature-based solutions” in recent years also reflects the mainstreaming of NBS concepts in urban planning, research policy, and environmental governance. Palermo et al. (2023) emphasized the significance of NBS for managing stormwater in urban areas, showing their effectiveness in decreasing surface runoff while improving infiltration and evapotranspiration. Such kind of interventions, including green walls, green roofs, vegetation, and permeable pavements, are essential for reestablishing urban hydrological cycles. Furthermore, Zeiser et al. (2023) examined that the implementation of sponge city approaches in urban environments not only supports the growth of trees by providing suitable root conditions, but it also helps in the mitigation of UHI.

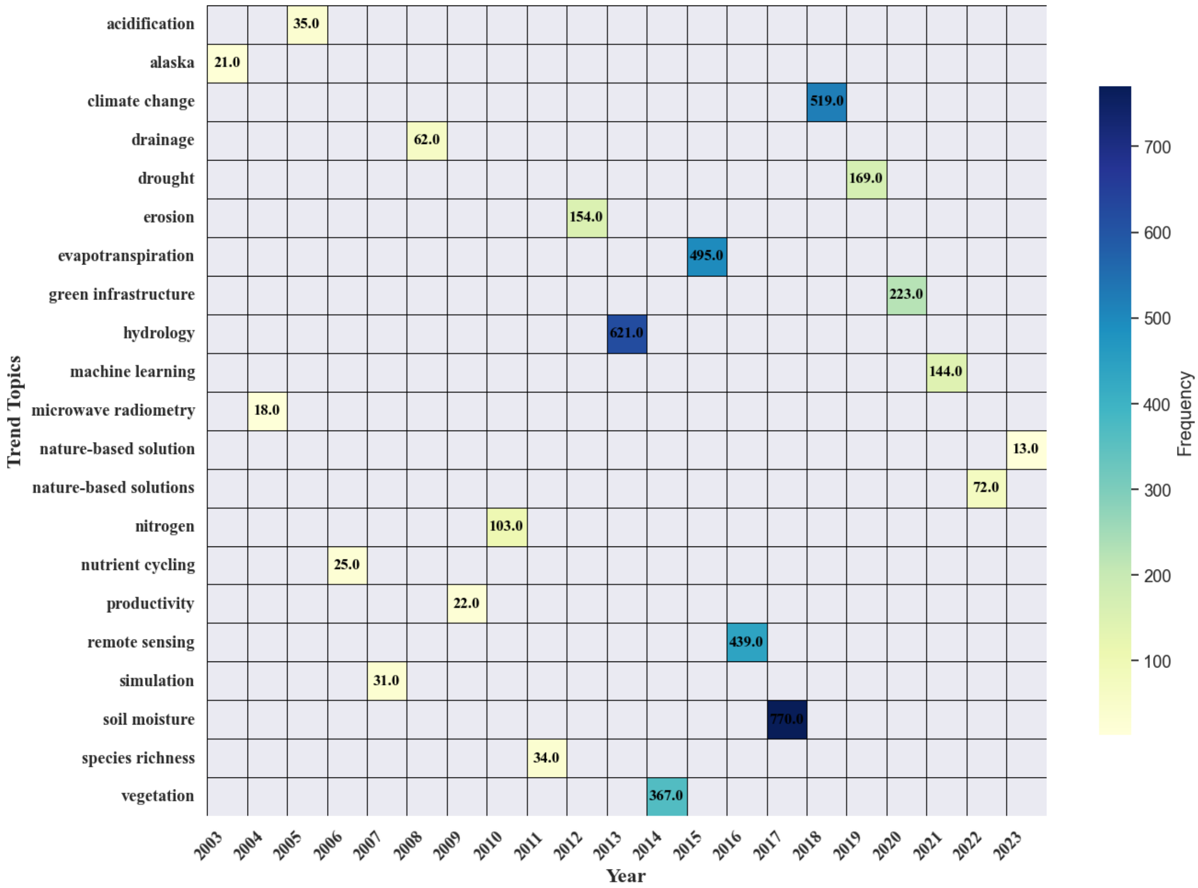

Figure 6. Temporal heatmap shows trending research topics in NBS and urban soil hydrology (2003-2023).

5.2. The short-term impact of different doses of SCGs, salt, and sand on the soil's hydrological and chemical properties

5.2.1. Impact on Soil Chemical Properties

The application of spent coffee grounds (SCGs), salt, and sand at two dose levels (1 and 2 t/ha) significantly influenced selected chemical properties of urban soil, including pH, electrical conductivity (EC), total acidity (TA), and nitrogen content (%N).

As shown in Figure 7A, soil pH values varied significantly across treatments. The application of SCGs at 2 t ha^{-1} notably reduced pH compared to the control, indicating a shift toward increased acidity. In contrast, the application of salt at 2 t ha^{-1} caused a shift toward alkaline conditions. Sand amendments had a neutral effect. Hargrove and Livesley (2016) noticed elevated soil pH in a glasshouse study, whereas lower soil pH values were observed in field conditions after the amendment of spent coffee grounds (SCGs).

In terms of electrical conductivity (Figure 7B), the addition of salt at both 1 and 2 t ha^{-1} resulted in a significant increase in EC, reflecting elevated salinity. However, neither SCGs nor sand caused statistically significant changes in EC compared to the control. Fay and Shi (2012) showed that the continuous usage of road salt has increased the salinity levels in soils near to the roads.

The total acidity of the soil (Figure 7C) was highest in the salt-amended plots, followed by SCG and sand treatments. Although all amendments affected TA significantly, differences between 1 and 2 t ha^{-1} within each treatment group were minimal.

Soil nitrogen content (Figure 7D) also varied across treatments. The highest nitrogen levels were observed in the control plots, while the lowest values occurred in the sand-amended soil. The incorporation of SCGs at 1 and 2 t ha^{-1} led to nitrogen reductions of approximately 2% and 9%, respectively, compared to the control. This suggests that short-term SCG application may temporarily suppress available nitrogen, possibly due to immobilization during the early stages of organic matter decomposition. Hardgrove and Livesley (2016) stated two pathways through which the application of SCGs suppresses the development of plants, such as biological nitrogen immobilization, and due to the presence of phytotoxic elements. Cruz and Marques (2015) reported that SCGs had no considerable impact on the nitrogen concentration in the soil over time.

The application of different soil amendments had a significant effect on soil carbon content (%), although CO_2 emissions did not show statistically significant differences between treatments.

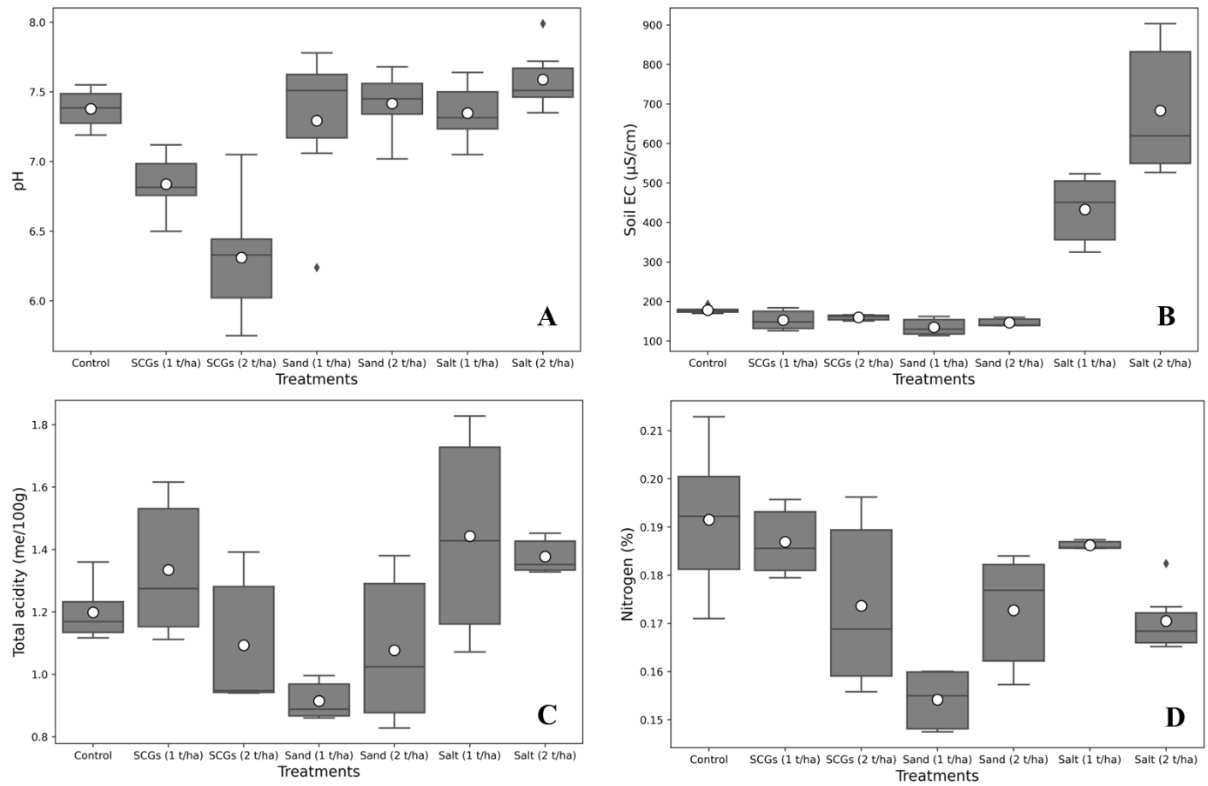

Figure 7. Boxplot of soil pH (A), soil EC (B), total acidity (C), and soil nitrogen (D) plotted against various soil amendments (control, SCGs, salt, and sand applied at 1 and 2 t ha^{-1}).

As illustrated in Figure 8A, the highest carbon concentration was recorded in soils amended with SCGs at 2 t ha^{-1}, and SCGs at 1 t ha^{-1}. These results confirm the organic character of spent coffee grounds as a carbon-rich material. In contrast, sand-amended plots exhibited the lowest soil carbon levels, consistent with their inert mineral composition. Comino et al. (2020) explained the short-term impacts of SCGs' application in two soil types for 30 and 60 days, and reported that the incorporation of 2.5% and 10% enhanced the soil organic matter content.

The highest CO_2 emissions rate (Figure 8B), was observed in the salt treatment at 1 t ha^{-1}, while the application of SCGs at 2 t ha^{-1} resulted in a notable reduction in CO_2 flux from the soil surface. Although these differences were not statistically significant, they may indicate a trend toward reduced microbial respiration or enhanced carbon stabilization under organic amendment. Abagandura et al. (2019) found that the incorporation of manure and biochar into sandy soil decreased CO_2 emissions.

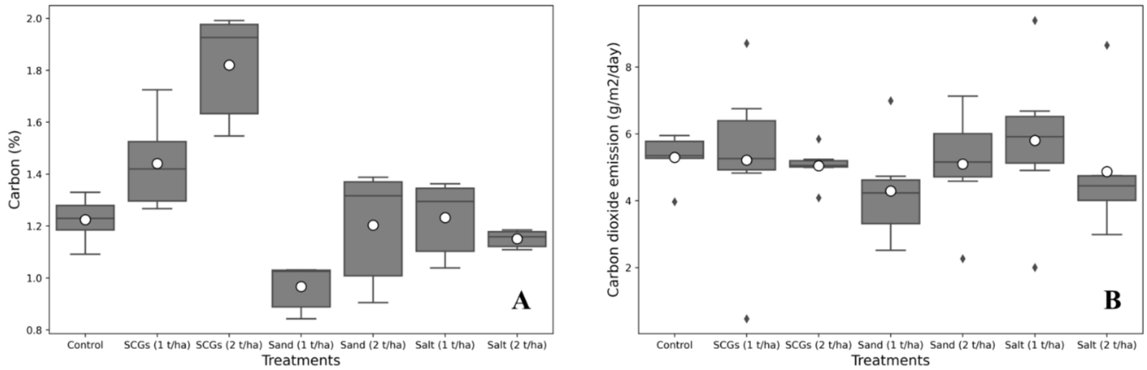

Figure 8. Boxplot of soil carbon (A) and carbon dioxide emissions (B) plotted against various soil amendments (control, SCGs, salt, and sand applied at 1 and 2 t ha^{-1}).

5.2.2. Soil Water Retention and Infiltration Properties

The volumetric water content of fresh soil samples (VWC1) was significantly enhanced by the incorporation of spent coffee grounds (SCGs), while salt amendments caused a marked reduction in this parameter. SCGs applied at 1 and 2 t ha^{-1} increased VWC1 by 9% and 18%, respectively, compared to the control, with the highest VWC1 observed in the SCG 2 t ha^{-1} treatment. In contrast, the lowest VWC1 occurred in the salt 2 t ha^{-1} treatment (Figure 9A). The water drop penetration time (WDPT1) also varied significantly across treatments. SCG application at 2 t ha^{-1} resulted in the shortest penetration time (2.33 s), while the control plot exhibited the longest time (4.83 s), indicating improved surface wettability in SCG-treated soils (Figure 9B). The WDPT was also checked on dry soil (dried at room temperature for 5 days), and the SCGs made the soil more hydrophobic due to the presence of organic matter. Cervera-Mata et al. (2023) determined that high quantities of spent coffee enhanced the soil water retention at both the permanent wilting point and field capacity.

Three indicators of soil water storage capacity, current water storage (Sa), storage after 4 hours (S4), and storage after 24 hours (S24), were significantly affected by the soil amendments (Figures 10A–C). In all cases, SCGs at 2 t ha^{-1} provided the most significant enhancement, whereas sand at 2 t ha^{-1} caused an apparent decline in all three parameters.

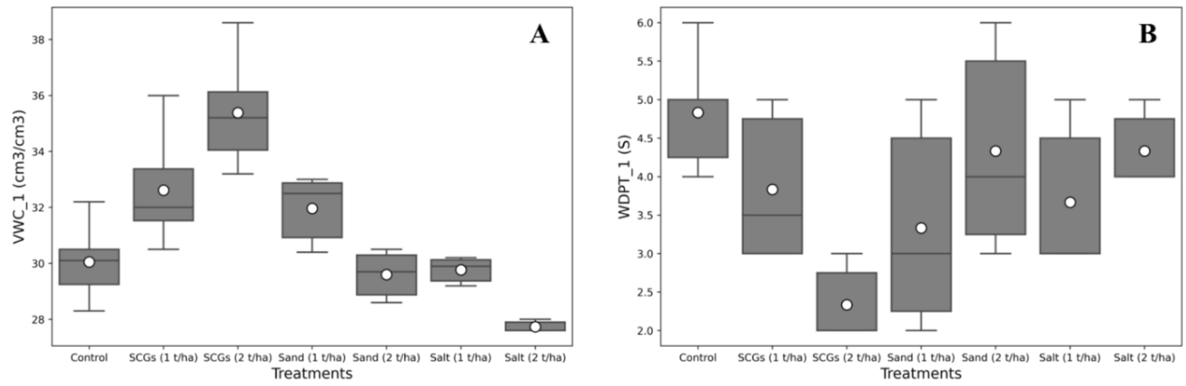

Figure 9. Boxplot of soil VWC_1 (A) and WDPT_1 (B) plotted against various soil amendments (control, SCGs, salt, and sand applied at 1 and 2 t ha^{-1}).

In addition, SCGs treatments notably improved the capillary water retention within the top 1 cm of soil (Figure 10D). SCGs applied at 1 and 2 t ha^{-1} increased capillary water by 14% and 32%, respectively, compared to the control. In contrast, salt and sand had the lowest capillary water content across all treatments. These findings confirm the strong water-retention potential of SCGs as an organic amendment in urban soils, in contrast to the unfavourable hydrological effects observed for salt and sand under short-term conditions. Numerous research studies have indicated that the addition of organic waste amendments can improve different soil properties, including the high soil's capacity to retain water and nutrients, enhance soil structure and infiltration rates, and support carbon sequestration (Haider et al., 2014; Quilty and Cattle, 2011).

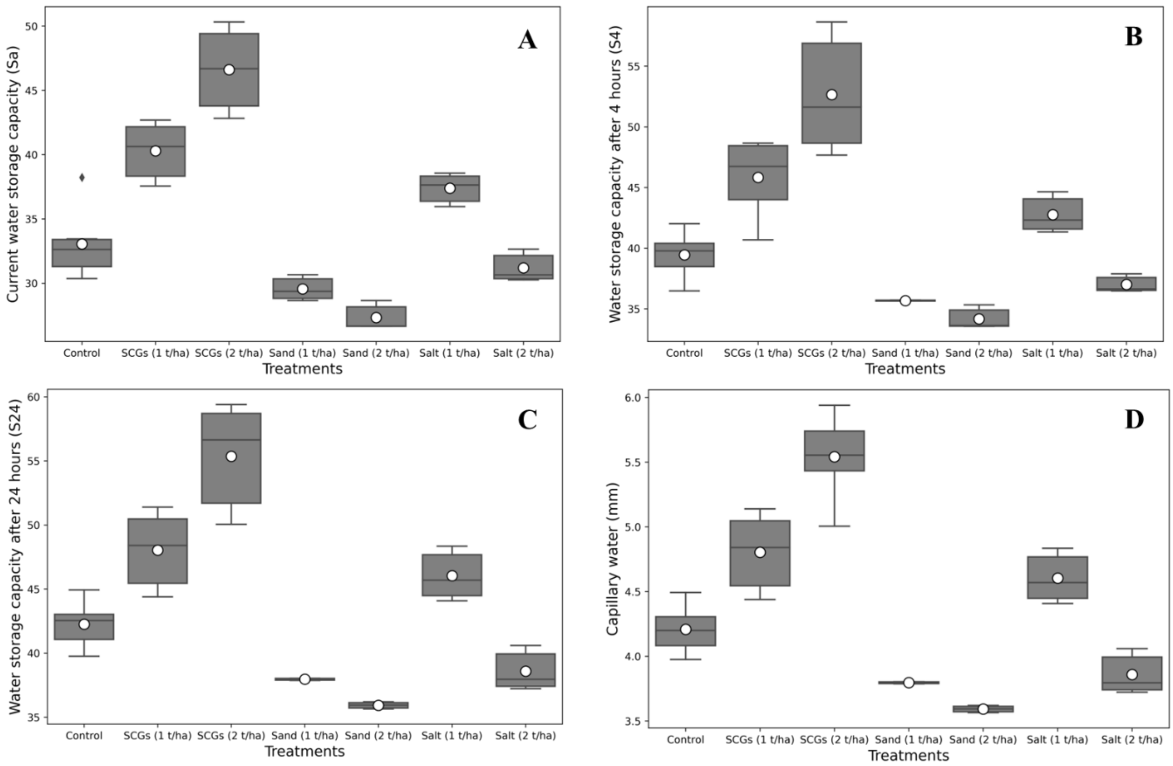

Figure 10. Boxplot of soil current water storage capacity (Sa) (A), water storage capacity after 4 hrs (S4) (B), water storage capacity after 24 hrs (S24) (C), and capillary water (mm) (D) plotted against various soil amendments (control, SCGs, salt, and sand applied at 1 and 2 t ha^{-1}).

5.3. The effect of the urban greenery management on soil water retention properties in an urban ecosystem

5.3.1 Effect of various vegetation covers and management on air temperature, air humidity, and soil temperature

The Kruskal–Wallis test revealed statistically significant differences ($p < 0.05$) in air temperature (°C) across the three vegetation types: mowed lawn, non-mowed lawn, and flower meadow. The highest average air temperature, 28 °C, was recorded in the mowed lawn, followed by non-mowed lawns (26 °C) and flower meadows (25 °C). According to Dunn's post hoc test, the air temperature above the flower meadows was significantly lower than that above mowed lawns, indicating a measurable cooling effect of diversified vegetation.

In contrast, air humidity did not differ significantly among the three vegetation types, suggesting comparable atmospheric moisture levels across the plots. However, both the median and mean air humidity were highest in the flower meadow plots, implying a potentially stabilizing microclimatic effect associated with increased vegetative complexity.

Soil temperature also varied significantly between treatments (Figure 11). The mowed lawn exhibited the highest soil temperature (27 °C), while non-mowed lawns and flower meadows recorded 24 °C and 23 °C, respectively. Pairwise comparisons showed that flower meadows had significantly lower soil temperatures than mowed lawns, and a significant difference was also observed between mowed and non-mowed lawns.

These results underscore the microclimatic benefits of reduced mowing and flower meadow establishment, particularly in terms of cooling air and soil surfaces under urban conditions. These results are in line with early studies that stated high soil temperature in regions with limited vegetation cover compared to forested soils. (Ozkan and Gokbulak, 2017; Ni et al. 2019). Urban green spaces play an essential role at the local scale in urban heat island mitigation by absorbing heat, improving humidity, and providing shade, thus helping in regulating surrounding air and soil surface temperatures.

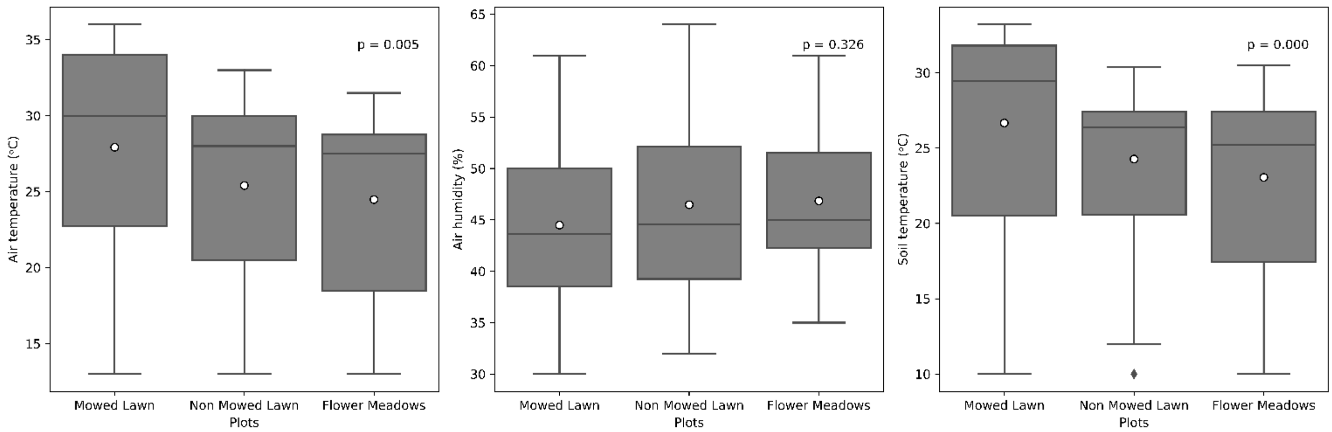

Figure 11. Boxplot of air temperature (°C), air humidity (%), and soil temperature (°C) in different vegetation covers and management

5.3.2 Influence of different vegetation management strategies on soil hydrological properties

The soil volumetric water content (VWC) was statistically different ($p < 0.05$) between the various vegetation cover types. The soil in non-mowed lawns retained the maximum water content (14 %), while the flower meadows showed the minimum VWC (11 %) (Figure 12). The lowest water content in the flower meadows may be attributed to high evapotranspiration rates, due to the presence of dense, taller, and diverse vegetation, and deeper root systems,

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which extract the maximum amounts of water from the soil. The literature shows that different plant communities with developed root systems, such as flower meadows, improve the water retention properties and soil infiltration (Wu et al., 2017; Niu et al., 2019).

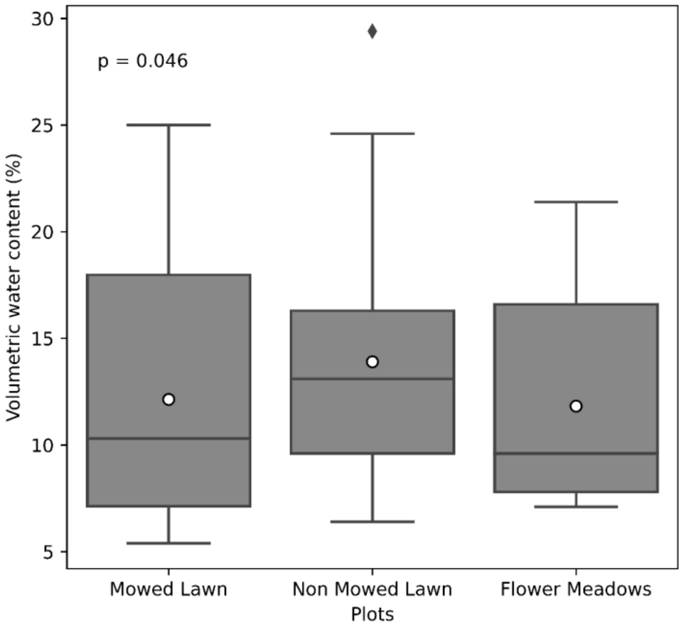

Figure 12. Boxplot of soil volumetric water content (%) in different vegetation covers and management

Statistical analyses revealed significant differences in both soil water infiltration time (seconds) and current water storage capacity (Sa) among the three vegetation types: mowed lawns, non-mowed lawns, and flower meadows. In contrast, no significant differences were observed in water storage after 4 hours (S4) and after 24 hours (S24), suggesting that long-term retention potential is relatively stable across vegetation types established on similar soils.

Among all treatments, the highest S24 was recorded in the flower meadows, while the lowest occurred in the mowed lawns. The mean Sa was approximately 34% in both flower meadows and non-mowed lawns, whereas mowed lawns exhibited a significantly lower value of 25.2% (Figure 13). These results confirm that reduced mowing positively influences the immediate soil water retention capacity.

Regarding infiltration time, the longest time (mean: 100 seconds) was measured in flower meadow plots, followed by non-mowed lawns (75 seconds) and mowed lawns (50 seconds). The infiltration rate was significantly lower (i.e., longer water time entry) in flower meadows compared to mowed lawns, which may reflect enhanced infiltration capacity due to increased surface cover, organic matter, and reduced compaction.

In contrast, the shortest infiltration time in mowed lawns likely reflects compacted surface layers caused by frequent mowing. This compaction not only restricts water entry but also negatively affects the soil's ability to retain moisture, reinforcing the benefits of reduced mowing and meadow establishment for improving urban soil hydrology. Lawns and meadows are highly effective in enhancing water infiltration, thus helping to reduce the soil erosion and flooding risks (Monteiro, 2017).

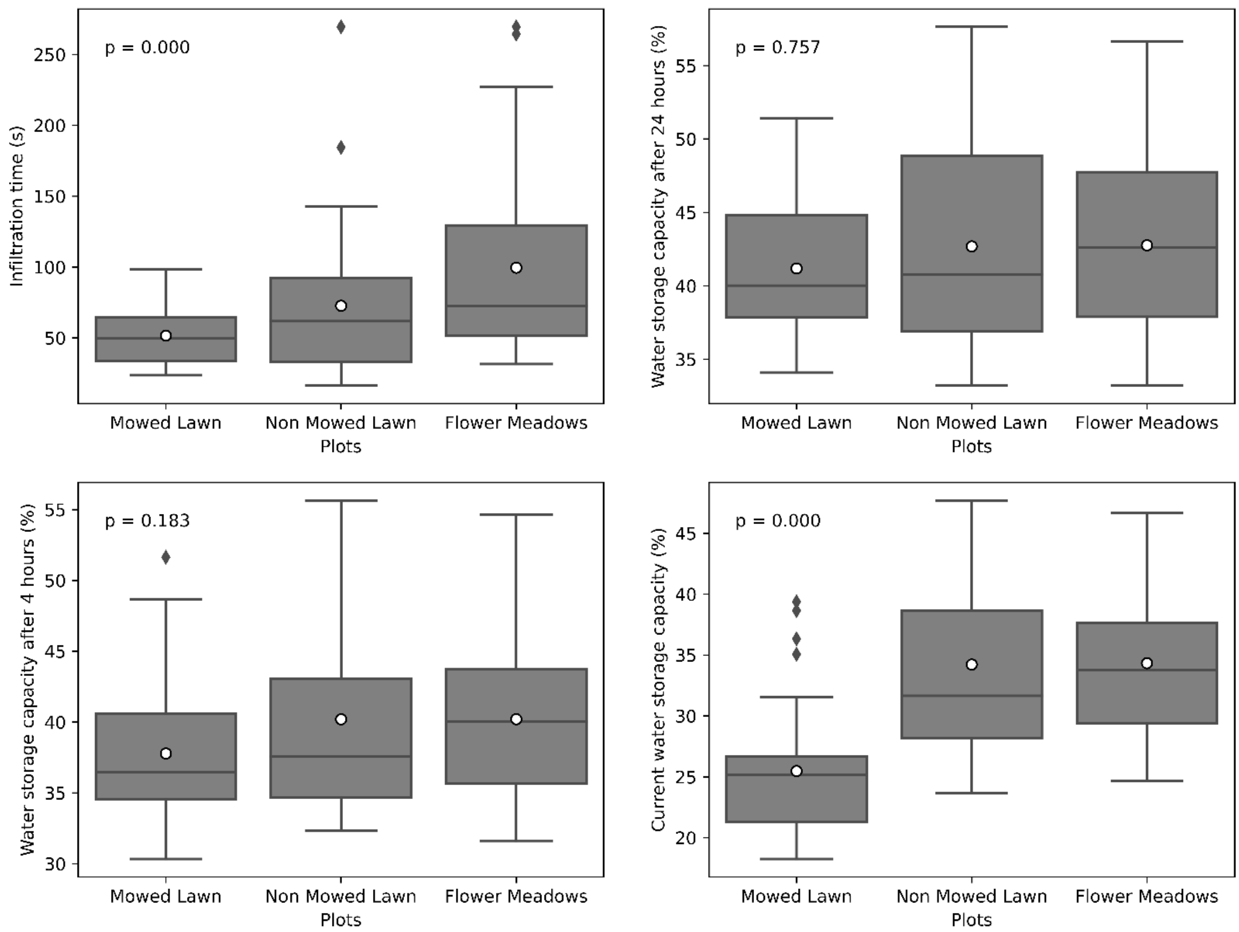

Figure 13. Boxplot of infiltration time (s), water storage capacity (S24 and S4), and current water storage capacity (S4) across various vegetation management strategies

5.3.3 Influence of different vegetation covers and management on soil carbon and nitrogen

Based on the Kruskal-Wallis test results, the soil nitrogen content (%) was statistically different ($p < 0.05$) among the various vegetation covers. In comparison, the carbon content (%) did not exhibit a significant variation ($p > 0.05$). Overall, the concentrations of nitrogen and carbon were notably low in these different plots. Among them, the non-mowed lawn showed the maximum percent of carbon as compared to other treatments. The nitrogen concentration remained below 0.2% in all three vegetation covers (Figure 14). Urban turf grass lawns are capable of carbon sequestration at a long-term rate of 0.1 kg C m-2 annually over 25-30 years (Townsend-Small, Czimczik, 2010).

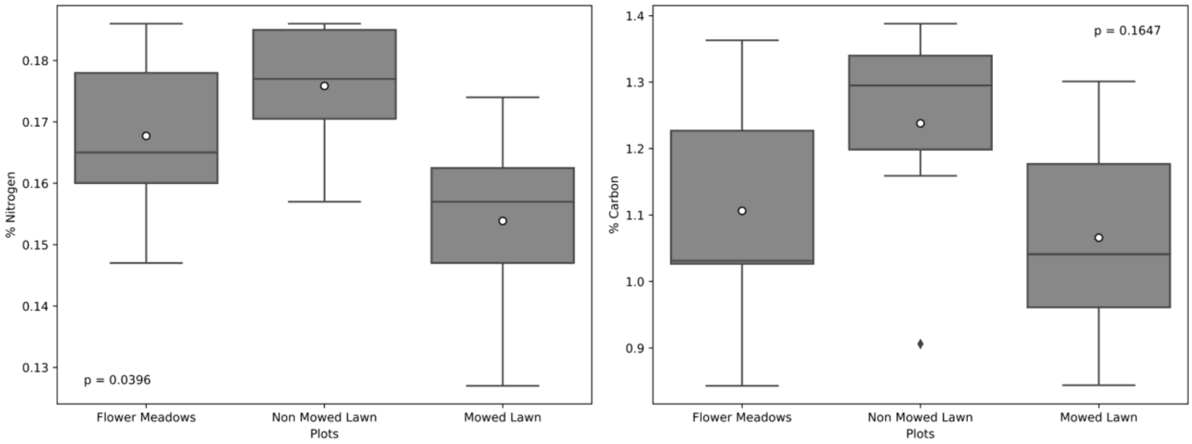

Figure 14. Boxplot of soil nitrogen (%) and soil carbon (%) across different vegetation covers and management

5.4. Simulated Effects of Climatic Variable Changes on Root Zone Soil Moisture

This analysis examined how projected increases and decreases in selected climatic variables affect root zone soil moisture (RZSM) in Kraków and Warsaw, based on ARDL model simulations.

In Kraków, a 10% increase in precipitation resulted in a consistent rise in RZSM under both short- and long-term conditions (Figure 15A). Conversely, a 10% reduction in rainfall caused a noticeable decline in soil moisture content over both time horizons (Figure 15B).

Relative humidity changes (Figures 15C–D) produced asymmetric responses. A 10% increase in relative humidity led to a general improvement in soil moisture content in both the short and long term. Interestingly, a 10% decrease in relative humidity produced a temporary increase in soil moisture in the short term, followed by a long-term decline, possibly due to lagged evapotranspiration feedbacks. The influence of precipitation on soil moisture in the root zone can vary according to numerous factors, such as vegetation cover types, climatic conditions, and soil characteristics (Banach et al., 2023).

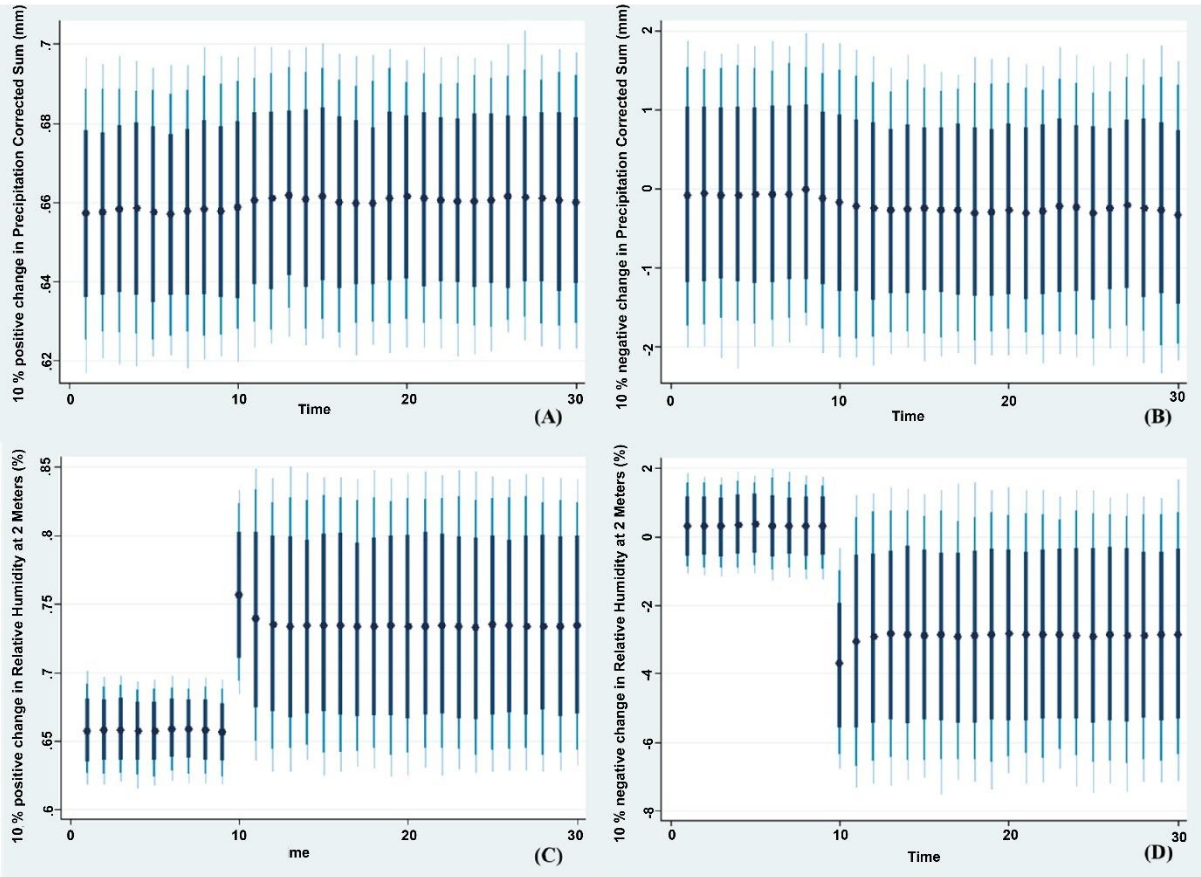

Figure 15. The dynamic ARDL simulation model shows the influence of: (A, B)10% positive and negative changes in precipitation (mm) on soil moisture. (C, D) 10% positive and negative changes in relative humidity (%) on root zone soil moisture in Krakow.

In Warsaw, Figures 16E and 16F show that a 10% increase in Earth’s skin temperature led to a steady reduction in RZSM across both time scales, whereas a 10% decrease in this variable resulted in a sustained increase in soil moisture availability. Xu et al. (2013) carried out a meta-analysis, noticed that elevated soil temperatures consistently decreased soil moisture levels across the study sites.

Similar trends were observed for wind speed at 2 m (Figures 16G–H). A 10% increase in wind speed decreased RZSM, while a 10% reduction led to improved soil moisture levels in both short- and long-term projections. The fluctuations in soil moisture are not only impacted by air temperature, but also by wind speed, humidity, and vapor pressure deficit (Wang et al., 2021). These simulations demonstrate that climatic variables, especially precipitation, temperature, and wind speed, exert substantial control over urban soil moisture dynamics. The model results also highlight the sensitivity of urban root zone soils to moderate and extreme fluctuations in weather patterns, reinforcing the need for climate-adaptive soil and vegetation management in urban planning.

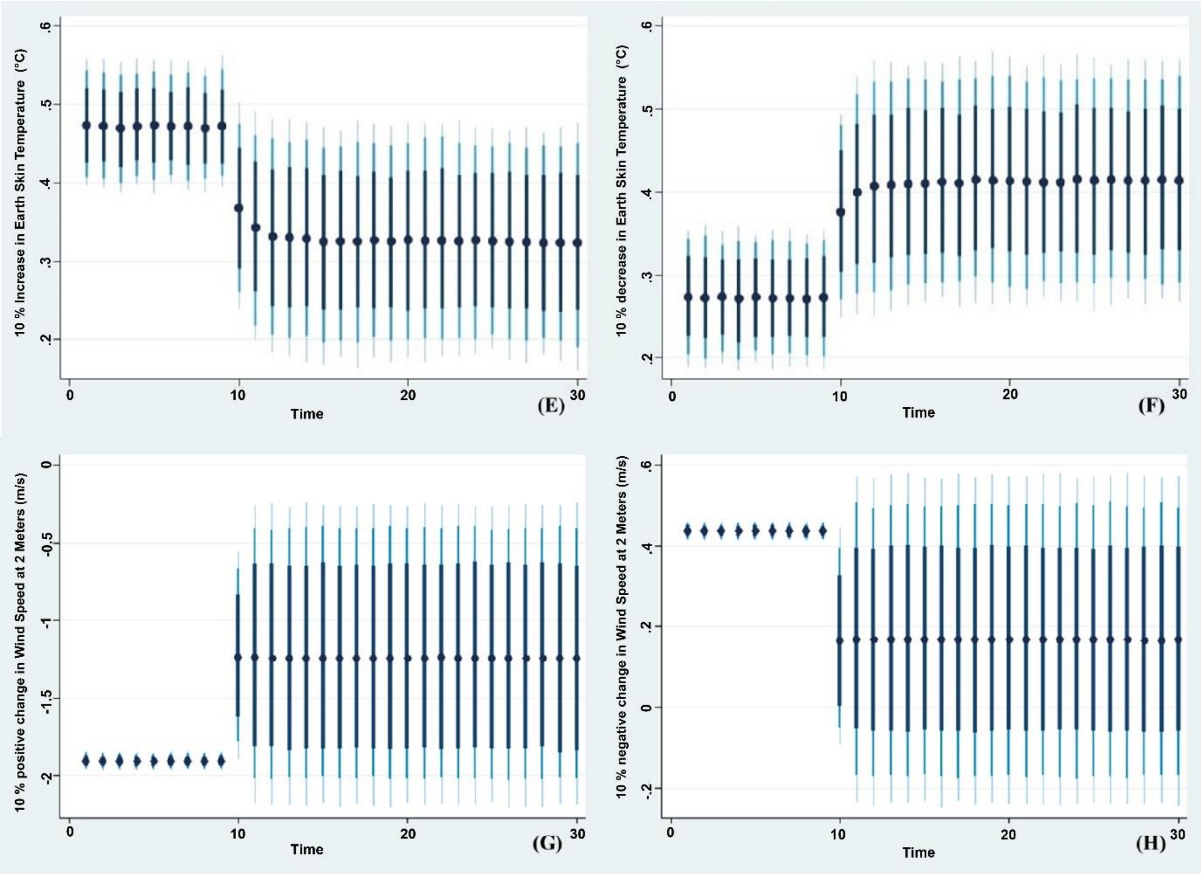

Figure 16. The dynamic ARDL simulation model shows the influence of: (E, F) 10% positive and negative changes in Earth skin temperature (°C) on soil moisture. (G, H) 10% positive and negative changes in wind speed (m/s) on root zone soil moisture in Warsaw.

6. Conclusions

This dissertation significantly advances the understanding of how urban soil hydrological functions can be assessed and improved through nature-based, site-adapted strategies. By integrating bibliometric synthesis, experimental soil treatments, and climate-scenario modeling, this research introduces a novel, interdisciplinary approach that captures localized soil-water responses and broader environmental dynamics. The findings contribute valuable knowledge and actionable recommendations for improving urban water retention, mitigating the impacts of climate change, and strengthening the resilience of lower levels of urban greenery.

The bibliometric analysis revealed a sharp and ongoing increase in global research interest in nature-based solutions (NBS) for urban hydrology over the past five decades. This review provided a strategic foundation for identifying knowledge gaps, mainly in underrepresented regions, and framing the experimental and modeling components of this dissertation within the evolving international research landscape.

The experimental field and laboratory investigations demonstrated the effectiveness of spent coffee grounds (SCGs) as an innovative, organic soil amendment. SCGs improved soil water retention, contributed to carbon sequestration, and mitigated salt-related degradation common in urban environments. However, the Water Drop Penetration Time (WDPT) test on air-dried soil samples revealed that SCGs also increased hydrophobicity due to their high organic matter content - an effect that underscores the importance of balancing water-holding capacity with infiltration potential when designing sustainable soil amendments. These findings support their practical use as part of circular economy strategies for urban soil restoration.

The vegetation management study highlighted the value of low-intervention green space practices, such as reduced mowing and the establishment of flower meadows, in enhancing soil moisture, cooling the local microclimate, and increasing soil biodiversity. While these practices do not replace the broader ecosystem services offered by urban trees, they serve as cost-effective, multifunctional complements to urban green infrastructure.

The modeling component provided insights into how climatic drivers such as precipitation, relative humidity, wind speed, and surface temperature influence root zone soil moisture under both positive and negative change scenarios. The differential responses observed between Kraków and Warsaw emphasize the importance of site-specific, climate-adaptive strategies in urban soil and vegetation management.

Altogether, this research presents a complete, scalable framework for understanding and enhancing urban soil hydrology through a combination of natural amendments, ecological maintenance practices, and data-driven climate modeling. It also demonstrates the value of integrating soil science, ecohydrology, and landscape design to improve urban resilience.

Future research should build on these findings by examining long-term effects of combined amendments, seasonal vegetation strategies, and interactions between soil, land use, and climate variability across diverse urban settings. Such interdisciplinary efforts are essential to developing practical, evidence-based tools for urban planners, green space managers, and policymakers trying to secure soil functions as a foundation of sustainable and climate-resilient cities.

7. References

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8. Scientific Achievements List

8.1 Published Papers (Not part of this thesis)

- Kupka, D., **Khan, M. O.**, Kwika, A., Słowik-Opoka, E., & Klamerus-Iwan, A. (2022). Experimental short-time wildfire simulation—Physicochemical changes of forest mucky topsoil. *Frontiers in Forests and Global Change*, *5*, 987010.
- Klamerus-Iwan, A., Ruiz, L. C., Gómez, C. M., Warczyk, A., Singh, P. D., **Khan, M. O.**, & Caballero-Calvo, A. (2024). Assessing water storage capacity and wettability of plants and woody fragments in post-fire environments: A case study in Los Guájares, SE Spain. *Trees, Forests and People*, *17*, 100607.
- Klamerus-Iwan, A., **Khan, M. O.,** Singh, P. D., Warczyk, A., & Stopyra, M. (2024). Water retention capacity of red-stemmed feathermoss Pleurozium schreberi Mitt. *sylwan*, *168*(02).

8.2 National and International Conferences and Seminars Attended

- **Muhammad Owais Khan,** 2023. "Impact of Climate Change on Soil Water Availability in Cities" lecture delivered in Erasmus BIP CLIMATE-SMART FORESTRY, Kraków 14-20.05.2023
- Kupka D, **Muhammad Owais Khan,** Kwika A, Słowik-Opoka E and Klamerus-Iwan Anna, 2022. Experimental short-time wildfire simulation—Physicochemical changes of forest mucky topsoil. Poster Presented in 6TH International Scientific Conference Biohydrology (6-9 September 2022 Krakow, Poland).
- **Muhammad Owais Khan,** Anna Klamerus Iwan, Dawid Kupka, Ewa Słowik-Opoka, 2023. Initial impact of different doses of coffee and salt on soil chemical and hydrological properties in an urban ecosystem. Poster Presented in International BonaRes Conference 2023 "Soil as a Sustainable Resource" 15–17 May 2023, Berlin, Germany
- **Muhammad Owais Khan,** A. Klamerus-Iwan, 2024. Poster presented at the 10th International Conference for Young Researchers (13-14 May 2024), University of Agriculture in Kraków, Poland.

8.3 Internship

I have completed a two-month internship from February 01, 2025, to March 30, 2025, at the University of Agriculture, Peshawar, Pakistan, under the supervision of Dr. Shazma Anwar. During the internship, I worked on a research project related to soil physico-chemical and soil hydrological properties, and the use of mulching and nitrogen sources. My role in this project included collecting soil samples and performing statistical data analysis. I also collaborated with other PhD research and Master's students.

water

MDPI

Review

Determining the Role of Urban Greenery in Soil Hydrology: A Bibliometric Analysis of Nature-Based Solutions in Urban Ecosystem

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Abstract: Nature-based solutions play an essential role in enhancing urban soil hydrology by improving water retention properties, reducing surface runoff, and improving water infiltration. This bibliometric analysis study reviewed the literature and identified the current trends in research related to nature-based solutions in urban soil hydrology. The study has the potential to highlight current research areas and future hot topics in this specific field. The research used the Scopus database to collect published articles from 1973 to 2023. The keywords ("trees" OR "vegetation" OR "green infrastructure" OR "blue green infrastructure" OR "greenery" OR "nature-based solutions" AND "hydrolog*" AND "urban" OR "city" OR "soil") were searched in the Scopus database, and 13,276 articles were retrieved. The obtained publications were analyzed for bibliometric analysis by using Bibliometrix (v4.3.0) and VOSviewer (v1.6.20) software. The maximum number of publications (970) related to nature-based solutions and urban soil hydrology was published in 2023. Additionally, countries such as the United States and China published 54.2% of articles of the global research in the field of nature-based solutions and urban soil hydrology, with 36% from the USA and 18.2% of articles from China. The bibliometric analysis depicted that Beijing Normal University led this specific research field with 540 articles. The top country in terms of collaboration was the USA, with 26.17% as compared to the global countries. The most productive researcher identified was Jackson, T.J., as he had the highest number of publications, showing his considerable contribution to the field. Furthermore, the most frequent keywords used in this research area were hydrology, ecosystem services, urban hydrology, remote sensing, nature-based solutions, climate change, runoff, stormwater management, water quality, vegetation, green roof, bioretention, and land use. The early research trending topics in this field from 2015 to 2023 were remote sensing, soil moisture, climate change, drought, green infrastructure, machine learning, and nature-based solutions. The bibliometric analysis identified limited interdisciplinary research integrations, not using well-significant and standardized methodologies for the evaluation of urban soil hydrology, and under-representation of research from developing countries as current research gaps. Future research directions highlight advanced methods such as combining data-driven technologies with traditional hydrological approaches, and increasing international collaboration, specifically in developing nations, to address urban soil hydrological problems properly.

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Keywords: nature-based solutions; urban soil hydrology; VOSviewer; bibliometric analysis; urbanization

1. Introduction

Urbanization is an essential measurement for evaluating a country's developmental level [1,2]. More than 50% of the global population currently lives in urban regions, and it is expected to rise worldwide [3]. According to a United Nations [4] report, it is estimated that by 2050, approximately 70% of the world's population will live in cities. The growing urban population, along with increasing global temperatures and more frequent heat waves [5], is expected to increase the intensity of the urban heat island effect. This phenomenon, which has been studied by [6,7], could have adverse effects on urban ecology, energy demand for cooling systems, and outdoor thermal comfort [8–11]. Several human health risks, including stroke, irritation, distress, and fatigue, are due to high temperatures in city centers, caused by the increased heat island effect, which influences the population's well-being and seriously leads to suicidal tendencies [12]. The urban environment's vital role in providing livable spaces and supporting resilient ecosystems becomes increasingly significant as city populations increase. In [13,14], the authors stated that the influence of the increased urbanization level and the rapid development of economic construction on hydrological processes could not be ignored. On one hand, climate change will significantly affect hydrological processes in the face of increasing extreme weather situations [15]. Multiple research investigations have confirmed that the changing climate has transformed regional hydrology, and urbanization has increased the changes in natural watersheds [16]. On the other hand, a large area of non-urban land or agricultural land is changed into impervious land in the process of urbanization, and therefore land-use change entirely changes natural hydrological processes [17,18]. Changes in the runoff generation process, runoff depth, infiltration, and evapotranspiration will result from changes in urban land cover [19,20]. Consequently, urban hydrological impacts are crucial to evaluate qualitatively and quantitatively. They play an essential role in urban and water resources management and planning and flood warning [21,22]. These fluctuations are difficult to explain. However, in urbanization, the complex relationship between land-use change and the hydrological process impacts every facet of the runoff process [2]. Furthermore, urban resources, including impervious areas, green spaces, building density, population, etc., are unequally distributed in cities. Hence, the rainfall-runoff distribution process becomes more complex and greatly depends upon the land-use changes and spatial and temporal distribution [14,23].

Amidst these challenges caused by urbanization, urban soils play a vital role in providing several urban ecosystem services, such as support for plant and vegetation growth, soil microorganisms, fertility maintenance, soil water retention, and removal of contaminants [24–27]. The soil science community is progressively recognizing the significance of soils in delivering ecosystem services in urban environments [28,29]. However, anthropogenic activities have destroyed urban soils' ecological and health functions, and urbanization has altered urban soil properties such as increased soil pH, high EC, and soil water deficits [30,31]. Urban soil has a crucial role in providing many ecosystem services that are vital for the wellness of humans and the resilience of urban areas [32–34]. On a local level, these ecosystem services consist of flood mitigation, reducing the urban heat island effects, absorbing air pollution, supporting physical infrastructure, growing food in cities, and providing access to green spaces for physical and mental health. Urban soil supports carbon storage and nutrient cycling at global and local scales. The effective management of urban soils can provide several ecosystem services, such as improving soil productivity, carbon storage, water flow regulation, mitigating climate change, and recreational benefits [35]. In contrast, non-urban soils support higher levels of ecosystem services, such as food production, etc.

To restore and enhance ecosystem services in urban environments, nature-based solutions, such as urban trees, green roofs, and urban vegetation, can be used. Targeted ecosystem services include rainwater management, mitigating urban heat islands, and reducing runoff, which all play a vital part in sustainable urban development [36,37]. Vegetation influences ecosystem services by using different vegetation types and conditions across various landscapes, therefore impacting soil and water properties important for ecosystem support and regulation. In [38,39], the authors stated that vegetation was essential to regulate energy balance via transpiration, respiration, photosynthesis, and other crucial processes. Concurrently, it also plays a pivotal role in climate change mitigation, regulating the water cycle, and changing soil structure [40–42]. Changes in vegetation influence the water cycle through changes in soil water infiltration, root water absorption, canopy transpiration, rainfall interception and redistribution, and the energy distribution process [43]. Hence, vegetation is considered necessary in the energy exchange, biogeochemical, and hydrological cycle process on the surface of land. Trees in cities offer shade and evaporative cooling to pedestrians [44]. Moreover, an improvement in ground vegetation can potentially improve stormwater retention, as [45] suggested. Hence, numerous policymakers advocate for the augmentation of urban greenery [37].

The process of urban centers' densification and infilling has resulted in a significant rise in impervious surface cover in several urban areas. This has resulted in a scenario where the quantity and speed of runoff water can exceed the drainage system capacity, causing localized urban floods and ecological damage to city streams [46]. The intensity and frequency of rainstorms have increased due to climate change, which may worsen this issue in cities globally [47]. The percentage of impermeable soil can be reduced by enhancing the vegetative cover. The addition of trees, shrubs, and lawn spaces has an instantaneous impact on reducing the influence of rainwater. This is achieved via direct intercepting, which reduces the flow of rainwater [48]. Plant leaves and natural mulching above the soil surface help to mitigate the adverse effects of heavy rains, hence minimizing soil erosion and maintaining fertility [45].

The bibliometric analysis has attained fame in the quantitative literature review method; it utilizes data mining, statistical analysis, and mathematical methods to reveal evolving patterns in the scientific research of a specific field [35,49,50]. This investigation evaluates the research literature, classifies the publication's output by year, and highlights the collaboration among authors, institutions, and countries at national and international levels. Additionally, it indicates potential directions for future study in global organic and inorganic carbon [51]. Databases, including Scopus and Web of Science, can be used to collect data for a bibliometric analysis. A bibliometric analysis is conducted from 1973 to 2023 to identify the research gap, authors' keywords, trending topics, annual number of publications, source country, institutions, journals, collaboration among countries, institutions, and authors. We aim to identify the patterns and trends in research related to nature-based solutions and urban soil hydrology by conducting a bibliometric analysis. This study does not attempt to provide a comprehensive review of empirical findings but instead highlights areas of growing interest.

2. Material and Methods

2.1. Data Source, Search, and Collection

Databases, including Scopus and Web of Science, are widely used for bibliometric analyses. Each database has its benefits and restrictions. The Scopus database provides broader coverage and a higher number of search document results [52]. Therefore, Scopus was used in this bibliometric analysis to review the role of nature-based solutions in urban soil hydrology. The bibliometric literature search was performed on Scopus on 13 November 2024. The literature search was carried out in the English language by selecting the "Topic" section, which contains "Article title, Abstract, Keywords" by using the following keywords: ("trees" OR "vegetation" OR "green infrastructure" OR "blue green infrastructure" OR "greenery" OR "nature-based solutions" AND "hydrolog*" AND "urban" OR "city" OR "soil"). In Scopus' online interface, there are several filters to narrow down and specify the literature search. First, we applied the filter "Range" from early 1973 to 2023, excluding the 2024 publications. The filters "Author name" and "Subject area" were left as they were because the authors did not want to exclude any author and subject area from the literature research. The selection process of document type in the Scopus database focused on research articles, conference papers, and review papers, because these are considered as original research/work done by scientists and researchers in their scientific fields. Other document types, such as conference review, book, book chapters, and editorial notes were excluded using the filters available in the Scopus database interface. The remaining filters were left unchanged because the authors were interested in a metrics analysis.

Furthermore, the search filter was narrowed down by selecting the English language for the published documents. After applying those filters, the remaining publication records were exported from the Scopus database in CSV format. After that, the duplicates and missing data were removed from the data. A total of 13,276 published articles were reviewed for the bibliometric analysis.

2.2. Bibliometric Analysis and Visualization

The initial data were analyzed using the tool "Analyze Results" from Scopus. A bibliometric analysis contains different statistical and mathematical methods. These bibliometric approaches evaluate research based on the available sample data (i.e., authors, keywords, citations, titles, journals, countries, institutions, etc.) [53]. Additionally, the main focus of a bibliometric analysis is to measure the quality and scientific impact of the scientific production [54]. It also deals with bibliographic networks (co-citation, co-keywords, co-authors, etc.) by understanding the social, intellectual, and conceptual structure [55]. The free online software "VOSviewer (v1.6.20)" was used to make bibliometric maps [56]. These maps provide an overview of the network collaboration among countries, authors, and institutions. VOSviewer also identifies research topics or fields used mainly by the researchers (e.g., most frequently used keywords by the authors) [57]. Biblioshiny (v4.3.0) software produces a user-friendly and interactive interface for bibliometric analysis offered by the R package "Bibliometrix". The main summary information was generated by the R software (v4.2.2) using the Bibliometrix package. The number of publications per country with their GDP map was generated in Python using the package Plotly [58]. The World GDP data were downloaded from the World Bank website (https://data.worldbank.org/indicator/ (accessed on 16 November 2024)). Aksnes et al. [59] used Biblioshiny software to determine the citation pattern, publication trends, and research theme in their study. Likewise, Chen et al. [60] used VOSviewer to visualize collaboration networks and map the research landscape in their research. Another study conducted by [51] utilized VOSviewer to identify and evaluate research topics and network collaboration (authors, countries, and academic institutions) and Biblioshiny for analyzing and visualizing bibliometric data. In this review study, we used VOSviewer and Biblioshiny software, which work with the R package "Bibliometrix" for our bibliometric analysis. These tools are broadly used for the same objective in various disciplines.

The main focus of our review was to find the research gap and collaboration among countries, institutions, and authors in this research area. Furthermore, the research collaboration among different countries, the relationship among research fields/topics, the main research area, trending topics, and thematic keywords evolution were also determined. The overall publication number and annual publications for nature-based solutions and urban soil hydrology were determined by summing the number of articles across all years and each year, correspondingly. The institutions and countries' research productivity was examined based on the author's affiliation with the published papers.

3. Results

3.1. General Information, Publications over Time, and Temporal Trend

The main summary information of this bibliometric analysis is presented in (Table 1). A total number of 13,276 documents were produced from 1923 sources, with a 10.71% annual growth rate. The average age per document was 11.4, whereas the average citation per document was 39.49. The document types published from 1973 to 2023 include 11,205 research articles, 1589 conference papers, and 482 review papers. The total number of authors was 33,351, of which the number of authors of single-authored documents was 770, and the number of single-authored documents was 859. Furthermore, the number of co-authored documents was 4.54, although the percentage of international co-authorship was 28.42%. Additionally, the analysis showed that the total number of keywords plus used in this bibliometric study was 36,589, and the number of author's keywords was 23,155.

Table 1. Main information summary of the bibliometric analysis.

Description	Results
Timespan	1973–2023
Books	2
Journals	1592
Conferences	329
Documents	13,276
Annual growth rate %	10.71
Document average age	11.4
Average citations per doc	39.49
Research article	11,205
Conference paper	1589
Review	482
Authors	33,351
Authors of single-authored docs	770
Single-authored docs	859
Co-authors per doc	4.54
International co-authorships %	28.42
Keywords plus (ID)	36,589
Author's keywords (DE)	23,155
References	600,702

3.2. Number of Publications over Time

A detailed analysis of the literature showed that a large number of research articles, review articles, and conference papers were published from different sources, including books and journals. The bibliometric analysis produced a total number of 13,276 papers published from 1973 to 2023, which were related to the role of nature-based solutions in urban soil hydrology (Figure 1). The early period from 1973 to 1990 showed a very low number of publications per year and the average number of publications per year was under 50 articles. The middle acceleration period (1990–2000) showed a significant increase in the number of publications per year, which suggested high research activity in the field of nature-based solutions and urban soil hydrology. The number of publications showed a peak growth after 2010 with the highest number of articles of 900 per year by 2023. That showed significant enhancement in this research field which may be due to the higher funding, collaboration among countries, and technological advancement increasing the research output.

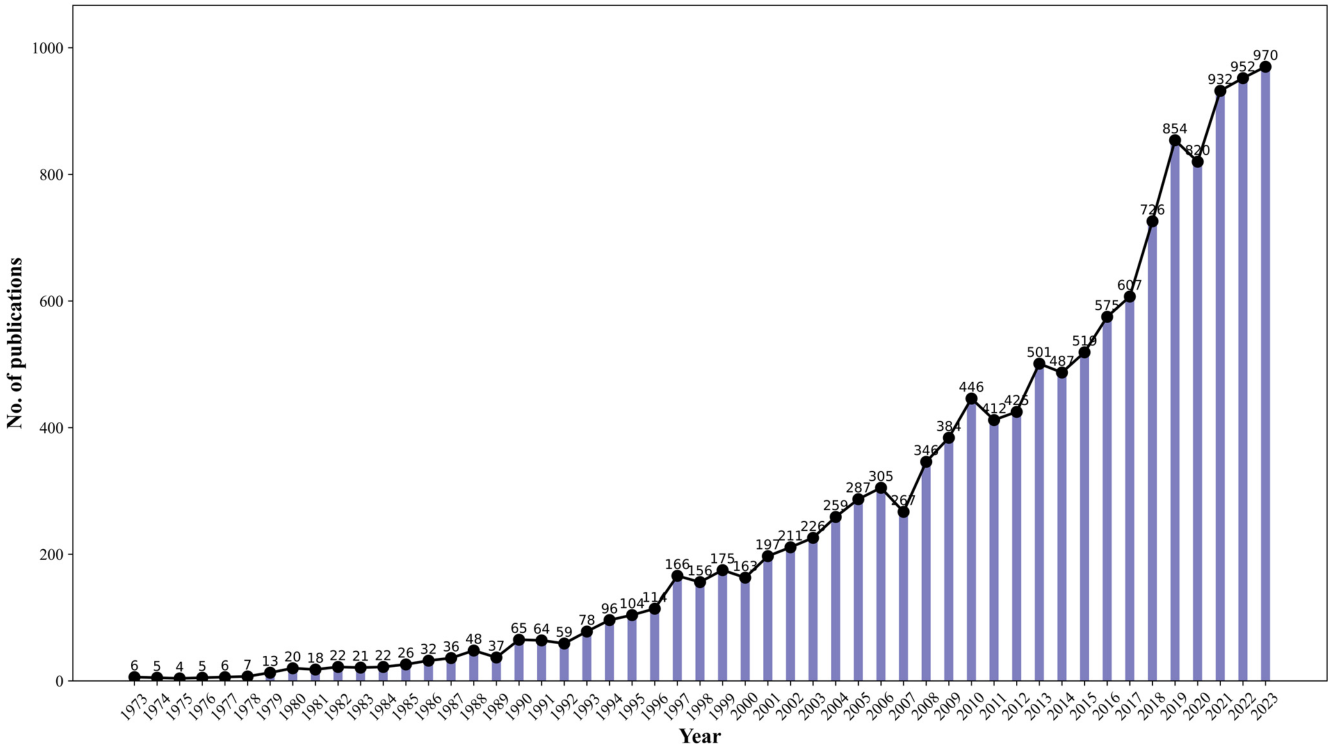

Figure 1. Trends in annual publication output from 1972 to 2023, highlighting the growing research interest in nature-based solutions and urban hydrology. Data were collected from the major academic database Scopus.

3.3. Global Contribution Map by Countries with GDP and Affiliations

Nature-based solutions in urban hydrology were studied in 159 countries across the globe, and 97 countries published more than five papers in this research area. The United States and China combined published 54.2% of the worldwide research relating to the application of nature-based solutions in urban soil hydrology, with 36% of the articles from the USA and 18.2% of publications from China. Germany (7.6%), the United Kingdom (7.1%), Australia (7%), Canada (5.5%), France (5%), Italy (4.6%), Spain (4.5%), and the Netherlands (4.5%) were secondary significant contributors in this research area. The geographical map (Figure 2) shows the top 10 high economic nations in the world, in which the USA, China, and Germany dominate the world economy, and they also contributed heavily in this research area in terms of research publications. The economic power of countries directly correlates with their research output, because the higher GDP enables those countries to invest more in education, technology, and infrastructure.

A bibliometric analysis is essential for gaining information about potential institutions' collaboration in a specific research area. The graph (Figure 3) depicts the top 10 affiliations in research on the role of nature-based solutions in urban soil hydrology. This can be helpful for researchers in this specific field for collaboration among important institutions. The leading Beijing Normal University published 540 articles in China, showing their historical and current efforts in scientific research. Next, the Tsinghua University Beijing produced

410 articles, while the University of California published 389 articles as well. A total of 271 articles were recorded as non-reported in this analysis.

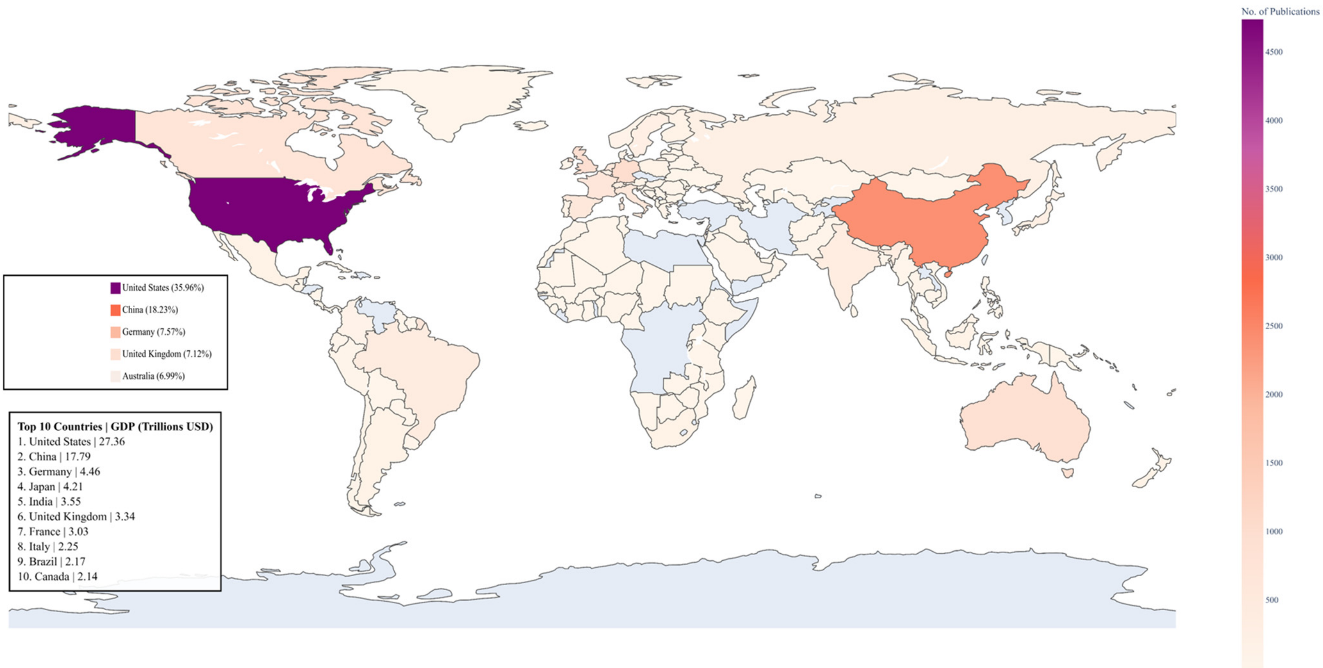

Figure 2. Top 10 countries producing a high number of publications on nature-based solutions and urban hydrology.

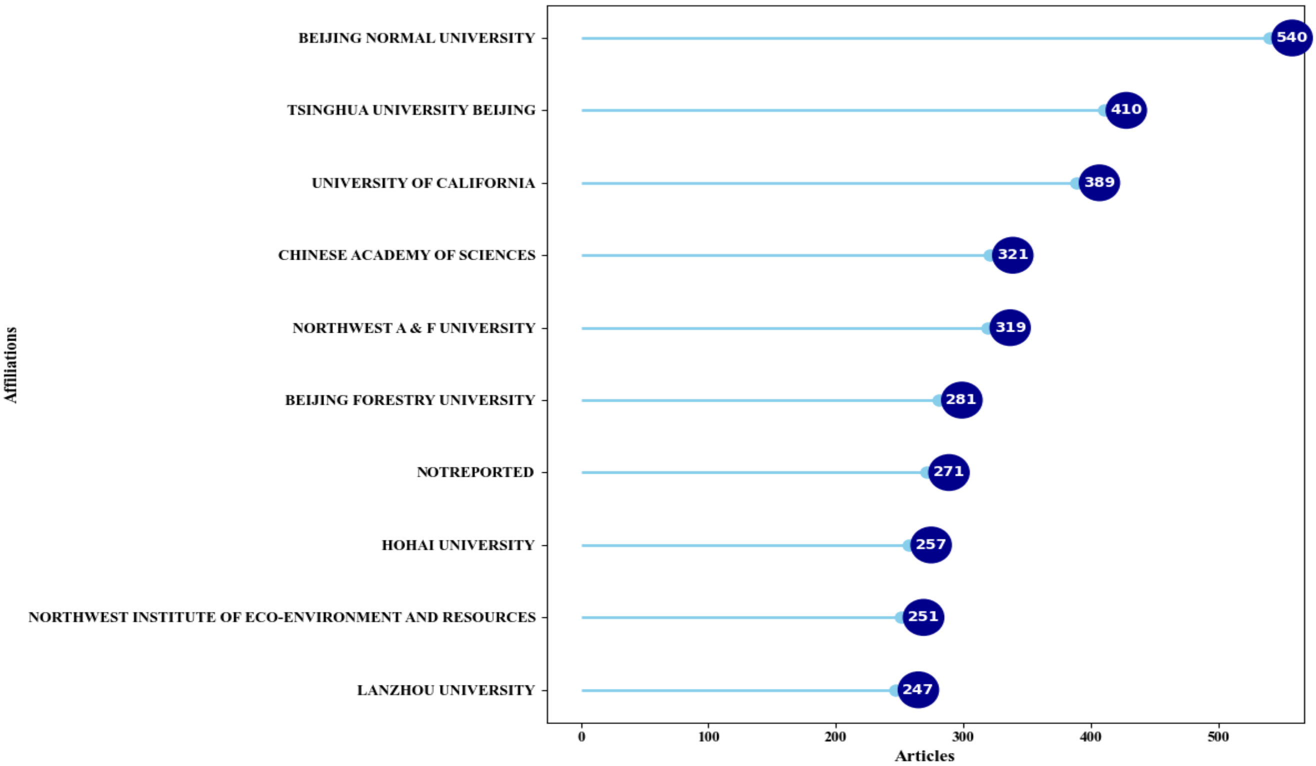

Figure 3. The top ten most relevant affiliations with the maximum number of articles.

3.4. Corresponding Author's Countries and Collaboration Among Countries

The corresponding authors with single- and multiple-country publications (SCPs and MCPs) are presented in Figure 4A. The corresponding authors are typically responsible for overseeing the research, managing the manuscript submission process, and representing the study's institutional or geographical origins. This role makes them a key indicator of a country's scientific contributions. Although first authorship also holds significance, we focused on corresponding authors as they are often seen as the primary investigators or points of contact, particularly in multi-country collaborations. The top contributing country was the United States with a total of 2833 articles, 2293 SCPs, and 540 MCPs, followed by the Republic of China with 1935 published articles in total, 1346 SCPs, and 589 MCPs, and Germany with a total number of articles 508, 294 SCPs, and 214 MCPs. Australia and Canada came in fourth and fifth position in terms of publication numbers, SCPs, and MCPs. The findings indicated that these leading countries made more significant investments in the scientific domain of nature-based solutions (i.e., vegetation, trees, green infrastructure, blue-green infrastructure, and greenery in urban soil hydrology). However, our results indicated that Sudan, Nigeria, Mali, and Lebanon produced a smaller number of articles, and more research is needed in these countries to combat urban hydrology problems.

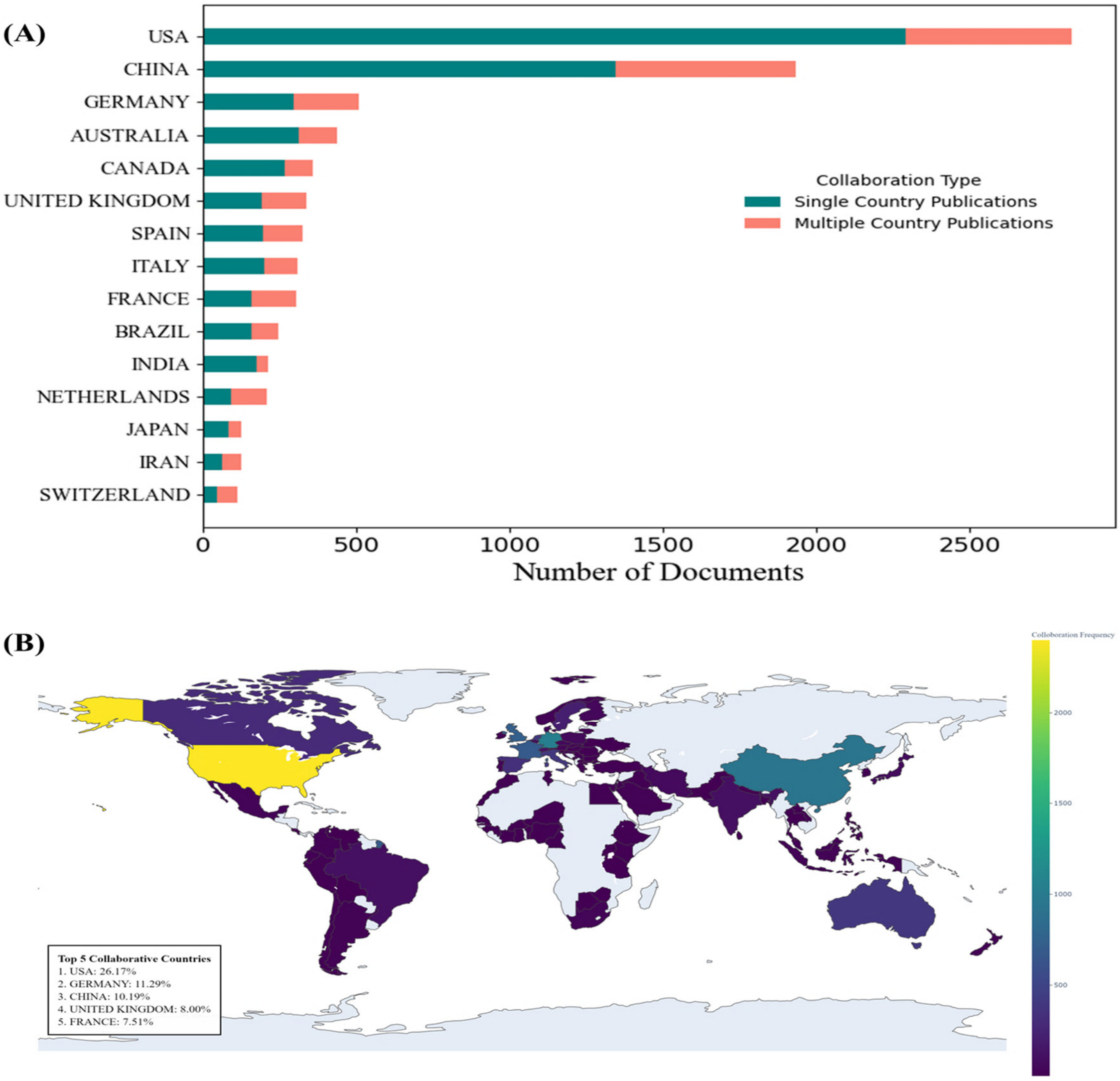

Figure 4. Corresponding authors' countries (**A**) and global countries' collaboration map (**B**), SCPs and MCPs: single- and multiple-country publications.

The top country in terms of collaboration was the USA, with 26.17% as compared to other countries (Figure 4B). Germany was the second most collaborating country in terms of research with other countries on the role of nature-based solutions in urban soil hydrology.

The results proved that Germany performed well in this research area on the European continent. The People's Republic of China came in third place in terms of collaboration percentage (10.19%).

3.5. Sources and Citation Analysis

Table 2 depicts the top 10 articles with the highest global citations on the Scopus database relating to nature-based solutions and urban soil hydrology. The articles cited in high numbers were primarily original and review articles. These studies illustrated the diverse impacts of urbanization on environmental systems, demonstrating the importance of integrated models and data platforms to manage future urban expansion and its environmental effects. Gill et al. [61] examined the role of green infrastructure in mitigating the effects of climate change in Greater Manchester. They highlighted how changes in urban surfaces, including less vegetation and high surface sealing, induced problems like urban heat islands and high surface runoff especially in future climate change. The research used energy exchange and hydrological models to assess how the city green infrastructure could assist in decreasing these harmful effects. They concluded that green infrastructure was essential in urban planning to adapt to climate change, where green spaces play a significant role in the regulation of temperature and runoff management. Another study conducted by [62] presented the latest dynamic global vegetation model to simulate key processes in the biosphere that affect the global carbon cycle, including respiration, photosynthesis, fire, and energy exchanges at the soil plant surface. They concluded that their model was useful to study the feedback between vegetation cover and climate changes across global scales. Xu et al. [63] modified the normalized difference water index (NDWI) to improve open-water features in remotely sensed imagery. The goal of that study was to address the limitations of the NDWI, which often mixes the water features with built-up land noise, by replacing the NIR (near-infrared) band with an MIR (middle infrared) one to generate a modified NDWI (MNDWI). These changes improved the accuracy and clarity of water feature extraction, especially in areas dominated by land backgrounds. This enhancement provided a more reliable tool for water resource evaluation particularly in urban complex environments. Niu et al. [64] introduced the Community Noah Land Surface Model with multiple parameterization options, which was designed to enhance land surface models by enabling the flexible parameterization of biophysical and hydrological processes. The main objective of that study was to address limitations in simulating soil moisture, snow, vegetation, and runoff processes while offering numerous options for specific physical processes modeling. The results showed that Noah-MP significantly improved the surface fluxes simulations, snow water, and runoff dynamics compared to early versions. Similarly, another model such as the Global Land Evaporation Amsterdam Model was introduced by [65], which estimated root zone soil moisture and terrestrial evaporation by using satellite data. The primary goal of that research was to improve the model representation of physical processes and to improve its use of newly available geophysical variables derived from satellite. The updated model demonstrated considerable improvement in its accuracy and application, which provided a more accurate and precise soil moisture and evaporation estimation at global scales.

Table 2. The top 10 articles with the highest number of global citations on Scopus.

Document Title	Journal Title	Document Type	Citations	Publication Year
1. Coupling and advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity	*Monthly Weather Review*	Research Article	4746	2001
2. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery	*International Journal of Remote Sensing*	Research Article	3865	2006
3. Improvements to a MODIS global terrestrial evapotranspiration algorithm	*Remote Sensing of Environment*	Research Article	2146	2011
4. The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements	*Journal of Geophysical Research Atmospheres*	Research Article	1850	2011
5. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status	*Remote Sensing of Environment*	Research Article	1590	2002
6. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture	*Geoscientific Model Development*	Research Article	1582	2017
7. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system	*Global Biogeochemical Cycles*	Review Article	1569	2005
8. Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)	*Remote Sensing of Environment*	Research Article	1560	1998
9. A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation	*Journal of Climate*	Research Article	1522	1996
10. Adapting cities for climate change: The role of the green infrastructure	*Built Environment*	Research Article	1358	2007

Mu et al. [66] aimed to enhance the MODIS global evapotranspiration (ET) method, first formulated by [67], by augmenting several aspects of its calculation and precision. The improvements included the simplification of vegetation cover fraction calculations, the computation of evapotranspiration as a sum of daytime and nighttime components, the incorporation of soil heat flux calculations, and the refinement of estimations for stomatal conductance. The results specified that the new algorithm yielded a worldwide annual total evapotranspiration estimate of 62.8×10^3 km^3, which was more consistent with other reported estimates compared to the prior algorithm's estimate of 45.8×10^3 km^3. Sandholt et al. [68] presented a simplified Temperature-Vegetation Dryness Index (TVDI) to evaluate the surface moisture conditions using satellite data such as surface temperature and the vegetation index. The primary aim was to provide a straightforward method to monitor soil moisture specifically in areas with less resources. The results demonstrated that the TVDI could capture the spatial variations in soil moisture more efficiently than conventional hydrological models. Chen et al. [69] improved simulations of surface heat fluxes and seasonal soil moisture conditions by using an integrated advanced land surface-hydrology model (LSM). The aim of that study was to provide accurate and precise boundary conditions for atmospheric models by incorporating high resolution characteristics and improving soil moisture. The study investigated how vegetation and soil texture maps influenced surface energy fluxes and land atmosphere feedback.

A total number of 154 journals published 13,276 articles related to ("trees" OR "vegetation" OR "green infrastructure" OR "blue green infrastructure" OR "greenery" OR "nature-based solutions" AND "hydrolog*" AND "urban" OR "city" OR "soil"). The top 110 journals published more than 20 articles. Furthermore, the top 10 most relevant sources published 3198 articles in total (Figure 5). Additionally, the highest number of articles, 783, were published in the *Journal of Hydrology*, followed by the *Hydrological Processes* and *Science of the Total Environment*, with 434 and 404 articles. The lowest number of articles were published in the *Journal of Ecological Engineering*. The local impact of various journals based on total citations is presented in Figure 6. The *Journal of Hydrology* stands out among other journals based on the highest number of total citations (48,457) on nature-based solutions and urban hydrology. The *Journal of Water Resources Research and Hydrological Processes* obtained second and third positions with total citations of 21,615 and 18,363. After the first top 10 journals, there was a significant decrease in the total citations, which showed that there were less significant journals in this research area, followed by a considerable number of journals with fewer citations. This analysis enabled researchers to identify the most important and influential journals in this research area (nature-based solutions and urban hydrology) to publish their work and find suitable collaborators.

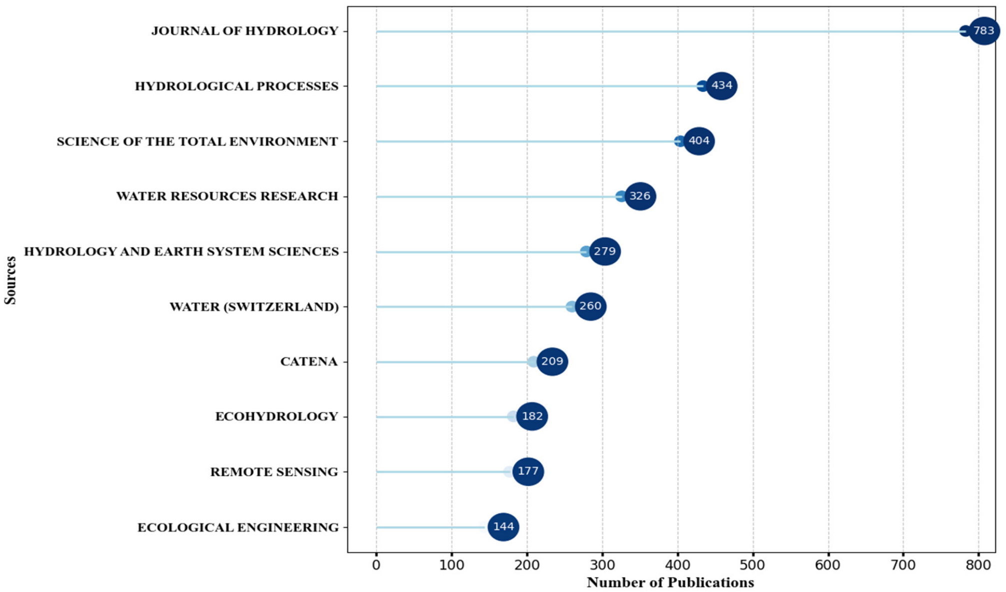

Figure 5. The top ten most relevant journals with the maximum number of articles.

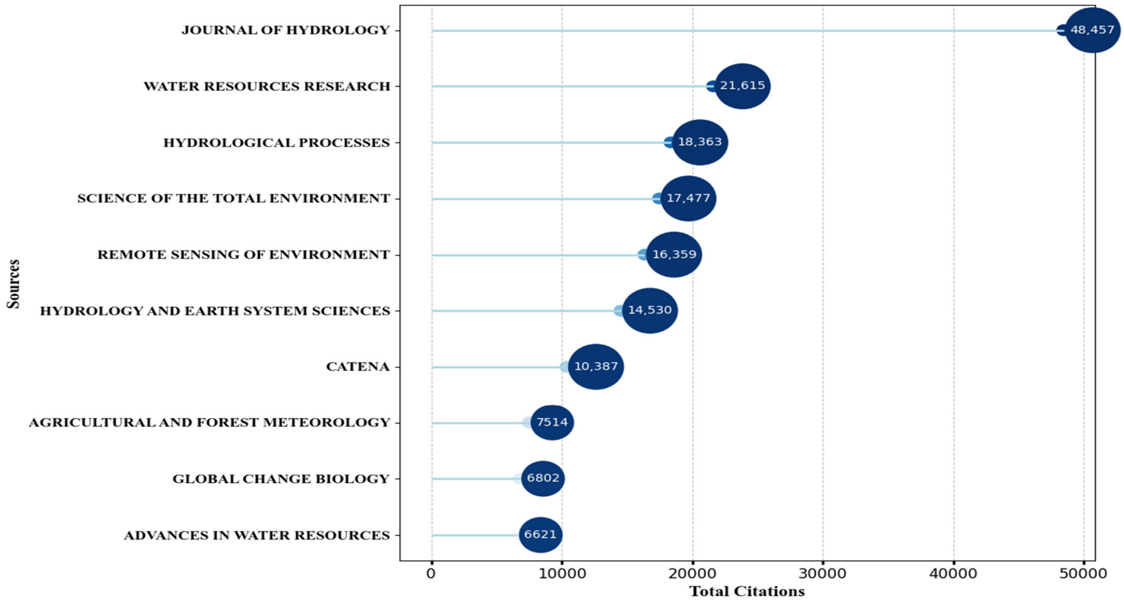

Figure 6. Top ten most relevant journals with the highest total number of citations.

3.6. Authors

The investigation of the most significant authors in the research area of nature-based solutions and urban hydrology delivered essential insights into the most influential authors (Figure 7).

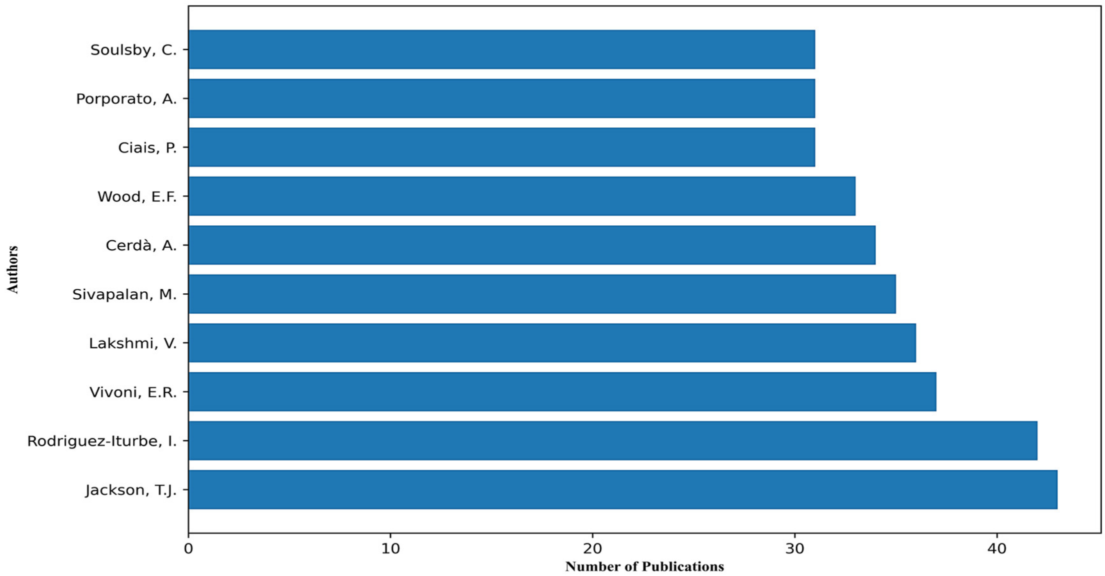

Figure 7. Top 10 most relevant authors with the highest number of publications.

The Sankey graphs (Figure 8A,B) show the collaboration and contributions of different institutions, sources (journals), and countries in specific research domains, such as soil moisture, climate change, hydrology, evapotranspiration, and vegetation. The People's Republic of China showed the most driven institutions, whereas the United States showed diverse representation across various topics and journals. The research theme soil moisture was the main focus of different institutions and countries, demonstrating its importance in the field of hydrology and climate related research. The keywords, including soil moisture, hydrology, evapotranspiration, vegetation, remote sensing, and runoff showed maximum incoming inflow from the affiliations and countries' direction, which depicted the maximum number of affiliations and journals in different countries working on these research topics.

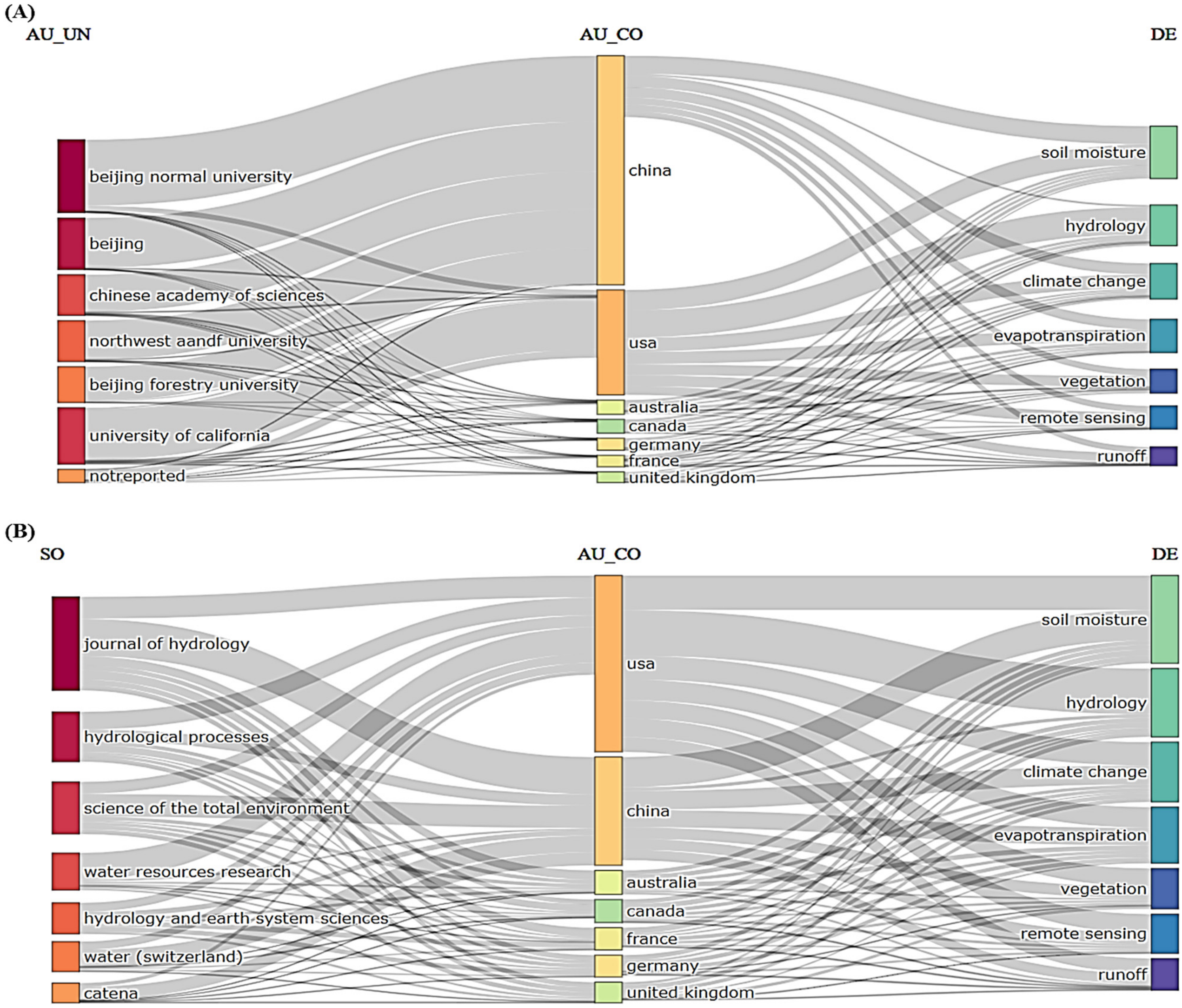

Figure 8. Three-field plot shows connections among (**A**) countries, universities, and keywords (**B**) countries, journals, and keywords.

3.7. Keywords Analysis and Conceptual Structure Map of Trending Topics

The analysis of co-occurring author keywords provides an insightful way to show the relation among trending research topics within a specific research area based on their co-occurrence (Figure 9). The size of each node represents the frequency of used author keywords in the literature. Moreover, the lines between nodes show the occurrence of keywords used by the authors in the same publications, and the thickness of the lines represents the strength of the keyword's co-occurrence. The most frequently used keywords in this research area were hydrology, climate change, water quality, soil properties, surface runoff, restoration, drainage, ecosystem services, soil moisture, evapotranspiration, ecohydrology, forest hydrology, soil water, throughfall, hydrological modelling, streamflow, urban hydrology, nature-based solutions, green infrastructure, low impact development, stormwater management, and infiltration. Keywords form different clusters, which are more likely to show specific research themes. For instance, the keywords "urban hydrology", "stormwater management", "nature-based solutions", "low impact development", "urbanization", and "green infrastructure" formed a cluster that concentrated mainly on the anthropogenic factor such as urbanization and the nature-based solutions that reduced the urban hydrological issues due to extensive urbanization. This research theme generally explains how nature-based solutions (such as green infrastructure and low impact development) and different processes can be combined with urban development to properly manage water resources, minimize the impact of flooding, and adapt to climate changes in global warming situations. Furthermore, keywords including "hydrology", "land use change", "climate change", "wetlands", "ecosystem services", "restoration", "drainage", and "surface runoff" formed a cluster that showed how various land practices significantly affect the hydrological processes causing high surface and altered water retention. Restoration and proper drainage can reduce the negative impacts by enhancing water retention properties and decrease surface runoff.

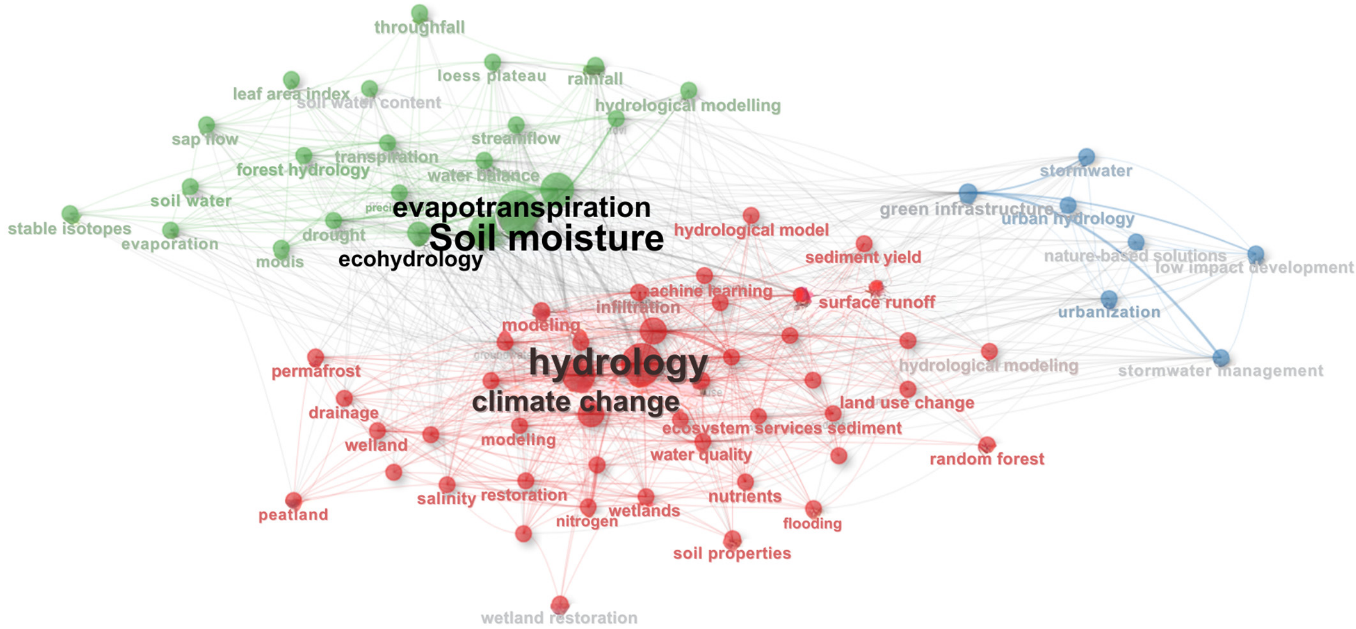

Figure 9. Bibliometric analysis of author keywords' distribution. The size of the keyword's circles shows the frequency of keyword appearance, and the lines show the relationships among keywords.

The conceptual structure map of the keywords shows the closeness of terms/keywords' relationship among each other in the literature (Figure 10). The *x*-axis (Dim 1, showing 38.55% of the variance) demonstrates the thematic gradient from urbanization, urban hydrology, low-impact development, and stormwater management on the right side to natural ecosystem services and processes on the left. The *y*-axis of the graph represents (Dim 2, accounting for 20.81% of the variance) the ecological modeling and hydrological research on the bottom, and nutrient dynamics on the top. The red color cluster shows a connection with the nature-based solutions (i.e., green infrastructure and low impact development) that play an important role in stormwater management in a changing climate in urban areas and that can also retain sustainable ecosystem services. These keywords are closely associated with the sustainable management practices of urban ecosystems and their integration into urban environments for the management of stormwater and improvement of the urban ecosystem. The blue cluster signifies research topics related to natural ecosystem services and watershed, such as "soil erosion", wetland restoration", "hydrology", "vegetation", and "water quality". These research themes are interconnected through their relevance to soil and water conservation, urban hydrology, and ecological modeling. Further, the green cluster consists of keywords/terms such as nitrogen and phosphorus, which show environmental nutrient dynamics.

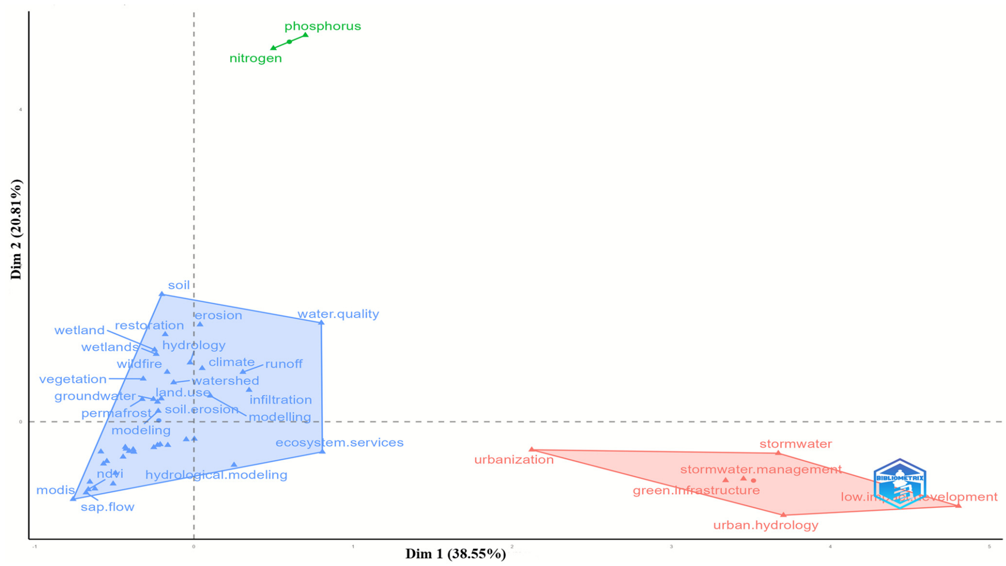

Figure 10. Conceptual structure map of the keywords with two dimensions showing the distribution of the keywords. The different color clusters represent keywords with strong relation with each other.

3.8. Hot Trending Topics in Nature-Based Solutions and Urban Hydrology with Respect to Time

The trending topics about the role of nature-based solutions (e.g., vegetation, green infrastructure, blue-green infrastructure, greenery, and trees) in urban soil hydrology, with respect to time is presented in Figure 11. The trending keywords of urban greenery, nature-based solutions, and urban hydrology varied strongly over time. The top research topics used in the literature from 2005 to 2015 were acidification, nutrient cycling, simulation, drainage, productivity, nitrogen, species richness, erosion, hydrology, vegetation, and evapotranspiration. The early research trending keywords from 2015 to 2023 were remote sensing, soil moisture, climate change, drought, green infrastructure, machine learning, and nature-based solutions.

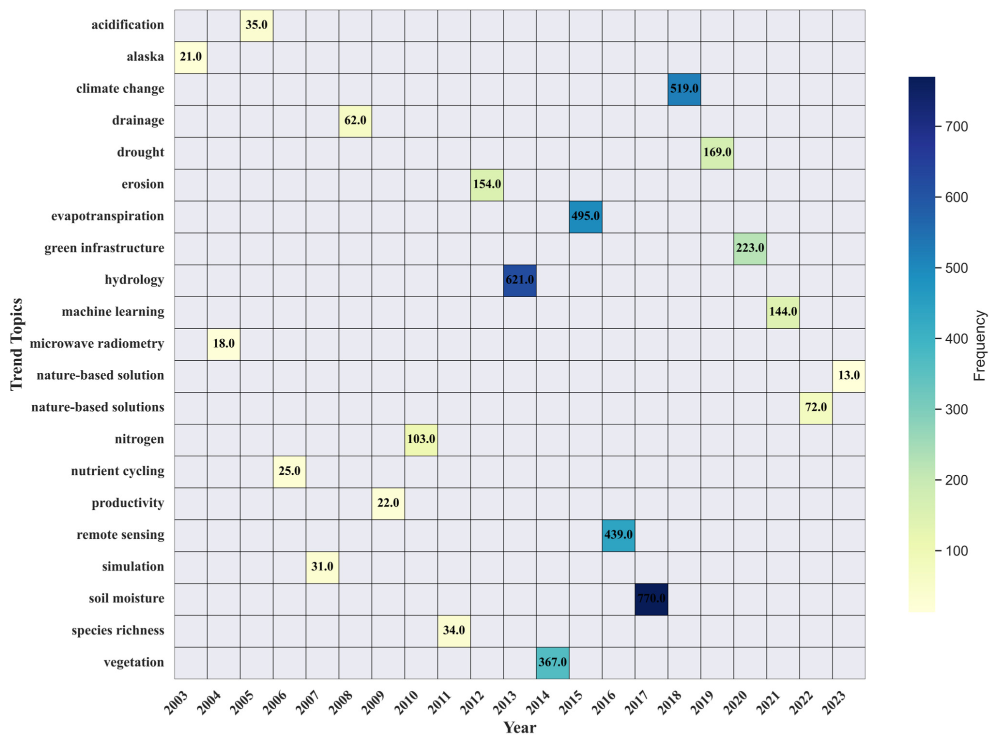

Figure 11. Heatmap of research trending topics in nature-based solutions and urban soil hydrology over time from 2003 to 2023.

4. Discussion

4.1. Publications Output over Time and Global Contributions by Countries and Institutions

Our results showed significant enhancement in the number of publications after 2010, highlighting the importance of collaboration between countries, and technological advancement and funding from the institutions increased the research outputs in this research area. This trend aligns with earlier research by [70], who reported a growing focus on ecological studies in urban environments. A bibliometric study by [71] also noted a surge in the number of publications after 2020, demonstrating escalating interest in NBS for stormwater management in urban areas.

Furthermore, our analysis suggests that the knowledge exchange network could help identify under-researched areas, especially when linked to international collaboration metrics. Urban policy plays a crucial role here, as integrating vegetation or green infrastructure or blue-green infrastructure into city planning can mitigate urban heat island effects and improve stormwater management.

The United States and China together contributed highly to the global research on NBS in urban soil hydrology. This demonstrated the research capacity and commitment of both countries in addressing challenges related to rapid urbanization and climate change. The high research contributions of USA and China were due to their high GDP, which made them able to invest more money in the field of nature-based solutions to combat future climate changes issues, including urban heat islands, reduced vegetation, less available water, and high pollution. The top two most productive institutions belonged to the People's Republic of China. The University of California was in third position in terms of the number of publications in the field of nature-based solutions and urban soil hydrology.

China and the USA dominated research related to NBS and urban hydrology (including stormwater management, flooding, and runoff). However, a majority of the institutions from China made notable contributions. Interestingly, although Germany, the United Kingdom, and Australia were secondary significant contributors in this research area, none of the institutions from these nations were ranked among the top publishing universities/institutions. This may be due to the fact UK and German researchers collaborated more internationally, producing co-authored papers with affiliations outside their own countries.

This outcome highlights the leading nations in NBS research and underscores the research productivity in these countries, offering a comprehensive understanding of NBS and urban hydrology on a global scale.

4.2. Top Reputed Journals Based on Article Number and Citations in the Field of Natured-Based Solutions and Urban Hydrology

The prominence of journals like the *Journal of Hydrology*, *Hydrological Processes*, and *Science of the Total Environment* in publishing research on nature-based solutions and urban soil hydrology reflects the increasing academic focus on this field. The *Journal of Hydrology* led this research area based on the highest number of articles and citations as compared to other journals; its dominance was not only due to the volume of publications, but also its consistent ability to attract highly impactful research. This trend shows the focus of scientific researchers on these research journals for publishing their work in this emerging research field. These results highlight the need for researchers to target journals with high impact and relevance to maximize the dissemination and recognition of their research work. Journals like *Hydrological Processes* and *Science of the Total Environment*, though less productive as compared to *Journal of Hydrology*, played complementary roles in advancing the field by providing researchers within nature-based solutions and urban soil hydrology. These differences among the journals allowed a diversity of research directions and publication platforms in this domain. By identifying these high impact journals, future researchers can strategically select prominent academic journals that not only increase the search visibility of their findings but also contribute meaningfully to the broader research on nature-based solutions and urban soil hydrology. Furthermore, experts in this specific field can utilize these data to publish their findings in prominent academic journals and to identify potential collaborators.

4.3. Most Productive Authors in the Field of Nature-Based Solutions and Urban Hydrology

The contributions of leading researchers, such as Jackson, T. J., with a high number of publications among top researchers in this field, represent a significant dedication to advance the understanding of nature-based solutions in urban soil hydrology. Jackson's extensive research work underscores his role as a top researcher in this specific field, impacting research directions and setting proper standards for quality and impact. In addition, collaborative networks among authors showed key dynamics in the global research landscape. Strong co-authorship links between researchers in the United States, China, and Germany highlighted that cross-institutional and cross-country collaborations were important for research innovations. These connections not only strengthen the scope of individuals studies but also increase the exchange of methodologies and perspectives, enhancing this specific field. These patterns highlight that impactful research arises from interdisciplinary and international collaborations. This analysis could provide proper guidance for early-career researchers to identify potential researchers and collaborators in the emerging field of nature-based solutions for urban hydrology management.

4.4. Global Collaboration Among Countries

China is the leading country in terms of international collaboration (multiple-country publications) among developing nations globally. This demonstrates its ability to enhance research and improve quality in developing nations. China is investing more resources in research related to urban water management. Li et al. [72] stated that urban water management was a significant problem around the globe due to climate change and rapid urbanization and developed the concepts of sustainable water management during the last decade. Further, they explained that nature-based solutions (sponge city, blue, green, gray infrastructure) were initiated in the European Union in 2015, and it started in China in 2013, showcasing its proactive stance on sustainable urban hydrology. It plays an important role in the issues related to water management in urban areas. The lower number of publishing research articles in this research area in developing countries does not necessarily show a lack of research motivation or ability, as these nations also face the same urbanization problems as the rest of the globe. Moreover, highly productive nations like China are significantly impacted by rising urbanization and climate change. As a result, there has been an increased focus on investing in research relating to nature-based solutions to combat these emerging issues [73].

International collaboration among countries is necessary to expand the area of nature-based solutions and their role in urban soil hydrology. The top country in terms of collaboration was the USA, compared to other countries, while China was the third most collaborating country in terms of research with other countries on the role of nature-based solutions (vegetation, greenery, trees, green infrastructure, or blue-green infrastructure) in urban soil hydrology. The results proved that China was performing well in this research area in Asia. The result proved that the USA was the main collaborating country in the world in the field of nature-based solutions i.e., vegetation, trees, green infrastructure, etc., and urban hydrology. This may be due to the advancement of the concept of nature-based solutions in the region and their strong commitment to tackle climate change by using multi-sustainable approaches. However, it is essential to understand that limited research collaboration between less developed countries can have a detrimental effect on their research capabilities and their ability to tackle issues related to climate change and urbanization. Hence, it is imperative for developing nations to collaborate with developed countries in this specific field of study to expand their research capabilities and deepen their comprehension of the significance of nature-based solutions for urban hydrology. This highlights the considerable international collaboration among the United States and other less developed countries on natured-based solutions and urban hydrology. This can further create more operative and advanced solutions, benefiting not only the United States but other countries facing the same issues and challenges.

4.5. Keyword Analysis for Nature-Based Solution and Urban Hydrology

The analysis of co-occurring author keywords provided significant research trends and clustering themes within the research field of nature-based solutions and urban hydrology. The keywords around topics such as "urban hydrology", "stormwater management", "nature-based solutions", "climate change", and "ecosystem services", "sustainability", and "flooding" formed a cluster that showed increasing focus on implementing natural-solution processes into urban water management systems. This research theme generally explains how natural landscapes and different processes can be combined with urban development to properly manage water resources, minimize the impact of flooding, and adapt to climate changes in global warming situations. Nature-based solutions and sponge cities are considered as pioneered methods for the management of urban water. Nature-based solutions, such as permeable pavements and green roofs decrease the amount of runoff and improve stormwater management [74,75]. Furthermore, keywords including "hydrology", "land cover", "land use", "climate", "watershed", conservation", "surface runoff", and "water resources" formed a cluster which showed how various land practices affect water behavior and availability in a changing climate [71,73,76]. The "runoff", "stormwater", "low impact development", "green roof", "infiltration", and "modelling" keyword cluster largely examined the significance of nature-based solutions, like low impact development techniques and their efficiency in the management of runoff resulting from stormwater [31,77,78]. The keyword "hydrology" showed a strong connection with other key topics like natured-based solutions, climate change, ecosystem services, urban hydrology, and remote sensing. These five highlighted keywords are potential trending topics that were not directly covered in our study; nevertheless, they have been utilized by other researchers in the literature review [79–81].

4.6. Current and Future Topics and Their Evolution Based on Trending Topics

The analysis of trending topics showed evolving research focus areas in urban soil hydrology and nature-based solutions over time. The prominent keyword "hydrology" was frequently used in the literature for the first time in 2013, reflecting the central role of urban water management in urban ecosystems and showing the increasing focus on integrating ecological solutions into urban development. The terms "vegetation", "green infrastructure", and "nature-based solutions" were crucial keywords in the literature, showing the importance of the nature-based solutions' (vegetation and green infrastructure) role in mitigating the adverse consequences of rapid urbanization such as the loss of biodiversity, climate change, drought, and increased runoff. Furthermore, keywords "natured-based solutions", "soil moisture", "green infrastructure", "runoff", and "remote sensing" were also important keywords in the literature and have been used by researchers in recent times. The application of nature-based solutions (e.g., green infrastructure, vegetation, urban forestry, etc.) are now widely acknowledged for their important role in stormwater management and runoff, reducing urban heat, and enhancing air quality in the cities. The use of remote sensing techniques could be helpful to enhance the effectiveness of nature-based solutions in urban soil hydrology. The ability to observe extensive environmental changes, including vegetation cover, water quality, and land-use changes, using satellite images and other remote sensing technologies provides an important tool for evaluating the performance of nature-based solutions across time. Utilizing this technology, researchers and policymakers could improve the implementation of nature-based solutions and gain a better understanding of their long-term effects on urban water management.

Future research could cover the integration of nature-based solutions (vegetation, green infrastructure, wetlands, urban forestry) in cities and their impact on stormwater management and runoff, biodiversity enhancement, reducing the urban heat island impact, and improving urban ecology and biodiversity. Palermo et al. [75] stated the importance of nature-based solutions in stormwater management in cities and their capacity to decrease surface runoff and improve infiltration rates and evapotranspiration. These nature-based solutions, such as green walls, green roofs, vegetation, and permeable pavements, play an essential part in restoring the urban hydrological cycles. Zhao and Yue, [74] illustrated that climate change caused waterlogging issues in China. They suggested that nature-based solutions could mitigate the impacts of climate-induced waterlogging. Another study [82] concluded that sponge-city systems in urban areas enhanced tree growth by providing appropriate conditions for root development and also mitigated urban heat island effects. Our results and the scale of research conducted worldwide clearly show that the role of urban greenery in soil hydrology is extremely important.

By examining the volume of publications, collaborations, and trends, our study highlights the growing global recognition of the importance of nature-based solutions (NBS) in urban hydrology.

Recommendations for stakeholders:

1. Integration of nature-based solutions (NBS) in urban planning: Stakeholders, including urban planners, policymakers, and municipal authorities, should prioritize the integration of nature-based solutions in urban development projects. These solutions, such as green roofs, urban forests, and permeable pavements, have demonstrated significant benefits in improving urban soil hydrology, managing stormwater, and mitigating the urban heat island effect. By incorporating NBS, cities can enhance their resilience to climate change and promote sustainable urban ecosystems.
2. Promotion of collaborative research: The study highlights the importance of international collaboration in advancing research on nature-based solutions in urban hydrology. Stakeholders should encourage and facilitate partnerships between universities, research institutions, and governments across different countries. Collaborative efforts will enable the sharing of knowledge, resources, and best practices, leading to more effective and innovative solutions to urban hydrological challenges.
3. Focus on under-researched regions: While countries like the United States and China lead in publications related to nature-based solutions, there is a need to focus research efforts on under-researched regions, particularly in developing countries. Stakeholders should allocate funding and resources to support research and the implementation of NBS in these regions, addressing local urbanization challenges and enhancing global knowledge.

5. Conclusions

The study presented a comprehensive bibliometric analysis from 1973 to 2023, highlighting the dynamic research growth in the research area of nature-based solutions (e.g., vegetation, trees, green infrastructure, blue-green infrastructure, and greenery) in urban soil hydrology. The bibliometric analysis showed considerable growth in scientific literature, with a yearly 10.71% growth rate in global research interest. It emphasized the importance of integrating ecological solutions, such as nature-based solutions, into urban regions to address hydrological challenges.

Furthermore, our analysis revealed that the USA and China were leading contributors, together accounting for half of the publications in this field. The steady increase in publications after 2010, with the highest number of articles in 2023, reflected growing academic and authors' personal interests in sustainable water management in cities worldwide.

Future research should focus on the implementation of nature-based solutions in less developed countries to enhance their understanding and capacity to solve urban hydrological issues. The citation and publications analysis also identified prominent journals for researchers to publish their work and collaborate internationally in this specific field. Moreover, methods focusing on long-term impacts of nature-based solutions on urban water systems will help us make our cities more sustainable and resilient anywhere around the globe.

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RESEARCH ARTICLE

Short-term impact of different doses of spent coffee grounds, salt, and sand on soil chemical and hydrological properties in an urban soil

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Abstract
Natural and human activities have deteriorated urban soil's health and ecological functions as compared to forest soils. Therefore, we hypothesized that any intervention in poor quality soil in urban area will change their chemical and water retention properties. The experiment was conducted in Krakow (Poland) in completely randomized design (CRD). The soil amendments used in this experiment consisted of control, spent coffee grounds (SCGs), salt, and sand (1 and 2 t ha^{-1}) in order to evaluate the impact of these soil amendments on the urban soil chemical and hydrological properties. Soil samples were collected after 3 months of soil application. The soil pH, soil acidity (me/100 g), electrical conductivity (mS/cm), total carbon (%), CO_2 emission (g m^{-2} day^{-1}), and total nitrogen (%) were measured in laboratory condition. The soil hydrological properties like volumetric water content (*VWC*), water drop penetration time (*WDPT*), current water storage capacity (S_a), water storage capacity after 4 and 24 h (S_4 and S_{24}), and capillary water P_k (mm) were also determined. We noted variations in soil chemical and water retention properties in urban soil after the application of SCGs, sand, and salt. It was observed that SCGs (2 t ha^{-1}) has reduced soil pH and nitrogen (%) by 14 and 9%, while the incorporation of salt resulted in maximum soil EC, total acidity, and soil pH. The soil carbon (%) and CO_2 emission (g m^{-2} day^{-1}) were enhanced and declined by SCGs amendment. Furthermore, the soil hydrological properties were significantly influenced by the soil amendment (spent coffee grounds, salt, and sand) application. Our results showed that spent coffee grounds mixing in urban soil has considerably enhanced the soil *VWC*, S_a, S_4, S_{24}, and P_k, whereas it decreased the water drop penetration time. The analysis showed that the single dose of soil amendments had not improved soil chemical properties very well. Therefore, it is suggested that SCGs should be applied more than single dose. This is a good direction to look for ways to improve the retention properties of urban soil and you can consider combining SCGs with other organic materials like compost, farmyard manure, or biochar.

Keywords Total carbon · Carbon dioxide emission · *WDPT* · Volumetric water content · Water storage capacity

Introduction

Soils play a crucial role in the Earth's system, and they are vital in achieving many of the UN Sustainable Development Goals (Keesstra et al. 2016a). According to the United Nations, soil protection is a key land-use policy issue, and strategies are needed to maintain soil quality, soil functions, and soil services for sustainability (Keesstra et al. 2018). Urban soils play an essential role in urban ecosystems, providing a growth medium for plants, vegetation, and soil microorganisms (Guilland et al. 2018). Soil water retention, fertility maintenance, and contaminant removal are services urban soils provide (Ozdemir 2019; Salmond et al. 2016). However, compared to natural forest soils, human activities have aggravated urban soils' health and ecological function (Weissert et al. 2016; Zhao et al. 2013). As a result,

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growing plants in this soil is typically complex, and maintaining green land is also costly (Zou et al. 2012; Miao and Shi 2015). Climate change and its consequences, such as drought, have recently become more severe and pervasive worldwide, particularly in arid and semi-arid areas (Solomon et al. 2007). Precipitation is becoming more unpredictable, average temperatures are rising, and soil and water resources are deteriorating daily (Knox et al. 2012). Furthermore, an extreme reduction in rainfall due to global warming has been shown to enhance the severity and frequency of urban droughts, posing a severe danger to the whole ecological services provided by urban green zones (Gillner et al. 2014; Mullaney et al. 2015). These issues could decrease the urban soil water retention properties and destroy various species, from yearly flowering grasses to perennial crossroad trees, resulting in massive economic and ecological losses.

Soil degradation caused by climate change and human activities has resulted in the deterioration of soil health worldwide, with effects such as soil erosion, nutrient depletion, organic matter reductions, and compaction (Olsson et al. 2019). Urban trees are hampered by several environmental factors that limit their growth and shorten their lives (Nilsson et al. 2001). Chloride salts are extensively used in cold weather cities to manage ice and snow on roadways and pathways throughout the wintertime. Transportation organizations use sodium chloride (NaCl) most often because of its availability, efficiency, and low cost (Transportation Association of Canada 2004). It has already been demonstrated that salt application for winter road maintenance increases soil salinity (Fay and Shi 2012). Urban trees can take up the accumulated salt from the soil during the growing period (Cunningham et al. 2008). As salt flow is highest near roadways, trees near salt-treated areas are most affected by salt stress (Cekstere and Osvalde 2013). Whereas de-icing salt is identified as a leading cause in the decrease of urban trees, its use has expanded over the past decade as a result of growing public demand for safe driving and better road traffic (Fay and Shi 2012). As a result, there is a broader societal interest in improving soil quality by adopting sustainable soil management techniques that improve soil properties, especially organic matter content (caused by grass mowing and leaf raking for many years), and so assist to develop healthy soil. Therefore, developing novel methods for enhancing urban soil quality and water retention capacity is valuable and significant.

rom the perspective of climate change, the knowledge of carbon sequestration and water retention in all types of ecosystems has gained significance as it may assist in the mitigation of and adaptation to them (Prasad and Pietrzykowski 2020). The availability of plant-available green water in the soil must be improved through the application of solutions based on nature (nature-based solutions), as well as controlling the amount and quality of blue water (surface water and groundwater) throughout the year(s) to prevent floods and droughts (Keesstra et al. 2021). In droughts, heat waves, and storms, dry soil becomes hydrophobic and less permeable, and in the event of heavy rains, it can contribute to local flood episodes (Zscheischler et al. 2018). By 2050, the world population is expected to grow between 8 and 11 billion people, with 66 percent of people living in cities (UNDESA 2014). Two critical difficulties for a highly urbanized world's population are providing essential resources (food, water, and power) to urban centers and the management of urban wastes produced in urban centers. New, inventive, and sustainable urban solutions are necessary to tackle these difficulties (Hoornweg and Bhada-Tata 2012). Soil amendments could be utilized in urban horticulture or food production, as well as soil remediation, as an example of how organic food waste created in cities could be exploited (Brown et al. 2011) and to enhance city sustainability and ecological impacts (Martinez-Blanco et al. 2009). It is not a new concept to use organic food waste as a soil additive; it has been used as a soil amendment by civilizations throughout history (Parr and Hornick 1992). Organic soil fertilizers can help crop growth by improving important physicochemical and biological characteristics (Brady and Weil 2008). 2014 Organic waste amendment has improved the nutrient availability, soil moisture, nutrient-holding capabilities, soil structure and water infiltration, soil pH, reduced nitrate leaching, soil biological characteristics, and long-term carbon sequestration (Haider et al. 2014).

A large quantity of spent coffee grounds (SCGs) is produced all over the world each year (15 million tons) (Kamil et al. 2019). According to Stylianou et al. (2018), SCG can be used as an organic soil amendment and has been proven to have many environmental benefits. Even though SCG is phytotoxic, it has been shown that it can improve soil physical and chemical fertility, and that it can affect the soil microbiota as well. SCG has a nitrogen level of 1.0 to 2.5 percent and a C/N ratio of 20 to 25, making it much higher than typical horticulture soils and soil microbial communities (Pujol et al. 2013). Researchers have evaluated the impact of SCGs on soil physical, chemical, and biological properties on Mediterranean soils (Cervera-Mata et al., 2021, 2022; Comino et al. 2020). They reported that the application of SCGs enhances water retention; total porosity; and N, P, and K concentrations and improves C cycle, while reduces the bulk density of the soil. Cervera-Mata et al. (2018) concluded that the usage of SCGs in soils enhances the SOC and reduces the emissions of CO_2 to the environment. The phenols in SCG are toxic to soil microbes and plants, but they also act as natural pesticides and herbicides (Cruz et al. 2012). Morikawa and Saigusa (2008) found that composted coffee grounds improved the growth of various horticultural crops in specified soils, while the results for non-composted SCG are less apparent. Although the results vary depending on the plant species, soil amendment with SCG can simultaneously increase plant biomass while lowering foliar N content (Yamane et al. 2014; Cruz et al. 2012). Since spent coffee grounds are acidic, it may lower soil pH (Mussatto et al. 2011).

Interdisciplinary exploration and understanding of the functioning of the urban greenery ecosystem in the changing abiotic conditions are necessary for modeling hydrological processes and the carbon cycle. We hypothesized that the addition of SCGs in poor quality soil in cities will not only change soil chemical properties, but will also improve the soil hydrological properties due to organic nature; nevertheless, a single dose of SCGs, salt, and sand is a determinant of the direction for further research. We designed this experiment in order to study how different doses of SCGs as an organic amendment source could improve the soil chemical and hydrological properties related to volumetric water content, water storage capacity, and capillary water, as compared to salt application in urban soil.

The results of the conducted research should be considered in a long-term perspective and are expected to broaden the knowledge both in the field of biological sciences and facilitate the verification of research methods in the field of hydrological sciences and environmental engineering.

Materials and methods

Description of experimental site and soil sampling

The experiment was conducted in winter season (2022) at the University of Agriculture in Krakow Campus, which is located in the urban area of the Krakow City. The study site was established in less frequented lawn, and before conducting experiment, the area was cleaned from tree's branches, leaves, and other unwanted material (Fig. 1). A moderately cold climate prevails in the city of Krakow from January to March, average rainfall was about 50 mm for the examined months, and the average temperature ranged from −2 to 3 °C. The average relative humidity of the air recorded at that time was 79%. The soil in the study plot was identified as Urbic Technosol according to the World Reference Base for Soil Resources (IUSS Working Group WRB-FAO 2015). The soils were formed on Quaternary sands, which are one of the main (along with loess and alluvium) parent materials within the city of Krakow.

The experiment was conducted in completely randomized design (CRD) and the individual plot area was 1×1 m^2. The treatments used in this experiment were spent coffee grounds (SCGs), salt, sand, and control (no soil amendment). Each treatment was applied in two levels consisting (1 and 2 t ha^{-1}) with one control plot. Each experimental unit was replicated six times. The soil samples were collected (10-cm depth) by using 100-cm^3 Kopecky cylinders after 3 months of treatment in order to assess the chemical and hydrological properties.

The soil amendment SCGs were collected from the different coffee shops. The SCGs were acidic in nature, the nitrogen content was 0.8–2.3%, and the C/N ratio was 18 to 22. The salt used in this study sodium chloride (NaCl) was collected from the "Kłodawa Salt Mine" region. The NaCl was 90% pure, and up to 8% the content of substances was insoluble in water. The potassium ferrocyanide ($K_4(Fe(CN)_6)$ 20 mg kg^{-1} was also added to the NaCl, which is an anti-caking agent. The sand utilized in this experiment was collected from the aggregate mine "Kruszywo" Krakow. The

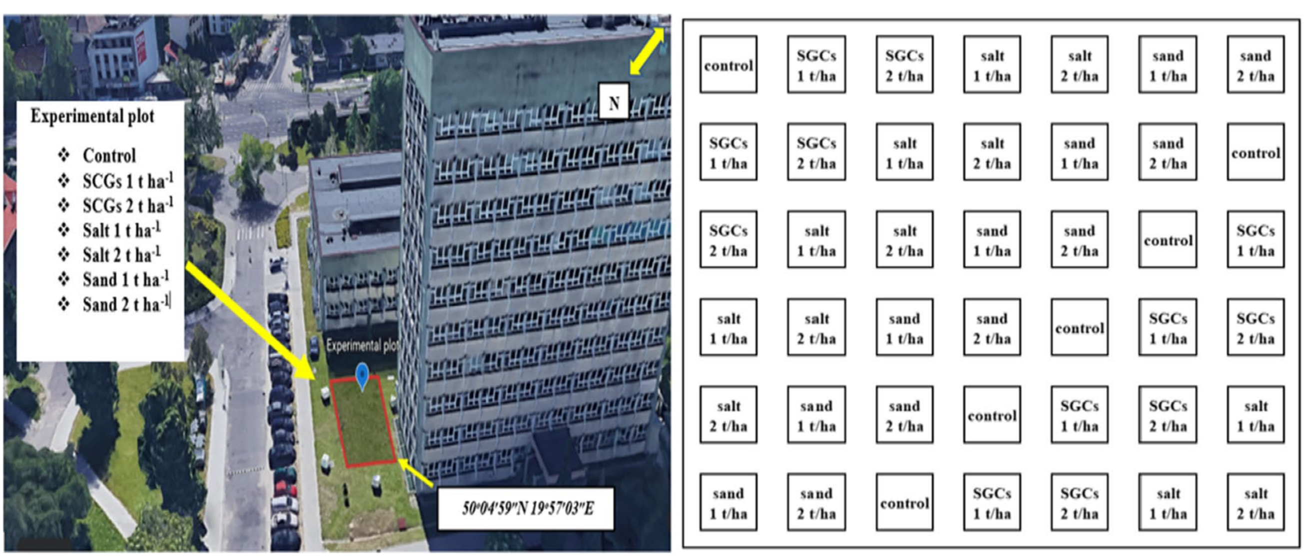

Fig. 1 Location of the study site and experimental layout

mineralogical composition of sand was silica (SiO_2) and the size was "fine" size ranged from 0 to 0.5 mm grade II.

Hydrological properities

Soil samples were collected from each experimental plot and we weighed fresh (M_f) and then immersed in distilled water under room conditions (±21 °C, humidity 30%). The samples were weighed 4 h (M_4) after the cylinders were completely filled with water, and then after 24 h (M_{24}) by adding the time the samples were out of water when weighing after 4 h. Then the samples were dried in a laboratory drier for another 24 h at 105 °C, obtaining a dry mass (M_d).

The current water storage capacity (S_a) was obtained by subtracting M_d from M_f and then S_4 was obtained by subtracting M_4 from M_d and S_{24} by subtracting M_{24} from M_d (Klamerus-Iwan et al. 2020). The water drop penetration time (*WDPT*) test determines how long it takes for a single water drop to enter a sample of soil (Doerr 1998; Hallin et al. 2013). A medical dropper was used to placed three to five drops of distilled water of a similar volume to the surface of each sample, and the duration it took for each drop to fully enter the soil was timed using a stopwatch. Using the drop penetration time measurement data for each soil samples, the average value ($WDPT_{av}$) and median ($WDPT_{me}$) were computed for further study. The *WDPT* measurement was performed in 2 variants: on a fresh sample (*WDPT_1*) and on samples taken in steel frames (20 × 20 × 20) and placed in laboratory conditions for 5 days (*WDPT_2*). This method allowed us to observe the reaction to drying of samples with additions of SCGs, salt, and sand to the soil.

The volumetric water content (*VWC%*) in the soil was measured by TEROS_12 (Meter n.d.). TEROS_12 sensor monitors the dielectric permittivity of the surface layer using an electromagnetic field. The sensor uses a 70-MHz oscillating wave to the sensor needles, which charge in line with the material's dielectric. The charge time is linked to the dielectric constant and *VWC* of the substrate. Microprocessor TEROS 12 measures the charging time and outputs a raw value based on the dielectric permittivity of the substrate. The raw data is then transformed to *VWC* using a substrate-specific calibration equation. *VWC* (θ) is given by the following equation:

$$\theta\left(m^3/m^3\right) = 3.879 \times 10^{-4} \times RAW - 0.695$$

The *VWC* measurement was performed in 2 variants: on a fresh sample (*VWC_1*) and on samples taken in steel frames and placed in laboratory conditions for 5 days (*VWC_2*).

A soil medium's water reservoir's maximum capacity is defined by its capillary capacity, which is calculated over long periods of time and under maximum storage conditions. In order to measure the capillary capacity (P_k), individual monoliths were soaked in water for 7 to 10 days, with their initial soaking of 2 to 3 days consisting of gradual filling with water (Ilek et al. 2017). The water in the containers was replaced every 2 days to avoid decay. The capillary capacity P_k (mm) was determined according to the following formula:

$$P_k = (v/V) \times 10$$

In this case, v represents the volume of water (cm^3) calculated by subtracting the difference between the mass of a given soil horizon, when it is at maximum water storage capacity, from the mass of that soil horizon, after drying to 105 °C. In the state of maximum water storage capacity (cm^3), V represents the volume of a given horizon.

The granulometric composition was determined by laser diffraction, divided into sand, dust, and clay. Laser Particle Sizer ANALYSETTE 22 was used to perform this division (Fritsch 2016).

Chemical analysis

Also, soil samples were collected from each experimental unit in plastic tube of 100-cm^3 volume. The soil samples were air dried; removed stones, roots, leaves, and other unwanted material; and then sieved through a 2-mm sieve for chemical analysis. Soil samples thus ready, 10 g was taken from each treatment and grounded in a ball mill (Fritsch) for the determination of nitrogen (N%) and carbon (C%) concentrations in a LECO TrueMac Analyser (Leco, St. Joseph, MI, USA). A potentiometric method using a combined electrode and soil suspension in distilled water (1:5 mass-to-volume ratio) was used to measure soil pH after 24 h of equilibration (Buurman et al. 1996). In order to determine the total acidity (TA), 10 g of soil was extracted with 1 M calcium acetate ($(CH_3COO)_2Ca$), shaken for 1 h, and filtered. The samples on filters were washed with 100 mL of extractant solution. Twenty-five milliliters of the obtained extract was titrated to pH 8.2 with 0.1 M NaOH using potentiometric titration (automated titrator Mettler Toledo) (Buurman et al. 1996).

Measurement of soil CO_2 respiration

A closed chamber incubation method with sodium hydroxide (NaOH) was used to evaluate soil carbon dioxide emissions (Hopkins 2006). We poured 30 mL of 1 M NaOH into a beaker and applied it to each soil column. In accordance with Eq. (1), CO_2 emission from the soil was converted into Na_2CO_3:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \quad (1)$$

A barium chloride solution was not needed to precipitate carbonates because the soil samples were free of carbonates. The soil columns with beakers were placed in an airtight plastic bag to make sure that the soil moisture remains unchanged and the proper measurement of CO_2 emission, and then stored in an incubator at 20 °C. Following a week of incubation, the sodium hydroxide excess was backtitrated using 0.5 M HCl through potentiometric titration (Automatic titrator, Mettler Toledo, Inc. Columbus, OH). According to Eq. (2), the backtitration was carried out.

$$NaOH + HCI \rightarrow NaCl + H_2O \quad (2)$$

The amount of carbon dioxide emission was depicted in $g_{CO2}\ m^{-2}\ day^{-1}$.

Statistical analysis

The analysis of variance (ANOVA) was done for the collected data using MS Excel, and the LSD (least significant difference) tests for the significant differences between treatments (control, SCGs, salt, and sand at the rate of 1 and 2 t ha^{-1}) were performed through Statistic software (Statistix 8.1). Tukey (HSD) test was done through Python software to test differences among treatment means for significance. The boxplots were created through python using seaborn library (Waskom et al. 2020). The principal component analysis (PCA) and the regression plots were done through R statistical software using packages “Factoextra,” “FactoMiner,” and “ggplot2” (Kassambara 2017; Le et al. 2008; Wickham 2016). The significance level 95% ($p < 0.05$) was tested in this experiment.

Results

The tests showed that all samples contained a total of 49.2% sand, 45% dust, and 5.8% clay. The results, based on the PTG 2008 standards, show that the area from which the samples were taken is composed mainly of clay formations, a subgroup of sandy loams.

The characteristic properties of this type of soil formations are that they do not dry out too quickly, providing plants with constant access to water, and their roots, access to oxygen, due to the fact that they are properly aerated, but their properties do not allow excess water to accumulate.

Soil chemical properties

The mixing of different doses of SCGs, salt, and sand significantly influenced the soil pH, electrical conductivity (EC), total acidity, and the soil nitrogen (%). The clear differences in soil pH with different doses of soil amendments can be seen in Fig. 2 A, where SCG doses (1 and 2 t ha^{-1}) have a significant affect on soil pH rather than sand and salt doses. Soil pH was more alkaline when treated with salt (2 t ha^{-1}) and the application of SCGs (2 t ha^{-1}) decreased the soil pH as compared to control plot. Additionally, a decrease in soil pH by 7 and 14% was recorded with the application of SCGs at doses of 1 and 2 t ha^{-1}. At 1 and 2 t ha^{-1} of salt, there was a noticeable rise in the electrical conductivity of the soil. However, other amendments, such as SCGs or sand at 1 and 2 t ha^{-1}, did not significantly affect soil's electrical conductivity (Fig. 2 B). Furthermore, compared to the control, salt addition raised soil EC by 143 and 283 percent, respectively. Soil EC was the lowest in the plot with 1 t ha^{-1} of sand. The statistical results indicated that the total acidity significantly varied after the incorporation of different treatments (SCGs, sand, and salt); however, their different levels (1 and 2 t ha^{-1}) results were not quite different from each other. The highest TA value was recorded in salt, followed by SCGs and sand. Furthermore, salt at the rate of 1 and 2 t ha^{-1} increased total acidity by 20 and 15 percent compared with control treatment (Fig. 2 C). The nitrogen concentrations in the soil after incorporation of different amendments, i.e., SCGs, salt, and sand at the rate of 1 and 2 t ha^{-1}, varied significantly from each other. The highest nitrogen concentration was recorded in the control plot, followed by SCGs at the level of 1 t ha^{-1}; however, the minimum nitrogen concentration was measured in the sand treatment at the rate of 1 t ha^{-1}. In addition, the mixing of SCGs at the rate of 1 and 2 t ha^{-1} significantly declined the nitrogen contents by 2 and 9 percent as compared to the control (Fig. 2 D).

Carbon (%) and CO_2 emission

The impact of different amendments significantly influenced the carbon (%) concentration in the soil, while the CO_2 emission was not significantly affected. The maximum carbon (%) content was noted in the plot, which was treated with SCGs at the rate of 2 t ha^{-1} followed by SCGs (1 t ha^{-1}) (Fig. 3 A). The minimum carbon concentration was recorded in the sand (1 t ha^{-1}) treatment. Furthermore, the maximum CO_2 emission was noted in the salt treatment (1 t ha^{-1}), and the SCG (2 t ha^{-1}) has considerably reduced the CO_2 emission from the soil (Fig. 3 B).

Soil hydrological properties

Volumetric water content

The impact of the different soil amendments depicted significant differences in the mean value of the soil volumetric water content in the fresh soil samples. The volumetric water content of the soil in the fresh state (*VWC*_1) has been dramatically decreased by the addition of salt (1 and 2 t ha^{-1}). In comparison, the application of SCGs (1 and 2 t ha^{-1}) has consistently improved the volumetric water content in the field by 9 and 18%, compared with control, respectively.

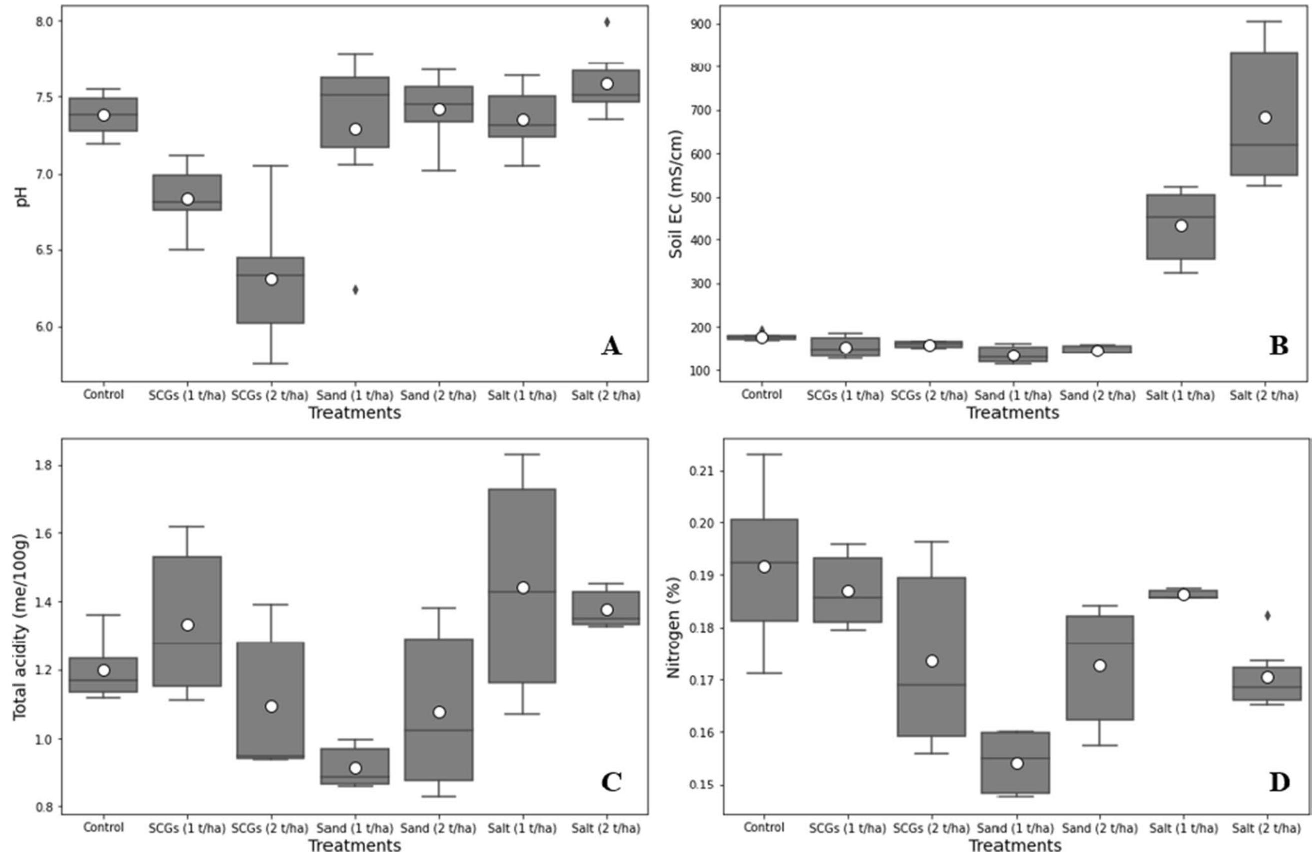

Fig. 2 **A**, **B**, **C**, and **D** Boxplot of the soil pH, EC (mS/cm), total acidity (me/100 g), and nitrogen (%) plotted against different treatments (control, SCGs, sand, and salt at the rate of 1 and 2 t ha^{-1}). The upper and lower whiskers represented the highest and lowest values, the middle line within the boxplot represents the median value, and the white circle inside the boxplot shows the mean value of each treatment

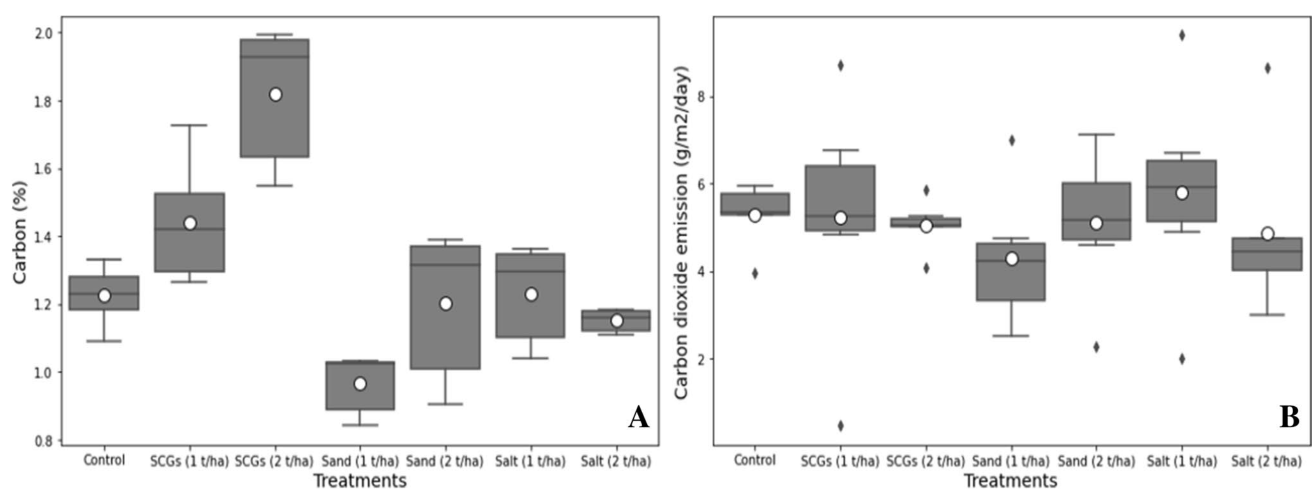

Fig. 3 **A** and **B** Boxplot of the soil carbon (%) and CO_2 emission (g/m^2/day) plotted against different treatments (control, SCGs, sand, and salt at the rate of 1 and 2 t ha^{-1}). The upper and lower whiskers represented highest and lowest values, the middle line within the boxplot represents the median value, and the white circle inside the boxplot shows the mean value of each treatment

The SCG (2 t ha^{-1}) treatment had the greatest computed *VWC*_1, whereas the salt (2 t ha^{-1}) treatment had the lowest *VWC*_1 (Fig. 4 A).

The integration of several soil treatments significantly influenced the data of volumetric water content in the soil samples after 5 days in the lab (*VWC*_2) (Fig. 4 C). The SCGs treatment (2 t ha^{-1}) has escalated (21%) *VWC*_2, followed by SCGs (1 t ha^{-1}) up to 20% in soil samples after 5 days at room temperature. Furthermore, the *VWC*_2 concentration plunged in other treatments after 5 days of drying at room temperature.

Water drop penetration time (*WDPT*_1 and *WDPT*_2)

The statistical analysis of the water drop penetration time data in the fresh soil samples (*WDPT*_1) showed significant variations among the application of different soil amendments. The least water drop penetration time (2.33 s) was taken in the treatment of SCGs at the rate of 2 t ha^{-1}, while the control plot took the maximum time (4.83 s) for the water drop to penetrate (Fig. 4 B). There was no considerable differences between SCGs (1 t ha^{-1}), sand (2 t ha^{-1}), and salt (2 t ha^{-1}) treatments. The incorporation of various soil treatments has considerably differentiated the *WDPT*_2. The highest water drop penetration time (42.8 s) was recorded in SCGs (2 t ha^{-1}) treatment, while the least time (7.5 s) for water drop penetration was taken in the control plot treatment (Fig. 4 D). Further, the impact of sand treatment at both doses (1 and 2 t ha^{-1}) showed no significant effect on *WDPT*_2.

Current water storage capacity (S_a), water storage capacity after 4 h (S_4), maximum water capacity after 24 h (S_{24}), and capillary water in the 1-cm layer of soil

The S_a, S_4, and S_{24} have been significantly impacted by the effects of various treatments, including SCGs, salt, and sand. Compared to other treatments, the application of SCGs (2 t ha^{-1}) improved these parameters. In contrast, the S_a, S_4, and S_{24} in soil samples have been dramatically reduced by the addition of sand (2 t ha^{-1}). In addition, the SCG (2 t ha^{-1}) has increased the S_a, S_4, and S_{24} by 71, 54, and 54%,

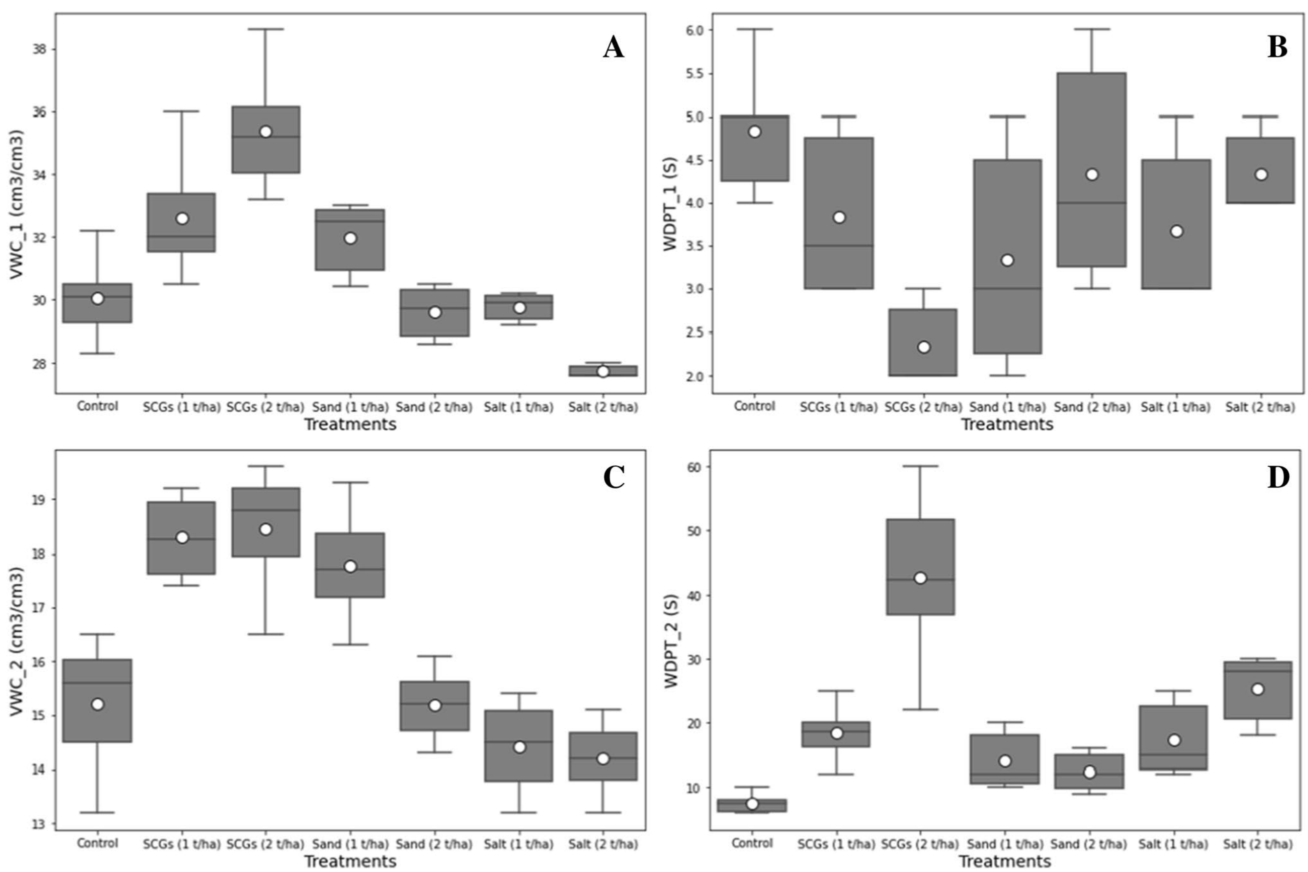

Fig. 4 **A**, **B**, **C**, and **D** Boxplot of the volumetric water content (*VWC*_1), water drop penetration time (*WDPT*_1), volumetric water content in soil after 5 days (*VWC*_2), and water drop penetration time (*WDPT*_2) plotted against different treatments (control, SCGs, sand, and salt at the rate of 1 and 2 t ha^{-1}). The upper and lower whiskers represented highest and lowest values, the middle line within the boxplot represents the median value, and the white circle inside the boxplot shows the mean value of each treatment

compared with the declining factor (sand, 2 t ha^{-1}), respectively (Fig. 5 A, B, C). The capillary water in the 1-cm layer of the soil was increased notably after incorporation of the soil treatment SCGs at the rate of 1 and 2 t ha^{-1} as compared to other amendments (Fig. 5 D). However, the application of sand and salt showed minimum capillary water in the soil layer as compared to the SCGs and control plot. Moreover, the SCGs treatment at the rate of 1 and 2 t ha^{-1} escalates the capillary water up to 14 and 32%, compared with control, respectively.

Linear correlation between S_a and S_4, S_a and S_{24}, S_a and capillary water P_k (mm), carbon (%) and *WDPT*_1 (S), and carbon (%) and *WDPT*_2 (S)

Figure 6 shows the correlation between current water storage capacity (S_a) and water capacity after 4 h (S_4), S_a and maximum water storage capacity after 24 h (S_{24}), S_a and capillary water (mm), carbon (%) and water drop penetration time (*WDPT*_1), and carbon (%) and water drop penetration time (*WDPT*_2). Figure 6 A depicts the correlation among current water storage capacity (S_a) and water capacity after 4 h (S_4). The *R* squared value is higher, which explains that the data is well fitted in this model. Further, the coefficient value indicates a positive relationship between dependent and independent variables. Finally, the *p* value shows statistically significant relationship between S_a and S_4. The linear regression between S_a and S_{24} is presented in Fig. 6 B, which indicates that increasing in the current water storage capacity also tend to increase the water storage capacity after 24 h in soil sample. The coefficient represents the positive relation among S_a and S_{24}, which means that water storage capacity after 24 h increases by increasing in current water storage capacity, and the *p* value (< 0.05) indicates the statistical significance among S_a and S_{24}. Figure 6 C shows the relation between current water storage capacity and the capillary water (mm) in the soil. The capillary water in the soil enhances with increasing trend in the current water storage capacity (S_a). The figure depicts the stronger positive linear relation among S_a and capillary water in the soil, and the

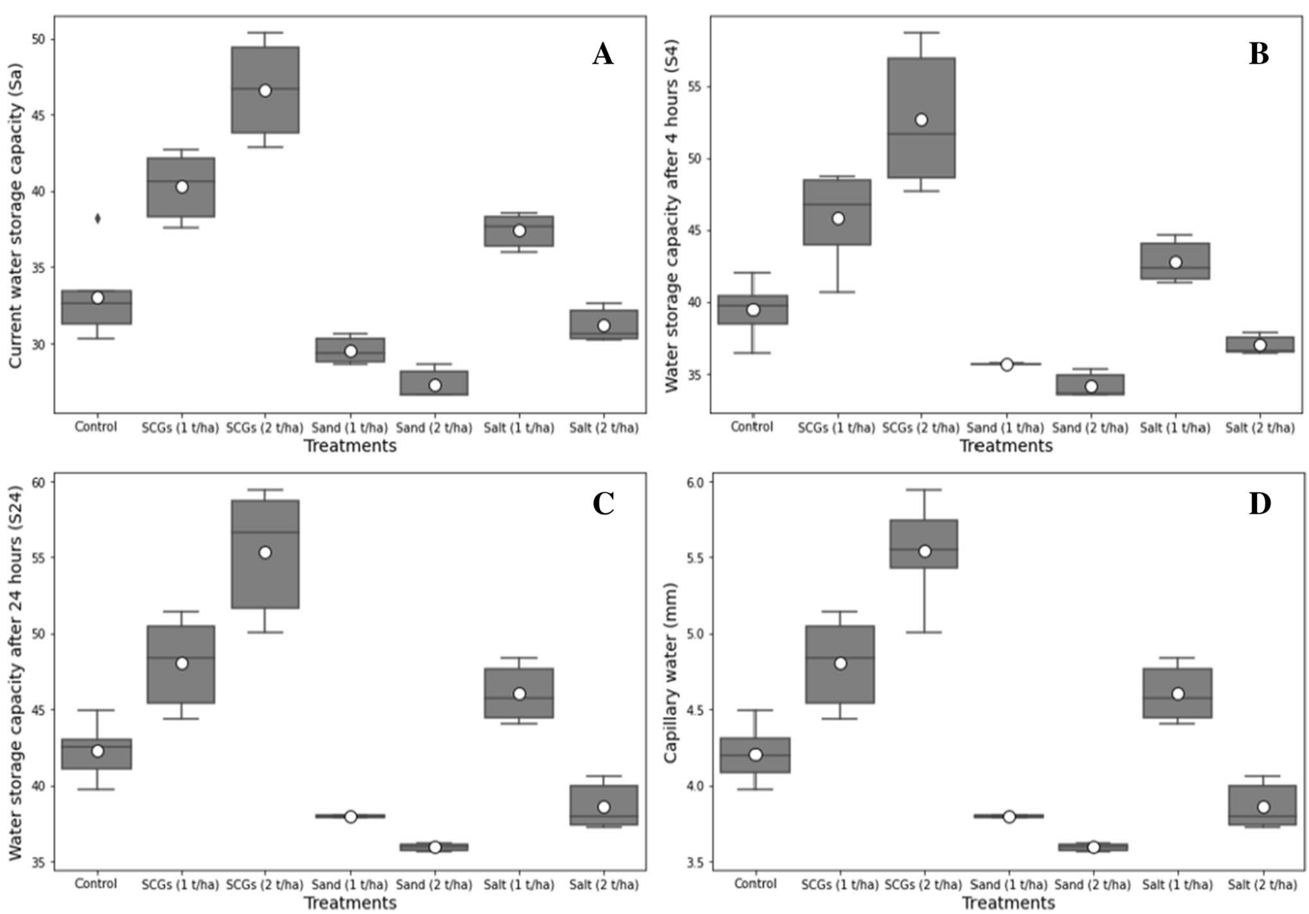

Fig. 5 **A**, **B**, **C**, and **D** Boxplot of the current water storage capacity (S_a), water capacity after 4 h (S_4), water capacity after 24 h (S_{24}), and capillary water P_k (mm) plotted against different treatments (control, SCGs, sand, and salt at rate of 1 and 2 t ha^{-1}). The upper and lower whiskers represented highest and lowest values, the middle line within the boxplot represents the median value, and the white circle inside the boxplot shows the mean value of each treatment

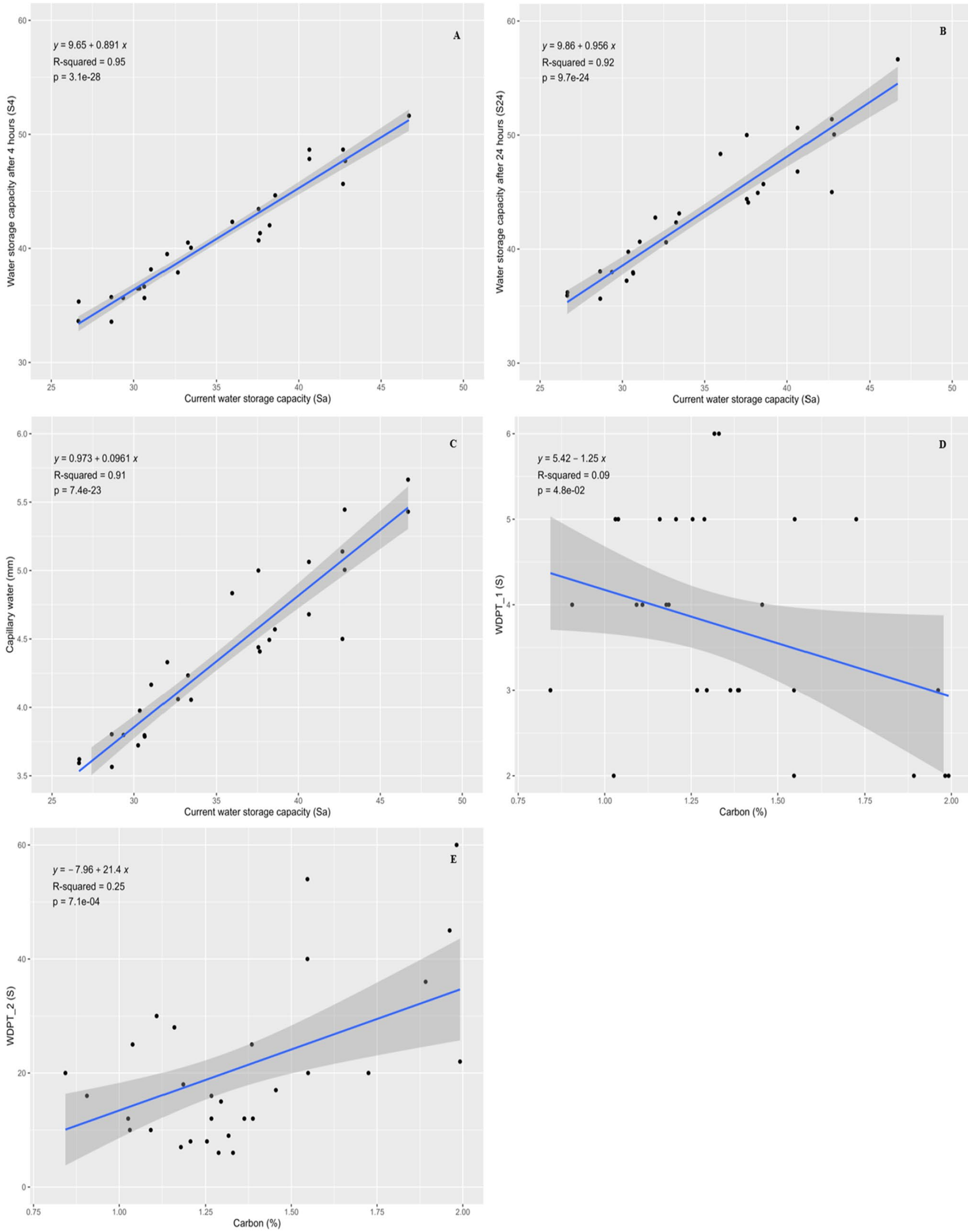

Fig. 6 **A**, **B**, **C**, **D**, and **E** Linear regression between current water storage capacity (S_a) and water storage capacity after 4 h (S_4), current water storage capacity (S_a) and water storage capacity after 24 h (S_{24}), current water storage capacity (S_a) and capillary water P_k (mm), carbon (%) and *WDPT*_1 (S), and carbon (%) and *WDPT*_2 (S)

R^2 value displays that this model explains 91 percent data. Figure 6 D shows the linear relationship between carbon (%) and water drop penetration time (*WDPT*_1) and the coefficient value describes the negative relationship among carbon and *WDPT*_1, which means that the water drop penetration time in fresh soil samples decreased with increasing in carbon content. Also, this model describes only 9 percent of the data. The linear regression between carbon (%) and water drop penetration time (*WDPT*_2) is presented in Fig. 6 E. The relation between dependent and independent variables was slightly positive, which describes that rising carbon (%) value slightly increases the water drop penetration time (*WDPT*_2) up to some extent. Further, the statistical differences among carbon and *WDPT*_2 are significant.

Principal component analysis

A principal component analysis (Fig. 7) was done to evaluate how different doses of SCGs, salt, and sand affect the parameters, such as S_a, S_4, S_{24}, *VWC*_1 (cm^3/cm^3), *WDPT*_1 (S), *VWC*_2 (cm^3/cm^3), *WDPT*_2 (S), C (%), CO_2 ($g/m^2/$day), and P_k (mm). The first two PCA depicted 46.34% total variations among various variables. The CO_2 emission (g m^{-2} day^{-1}), total carbon (%), S_a, S_4, S_{24}, and P_k (mm) occupied the upper right quadrant of the plot, and the *VWC*_1, *VWC*_2, and *WDPT*_2 occupied the lower right quadrant.

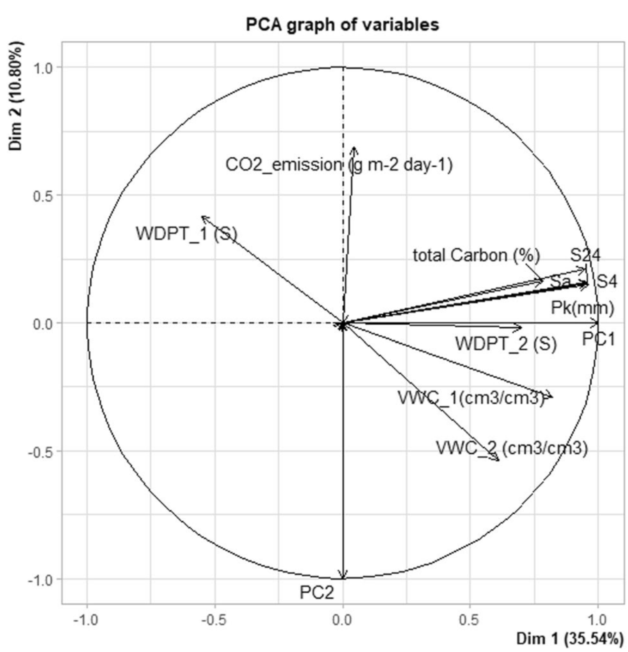

Fig. 7 Principal component analysis (PCA) shows variance of the different variables (soil chemical and hydrological properties) of soil measured. S_a, current water storage capacity; S_4, water storage capacity after 4 h; S_{24}, water storage capacity after 24 h; *VWC*, volumetric water content; *WDPT*, water drop penetration time; P_k, capillary water

The PCA graph shows the strong relationship of total carbon (%) with S_a, S_4, S_{24}, and P_k (mm); however, the relationship between the total carbon (%) with *VWC*_1, *VWC*_2, and *WDPT*_2 was very weak. Additionally, the *VWC*_1 (cm^3/cm^3) and *WDPT*_1 (S) lie in opposite direction to each other. The relationship between total carbon (%) and CO_2 emission (g m^{-2} day^{-1}) was negligible.

Discussion

Soil chemical properties

The impact of SCG application to the soil considerably reduced the soil pH by 7 and 14%, respectively. The reduction of soil pH was due to the acidic nature of the spent coffee grounds which have the ability to reduce soil pH. Another possible reason in reduction of soil pH could be due to the organic acids present in the SCGs such as chlorogenic acid and citric acid, which can decrease the soil pH. Hardgrove and Livesley (2016) explained that the application of spent coffee ground increases the soil pH in glasshouse trail, whereas the SCG decreases the soil pH in field trail. Another study conducted by Kasongo et al. (2011) depicted that SCG amendment significantly increased the soil pH. Soil EC (mS/cm) were significantly increased by salt treatment (1 and 2 t ha^{-1}) by 143 and 283%, correspondingly. Soil salinity increased due to available soluble salt ions by the application of salt. According to Fay and Shi (2012), increased salinity of roadside soils has been linked to the prolonged usage of salt for winter road maintenance. The total acidity was increased with the application of salt treatment, followed by SCGs. Salt increased total acidity up to 20 and 15% by the application of 1 and 2 t ha^{-1}. Salts like Cl^- are easily dissolved in moist soil, and this process releases H^+ into the soil solution, increasing soil acidity. The soil nitrogen (%) was higher in the control plot as compared to various amendment applications, which described that the application of the SCGs to the soil has reduced the nitrogen percentage in the soil. When significant amounts of carbon are introduced to the soil, generally followed the degradation and death of surrounding plants, nitrogen levels in the soil are lowered. The nitrogen that is available to the plant will be rapidly depleted by microorganisms as they break down the new carbon source. Hardgrove and Livesley (2016) described two mechanisms by which spent coffee ground could hinder plant growth, which include biological nitrogen immobilization and phytotoxicity. Another study (Cruz and Marques 2015) suggested that SCGs had no significant effect on the soil nitrogen concentration over time. The addition of SCGs at low level (10%) can be effective in the soil, but the concentration of nitrogen decreased with increasing level (20%) of SCG application to the soil (Cruz et al. 2012). A more recent investigation found that the soil nitrogen content for growing lettuce has significantly decreased (35% reduction with 15% SCG) (Cervera-Mata et al. 2019).

Plants that preferentially take up nitrate or have high N needs should have the greatest growth inhibition due to poor soil NO_3^- availability and net NO_3^- immobilization after SCG soil addition (Kahmen et al. 2009). The amount of carbon (%) in the soil has significantly influenced by the various treatments. The highest carbon (%) content was achieved at the rate of 2 t ha^{-1} SCGs followed by SCG (1 t ha^{-1}) amendment. Comino et al. (2020) investigated the impact of SCG on two types of soils for a shorter period of 30 and 60 days and concluded that 2.5 and 10% SCG application showed enhancement in the organic matter fraction of the soil. Hirooka et al. (2022) described that the application of SCGs had no significant effect on total carbon and nitrogen content in soil after first year of application, while the top-dressing application of SCGs after 2nd and 3rd year had significantly enhanced the soil total carbon and nitrogen concentration. The CO_2 emission was not significantly impacted by applying various treatments (SCGs, salt, and sand) at various levels (1 and 2 t ha^{-1}). SCGs reduced the CO_2 emission as compared to other treatments due to C sequestration in the soil. Abagandura et al. (2019) concluded that the addition of biochar and manure reduced CO_2 emission in the sandy soil.

Soil hydrological properties

The volumetric water content (*VWC*_1) in the fresh soil samples was increased by SCGs (2 t ha^{-1}). The reason behind the highest *VWC*_1 was the organic nature of the SCGs which enhances the physical structure (soil bulk density, specific surface area, soil structure, and total porosity) of the soil, thus increased volumetric water content. The volumetric water content (*VWC*_2) in soil samples after 5 days was retained by SCG application (1 and 2 t ha^{-1}) up to 20 and 21%, which showed that soil can retain water for more time even in drought condition could be due to the presence of soil organic matter up to certain limit. When compared to the control soils, the proportion of applied soil water that percolated through the soil columns was considerably ($p < 0.05$) lower for the amended soils, demonstrating an improvement in water retention capacity (Kasongo et al. 2011). Cervera-Mata et al. (2023) concluded that the amount of water retention at field capacity and permanent wilting point was increased with increasing amount of SCGs. The lowest water drop penetration time (*WDPT*_1) in the fresh soil samples was recorded in the SCG treatment (2 t ha^{-1}), while the highest time for water drop penetration time (*WDPT*_2) after 5 days was also noted in soil sample taken from the plot treated with (SCGs, 2 t ha^{-1}). The more time taken by the drops to absorb in the soil could be due to the presence of organic matter in the SCGs which release some hydrophobic compounds due to which water repelled by the soil surface. Due to an increase in the hydrophobic nature of organic matter in soil in dry conditions, organo-mineral coatings could reduce the wettability of aggregate surfaces (Vogelmann et al. 2013). Fu et al. (2021) concluded that SOC content was positively associated with the persistence of soil water repellency. They also explained that wettable soils had SOC contents of less than 2%, and water-repellent soils had SOC contents of more than 4%. Studies that focused on a particular land-use and soil types indicated positive associations among *WDPT* and soil organic matter in air-dried soils (Lozano et al. 2013; Martínez-Zavala and Jordán-López 2009), but other research indicated weak relationships when multiple land uses were considered (Doerr et al. 2006, 2009). The current water storage capacity (S_a), water capacity after 4 h (S_4), and water capacity after 24 h (S_{24}) were significantly enhanced by the incorporation of the SCGs (2 t ha^{-1}) as compared to other treatments. The enhancement of the S_a, S_4, and S_{24} may be due to the organic amendments which improve soil physical properties (soil structure, soil porosity, soil texture, and soil bulk density). Several soil characteristics have been shown to improve after organic waste amendment, including soil water- and nutrient-holding capacity, soil structure and water infiltration, and long-term carbon sequestration (Haider et al. 2014; Diacono and Montemurro 2010; Quilty and Cattle 2011). SCGs can be applied as mulch or as a soil additive. Similar to other mulch materials, it reduces soil temperature when used as mulch and keeps water in the soil by having a high water-holding capacity (Ballesteros et al. 2014). Adi and Noor (2009) asserted that the fine grinding of SCGs offered a number of benefits, including improving the texture of the compost and increasing its water retention capacity. Ndede et al. (2022) reported the same result that the sand-biochar combination underwent aggregation after being thoroughly mixed, which strengthened its physical structure and increased its capacity to hold more water for a longer period of time. Hardgrove and Livesley (2016) resulted that the incorporation of spent coffee grounds at 5% considerably enhanced water-holding capacity of sandy and loamy soil in glasshouse experiment. They proposed that the application of spent coffee grounds at the rate of 20% had considerably resulted in better moisture content than those compared with spent coffee grounds (10%) can lead to soil hydrological benefits. The mixing of organic matter can quickly raise the WHC of less water holding capacity soils (Basso et al., 2013). The capillary water in the soil was enhanced notably after the amendment of the SCGs (1 and 2 t ha^{-1}) as compared to other treatments. The presence of organic matter in the soil treated with SCGs might improve the soil porosity and soil structure resulted in high capillary water availability.

The linear regression between current water storage capacity (S_a) and water capacity after (4 and 24 h) depicted that increasing current water storage capacity also increases the water storage capacity for 4 and 24 h. Consequently, the current available water storage directly affects the soil's water storage capacity after 4 and 24 h. Also, the linear regression between current water storage capacity (S_a) and water capillary in the upper layer of soil was strongly correlated with each other. As the current water storage (S_a) in the soil increases, the capillary water in the soil also increases. The linear regression between carbon (%) and water drop penetration time in fresh and dry samples showed negative and slightly positive correlations, which explains that increasing carbon content in the soil decreases and increases water drop penetration time in fresh and dry soil samples. The reason behind increasing water drop penetration time in dry sample may be because the organic matter may release some hydrophobic compounds which make the soil water repellent. Organic hydrophobic or amphiphilic chemicals that are coated on mineral surfaces or in the interstitial space are what create the phenomenon of SWR (Doerr et al. 2000). The presence of SWR can be influenced by the following factors: vegetation type, microbial activity, soil texture, soil *VWC*, and chemical properties of OM (Doerr et al. 2000). Similar results were shown by Fu et al. (2021) that revealed the soil water repellency persistence characteristics (*WDPT*, θ_{low}, and θ_{non}) were significantly linked with soil organic carbon concentration, indicating that soil organic carbon plays a crucial role in the evolution of soil water repellency. According to earlier research (Jeyakumar et al. 2014; Deurer et al. 2011; Lozano et al. 2013), SWRP is likely to increase with a rise in SOC. The likelihood of this occurred because soils with higher SOC contents typically contained more hydrophobic organic components (Mao et al. 2016). Studies that focused on a particular land-use and soil types indicated positive associations among water drop penetration time and soil organic carbon in air-dried soils (Lozano et al. 2013; Martínez-Zavala and Jordán-López 2009), but other research indicated weak relationships when several land uses were considered (Doerr et al. 2006, 2009).

Conclusions

The obtained results from this experiment concluded the following conclusions:

1. The addition of SCGs (2 t ha^{-1}) to the soil decreased the CO_2 emission from the soil as compared to the control treatment, which suggested that carbon was stored in the soil as a result of carbon sequestration. Therefore, it is suggested to use organic matter in the urban soil in order to mitigate greenhouse gases emission from the soil.
2. The addition of SCGs enhanced the hydrological properties of the soil, which are essential for lower vegetation and tree growth in urban areas. The salt application in the urban soil during the wintertime enhances the soil salinity to a great extent, which destroys the growth of small vegetation and trees near roads. As a result, the urban greenery is deteriorating due to the extensive use of salt on the roads in the wintertime. To combat the detrimental effects of salt, it is advisable to utilize organic material in urban soil, such as SCGs, compost, farmyard manure, or biochar.
3. The single-dose application of different soil amendments had not changed soil chemical and hydrological properties very well. Therefore, it is suggested to conduct future research with SCGs converted to biochar, or SCGs combined with farmyard manure, compost, or biochar with more than one dose of application.

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Data availability Data is available from the corresponding author with a formal request.

Declarations

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Consent to participate Not applicable.

Consent for publication All authors have read and approved this manuscript.

Competing interests The authors declare no competing interests.

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Original article

Impact of the management of the lower level of urban greenery on water retention in urban ecosystems

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ABSTRACT

The different vegetation covers and management play an important role in improving soil water retention properties. The present research was carried out on the campus lawns of the University of Agriculture, Krakow, Poland, from May to October 2023, to examine the impact of vegetation covers and management, including mowed (A) and non-mowed lawns (B) or flower meadows (C) on soil water retention properties. The experimental plot size for each type of cover was 5 × 5 m^2. Soil samples were collected monthly to measure water retention properties, such as current water storage capacity (Sa) and water storage capacity after 4 and 24 hours (S4 and S24). The volumetric water content (VWC (%)), soil water infiltration (seconds), soil temperature (°C), air temperature (°C), and humidity (%) were also measured. Parameters related to soil repellency and soil chemical properties, such as the percent nitrogen and carbon, were also determined. The Kruskal-Walli's test revealed that the air temperature (°C), soil temperature (°C), volumetric water content (%), infiltration (seconds), nitrogen (%), and Sa (%) were statistically different among different vegetation covers A, B, and C. However, air humidity (%), S4 and S24, and carbon (%) were not statistically different in vegetation covers. The flower meadows recorded lower air temperatures (25 °C) and soil temperatures (23 °C), while the mowed lawn recorded higher air and soil temperatures (28 °C and 27 °C). The non-mowed lawn stored maximum VWC (14 %), and the flower meadow plot took the longest time (100 seconds) to infiltrate the water. The highest mean Sa, around 34 %, was observed in flower meadows and non-mowed lawns, while the lowest Sa was calculated in mowed lawns (25.2 %). It is concluded from the results that the establishment of flower meadows and non-mowed lawns should be encouraged in urban areas to conserve soil water, but mainly to reduce the heat island effect and improve the microclimate.

1. Introduction

Urban green spaces, including public parks, forests, meadows, residential gardens, and grassy lawns, are important in providing diverse ecosystem services that support environmental sustainability and human well-being (Rall et al., 2015; Aronson et al., 2017). Urban forests and parks are living systems integrated into highly anthropogenic landscapes. Urban greenery is connected through physical, chemical and biological interactions, which enable urban green spaces to provide many environmental services both on global and local scales (Swann, 2018).

In many cities, where the introduction of higher vegetation is impossible, low greenery such as lawns significantly enhances soil water retention capacity. Among the various kinds of urban green spaces, extensively managed grassy lawns are widespread and have emerged as a predominant component of urban green spaces worldwide (Ignatieva and Hedblom, 2018; Ignatieva et al., 2020). These green spaces are managed through regular mowing activities for cultural, recreation, and aesthetic values (Kowarik, 2011; Aronson et al., 2017). Mowed urban lawns tend to enhance soil compaction and bulk density, reducing soil porosity and infiltration rates (Gregory et al., 2006). As a result, this promotes water runoff and accelerates soil erosion. Lee et al. (2017) concluded that converting urban lawns into hardscape rather than meadows can cause negative outcomes, including increased urban heat levels and elevated stormwater runoff.

Soil hydrological processes, including water retention, infiltration, and permeability, are essential for regulating urban microclimates, influencing photosynthesis, plant transpiration, runoff production, and

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groundwater recharge (Yin et al., 2017; Lopes-Mazzetto et al., 2018; Riveros-Iregui et al., 2007; Lu et al., 2011; Chang et al., 2015). These processes are strongly affected by vegetation types and climatic conditions, particularly precipitation and temperature (Xu et al., 2011; Kammer et al., 2013; Holsten et al., 2009). The plant-soil interactions greatly impacted the changes in soil moisture (Garcia-Estringana et al., 2013). The vegetation type is often associated with specific soil properties and different community structures and architectures. Therefore, variation in vegetation have a major influence on the pattern of soil moisture (Lull and Reinhart, 1955).

Climate change alters precipitation patterns and temperature extremes, leading to significant shifts in soil water content (O'Gorman, 2012; Ramos and Martínez-Casasnovas, 2010; Suseela et al., 2012). Additionally, human activities strongly influence soil hydrological functions (Barnett et al., 2008).

Recently, the focus of urban green spaces management has significantly increased to promote diverse native flower meadows to improve ecosystem services, including environmental sustainability (e.g., water conservation), biodiversity conservation (e.g., pollinator support), preservation of culturally valuable plant species, and the reduction of both economic and environmental costs related with traditional lawns management (Norton et al., 2019; Hedblom et al., 2017; Smetana and Crittenden, 2014). These alternative vegetation management strategies, such as establishing flower meadows and reducing mowing frequency in urban green spaces, have gained attention as Nature-Based Solutions (Keesstra et al., 2018; Savva et al., 2013). These approaches can enhance soil water content, mitigate the urban heat island effect, and improve water management by increasing soil infiltration and reducing erosion (Yang et al., 2012; Wang et al., 2012; Toohey et al., 2018; Paudel and States, 2023). Flower meadows might offer high effectiveness in reducing the urban heat island effect compared to lawns, as their diverse and taller vegetation is best at intercepting solar radiation, providing better shading on the soil surface more efficiently (Shashua-Bar et al., 2009). Monteiro (2017) emphasized the importance of urban turfgrass lawn in reducing water runoff and flooding, as well as decreasing soil erosion. Smetana and Crittenden (2014) concluded that meadow vegetation is highly effective in enhancing rainwater retention by decreasing flooding. Diverse urban meadow vegetation not only improves soil water retention, but also demonstrates higher drought tolerance and less water requirement than traditional urban lawns (Paudel and States, 2023). However, urban soil's hydrological processes and functions are highly influenced by the urban green space's characteristics, such as plant species, surface litter, community structure, and management practices (Pouyat et al., 2006; Ossola et al., 2015). Therefore, different plant communities and litter profiles of lawns and meadows may have significantly different abilities to support soil health and regulate stormwater flow.

However, the relationships between vegetation management, soil moisture, and soil hydrological properties under changing climatic conditions are complex and poorly understood. In particular, soil water repellency (SWR) and soil wettability are critical but often overlooked parameters that can rapidly change due to soil dryness and high temperatures (Doerr et al., 2000; Wittenberg et al., 2019; Farahnak et al., 2019).

Therefore, this study aims to evaluate the role of lower urban greenery layers (mowed lawns, non-mowed lawns, and flower meadows) in modifying soil hydrological properties and atmospheric conditions, focusing on soil water retention properties. Simple, nature-based interventions in urban greenery management offer promising, cost-effective strategies to regulate soil microclimate and enhance urban resilience to climate change.

Specifically, we seek to answer:

1. To what extent do simple vegetation management practices, such as reducing mowing frequency, enhance soil retention properties, regulate soil temperature and moisture, and thus improve urban microclimates?
2. How can low-maintenance, nature-based practices help mitigate droughts and urban flooding risks?

The work contains research results showing the difference in the generally understood soil retention properties between a mowed lawn (A), and non-mowed lawn (B), and a flower meadow (C) in the city of Krakow (Poland). We hypothesized that soil hydrological properties and micrometeorological conditions significantly differ among different vegetation types (non-mowed lawn and flower meadows) and in response to mowing activities in urban soil.

The research was conducted in Krakow (Poland), a country facing significant freshwater scarcity (1411 m^3) per capita, compared to the EU average being twice as high (https://www.worldbank.org/en/country/poland). Therefore, our questions are not only regionally important but also universally relevant for urban water management.

2. Materials and methods

2.1. Site description and soil sampling

The current research was conducted on the campus of the University of Agriculture, Krakow, Poland, which is situated in the city's urban area. The experiment lasted from May 2023 to October 2023. The study sites included three vegetation types: mowed lawns (A), non-mowed lawns (B), and flower meadows (C) (Fig. 1). There were seven places on each surface (A, B, C) where measurements were taken three times each month over six months from May, 2023 to October, 2023. These seven locations on each vegetation plot (mowed lawn, non-mowed lawn, and flower meadows) were treated as replicates. Both the mowed lawn (A) and the non-mowed lawn (B) have typical grass plants, including common yarrow (*Achillea millefolium*), common daisy *(Bellis perennis*), plantain (*Plantago* spp), meadow *(Ranunculus acris*), and white clover (*Trifolium repens*), as well as grasses of the type's fescue *(Festuca spp*.), bent grass (*Agrostis spp.*), ryegrass (*Lolium* spp.), and bluegrass (*Poa spp*.). The flower meadows (C), established in 2022, were sown with the "Polish Flower Meadow" mixture, adapted to local soil and light conditions, containing colorful meadow species such as pyrethrum *(Chrysanthemum cinerariifolium*), buttercup (*Ranunculus spp*), vetch *(Vicia spp.*), and field poppy (*Papaver rhoeas*). Before sowing, the turf layer was removed, and seeds were mixed with sawdust or sand to ensure even distribution. The recommended sowing seeding density was 2 g/m^2.

The green areas on the university campus were originally established approximately 40 years ago. Until recently, all lawns were regularly mowed. However, three years ago, in line with ecological strategies to enhance biodiversity, selected lawn areas were left unmowed, and some were converted into flower meadows.

Importantly, surfaces A, B, and C were treated uniformly: no irrigation systems were installed (only rainfall served as a water source), no fertilizers were applied, and the same environmental conditions (weather and air pollution) prevailed, as all sites were located within the same campus area. Each experimental plot (A, B, and C) was 5×5 m^2.

The soil underlying the experimental plots was classified as Urbic Technosol, based on the World Reference Base of Soil Resources (IUSS Working Group WRB-FAO, 2015). Krakow's soils are typically developed from Quaternary sands, loess, and alluvial deposits.

2.2. Soil hydrological properties

Kopecky cylinders made of stainless steel, with a volume of 100 cm^3 (5.1 cm height, and 5.0 cm diameter), were used to collect soil samples from each experimental plot every month to determine soil water storage properties. Samples were weighed immediately for fresh mass (Mf), submerged fully in water under room conditions (humidity 30 %, ~21°C), and weighed after 4 hours (M4) and 24 hours (M24).

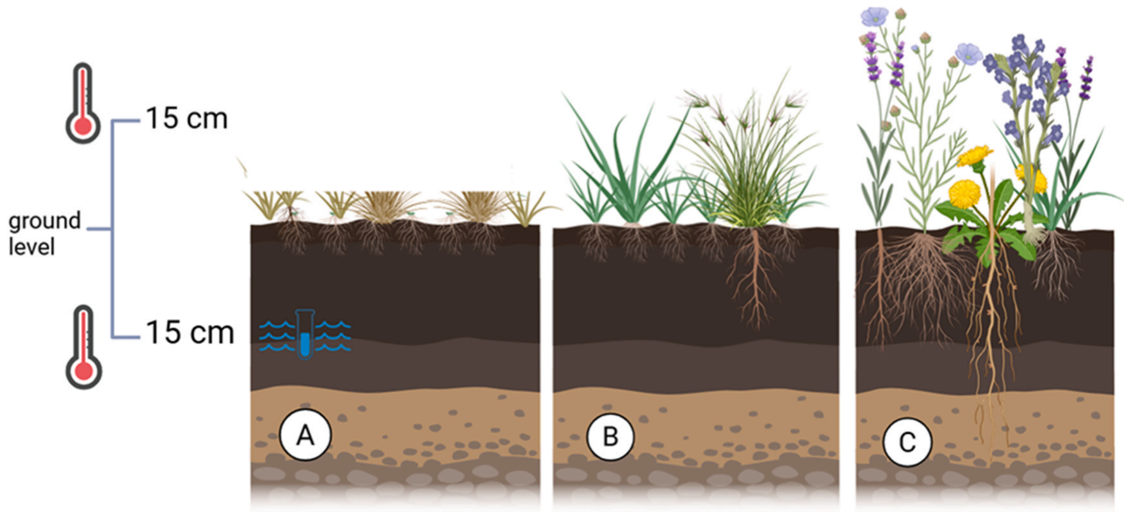

Fig. 1. Graphical representation of the vegetation covers and management; Air Temperature Measurement (at 15 cm above ground) Soil Temperature Measurement (up to 15 cm below soil level) Soil Water Content, Infiltration Measurement at ground level; A – Mowed Lawn; B – Non-Mowed Lawn; C – Flower Meadows.

Subsequently, samples were oven dried at 105°C to obtain dry mass (Md).

Water storage capacities (Sa, S4, and S24) were calculated using the differences between mass measurements (Khan et al., 2023; Klamerus-Iwan et al., 2020) by the following formulas.

$$S4 = \left(M4 - \frac{Md}{Md}\right) \times 100 \quad (1)$$

$$S24 = \left(M24 - \frac{Md}{Md}\right) \times 100 \quad (2)$$

$$Sa = \left(Mf - \frac{Md}{Md}\right) \times 100 \quad (3)$$

S4; water storage capacity after 4 hours, S24; water storage capacity after 24 hours, Sa; current water storage capacity, M4; mass of soil samples after 4 hours, M24; mass of soil samples after 24 hours, Mf; fresh mass of soil samples, Md: dry mass of soil samples

Soil bulk density was calculated as the dry mass divided by the sample volume. Additionally, after sieving through a 2 mm sieve, soil texture was analyzed using a Fritsch GmbH Laser Particle Sizer ANALYSETTE 22, determining the content of sand, silt, and clay (FRITSCH, 2016).

The soil temperature and the soil volumetric water content were determined using the TEROS_12 (Meter). The instrument contains a sensor that records the dielectric permittivity by using the electromagnetic field of the surface layer. An Oscillating wave (70 MHZ) is used by the TEROS_12 sensor, which charges the sensor needles by the substance used. Subsequently, the charge time is linked to the substrate's dielectric constant and VWC. The microprocessor of the TEROS_12 calculates the charging and generates an output raw value of the substrate based on the dielectric permittivity. After that, the raw data value is changed to VWC (θ) using the specific equation.

The following equation gives the volumetric water content (θ, (m^3/m^3), where RAW is the raw sensor output (dimensionless) obtained from the soil moisture sensor:

$$\theta(m^3/m^3) = 3.879 \times 10^{-4} \times RAW - 0.695 \quad (4)$$

The soil water infiltration time was measured using a mini disk infiltrometer (MDI) (Decagon Devices, Inc., Pullman, WA).

Air temperature measurements were performed at a height of 15 cm above the ground using a Mutech thermo-hygrometer to accurately capture the direct influence of vegetation management practices on the near-surface microclimate, while minimizing the effect of broader urban factors that are typically stronger at greater heights.

All measurements (soil and atmospheric parameters) were conducted simultaneously and at a single point in time to represent the real-time, combined effects of environmental conditions across different vegetation types. Measurements were systemically taken three times per month on the 10th, 20th and 30th day throughout the entire observation period. This regular 10-day interval ensured consistent data collection across all plots, allowing us to avoid bias caused by immediate weather events, such as rainfall or temperature extremes, and provided a representative picture of long-term trends rather than isolated meteorological fluctuations.

Soil water repellency (SWR) was assessed using two complementary methods. First, the Water Drop Penetration Time (WDPT) test was performed by applying five drops (approximately 5 μL each) of distilled water to fresh soil samples using a micropipette under controlled laboratory conditions (temperature 21°C; relative humidity 35 %). The time required for each drop to infiltrate the soil surface was recorded. Soils were classified into repellency classes according to the criteria proposed by Dekker and Jungerius (1990), Doerr et al. (2000), and Dekker et al. (2009). The soil wettability classification system classified soil as wettable (WDPT $\leq$ 5 s), slightly to moderately repellent (WDPT 5–600 s), and severe to extreme repellent (WDPT $>$ 600 s).

After drying the soil samples, an alcohol molarity test (MOL) was performed. This involved sprinkling five drops of C_2H_5OH solutions with ten concentration levels, ranging from 0 % to 22.5 %, which varied at a step of 2.5 %, starting with the lowest. The aim was to determine the minimum ethanol concentration of the solution that infiltrated within 5 seconds, following the procedure described by Hewelke et al. (2016).

Together, these two methods comprehensively evaluated soil wettability and changes in soil hydrophobicity under different vegetation management treatments.

2.3. Soil chemical properties

Soil samples (10 cm depth) from each experimental unit were collected in plastic tubes of 100 cm^3 volume and were analyzed for chemical properties, including nitrogen (%) and carbon (%). The soil samples were then kept at room temperature for drying and ground.

After that, the samples were cleaned of leaves, roots, stones, and other unwanted materials. The cleaned samples were then passed through a 2 mm sieve. Ten grams of the ready soil samples were taken from each treatment. A LECO TrueMac Analyzer was used for the nitrogen and carbon analysis in the 10-gram samples (Leco, St. Joseph, MI, United States).

2.4. Statistical analysis

Before conducting any statistical tests, we checked the data normality by making histograms and Q-Q plots, followed by the Shapiro-Wilk test for normality. The data were found to be non-normally distributed. To address this, we applied the Box-Cox transformation to normalize the data. However, the data didn't follow a normal distribution pattern even after applying the Box-Cox transformation. For non-normally distributed data, we chose to use non-parametric tests. For this purpose, a Kruskal-Wallis test was conducted to determine potentially significant differences among the three vegetation covers for each parameter in the dataset. Furthermore, Spearman correlation was carried out to determine the relationships between different variables.

In addition to the above tests, we performed Principal Component Analysis (PCA) to reduce the dimensionality of the dataset and identify key patterns in the data. PCA was important as the data contained several correlated variables, and dimensionality reduction was necessary to specify the most significant variables without losing essential information. This method also helped visualize and interpret the overall structure of the relationships between variables. Furthermore, regression analysis was conducted to model the relationship between soil temperature (°C) and volumetric water content (%), and soil temperature (°C) with infiltration time (S). All statistical analysis and graphic visualizations were carried out using Python libraries, including pandas (McKinney, 2010), NumPy (Harris et al., 2020), SciPy stats (Virtanen et al., 2020), seaborn (Waskom, 2021), matplotlib (Hunter, 2007), sklearn preprocessing, and sklearn decomposition (Pedregosa et al., 2011).

3. Results

Results were obtained for water drop penetration time (WDPT) on fresh samples. The drop absorption time for all surfaces A, B, and C was no longer than 5 seconds, and oscillated between 0 and 3 seconds. The alcohol molarity test performed on dried samples for each surface showed that a 2.5 % C_2H_5OH concentration was absorbed in less than 5 seconds; therefore, higher concentrations were not applied.

Both soil water repellency tests showed that the soil under all land covers (A, B, and C) was highly wettable when moist, but its hydrophobicity increased with drying. The soil bulk density in mowed (A), non-mowed lawn (B), and flower meadow (C) was nearly the same, with the values 1.66, 1.65, and 1.57 g/cm^3. Regardless of vegetation cover, the soils are urbisoils with dominant sand or clay (clay-sandy soils).

3.1. Impact of different vegetation covers on air temperature, air humidity, and soil temperature

The Kruskal-Wallis test indicates significant differences ($p < 0.05$) in air temperature (°C) among the different plots. The highest mean air temperature (28 °C) was recorded for mowed lawn, followed by non-mowed lawn and flower meadows, with mean values of 26 °C and 25 °C, respectively. The Kruskal-Wallis test showed non-significant differences ($p > 0.05$) in air humidity among the plots, indicating similar results across treatments. However, the highest median and mean air humidity were measured in flower meadows. Furthermore, soil temperature varied significantly among the mowed, non-mowed lawns, and flower meadows. The maximum mean soil temperature, approximately 27 °C, was measured in the mowed lawn, followed by the non-mowed lawn and flower meadows, with values of 24 °C and 23 °C, respectively (Fig. 2).

3.2. Influence of various vegetation covers on volumetric water content

The statistical analysis showed significant differences ($p < 0.05$) in volumetric water content across different vegetation covers. Non-mowed lawn soil stores more water per unit volume (mean value of 14 %), while the lowest volumetric water content (mean value of 11 %) was observed in flower meadows (Fig. 3). The lower VWC in flower meadows plot (C) may result from high evapotranspiration due to the diverse, denser and taller vegetation, along with deeper root systems, which draw more water from the soil. This also aligns with the lower air temperature in flower meadows (Fig. 2), which possibly shows cooling effects through strong evapotranspiration.

3.3. Impact of different vegetation management and covers (mowed, non-mowed lawn, and flower meadows) on soil hydrological properties

The soil water infiltration time (seconds) and soil current water storage capacity (Sa) significantly differed across the mowed lawn, non-mowed lawn, and flower meadows. In contrast, the water storage capacities, S24 and S4 were not statistically different from each other in 3 different plots. This indicates that, on the same soil, the potential water capacity (S24) remains similar, but vegetation has a noticeable impact on the current water storage capacity. The highest S24 was measured in the flower meadows, while the lowest was observed in the mowed lawn. The highest mean Sa, approximately 34 %, was observed in the flower meadows and non-mowed lawn. In contrast, the lowest Sa was found in the mowed lawn (25.2 %) (Fig. 4). The soil water infiltration time was maximum with a mean value (100 seconds) in flower meadows, followed by non-mowed and mowed lawns (75 and 50 seconds). The infiltration rates were lower in the mowed lawn (A), which is possibly due to the soil compaction from regular mowing activities, which may limit water percolation and water retention capacity.

3.4. The influence of soil temperature on its terrain properties

The graph (Fig. 2) shows that the soil temperature (as well as the air above the soil) is higher in lawns that are regularly mowed. Therefore, in the next stage, it was decided to check how quantitatively this higher temperature may translate into changes in VWC or infiltration time (Fig. 5). An increase in temperature by 23 degrees Celsius reduced VWC by 24 % and infiltration time by 250 seconds.

3.5. Impact of different vegetation management on soil nutrients (% Nitrogen and % Carbon) composition

According to the Kruskal-Wallis test result, the soil nutrients, such as percent nitrogen, was significant ($p < 0.05$), and percent carbon was not significant ($p > 0.05$) among different plots. Furthermore, the nitrogen and carbon concentrations were very less in these plots. Although the highest % carbon value was noted in the non-mowed lawn, as compared to other plots. The percent nitrogen was even less than 0.2 % in all three plots (Fig. 6).

3.6. Spearman's Correlation matrix

Fig. 7 represents a heatmap of the Spearman's correlation matrix for all the variables measured in this experiment. Air temperature shows a strong positive correlation with soil temperature (0.90), highlighting that warmer air temperature is associated with warmer soils. However, it is negatively correlated with VWC (-0.71), and slightly negative correlation with current water storage capacity (-0.28). This shows that higher air temperature is connected with dry soil conditions and decreased water storage capacity. On the other hand, air humidity depicts weak positive correlations with current water storage capacity (Sa)

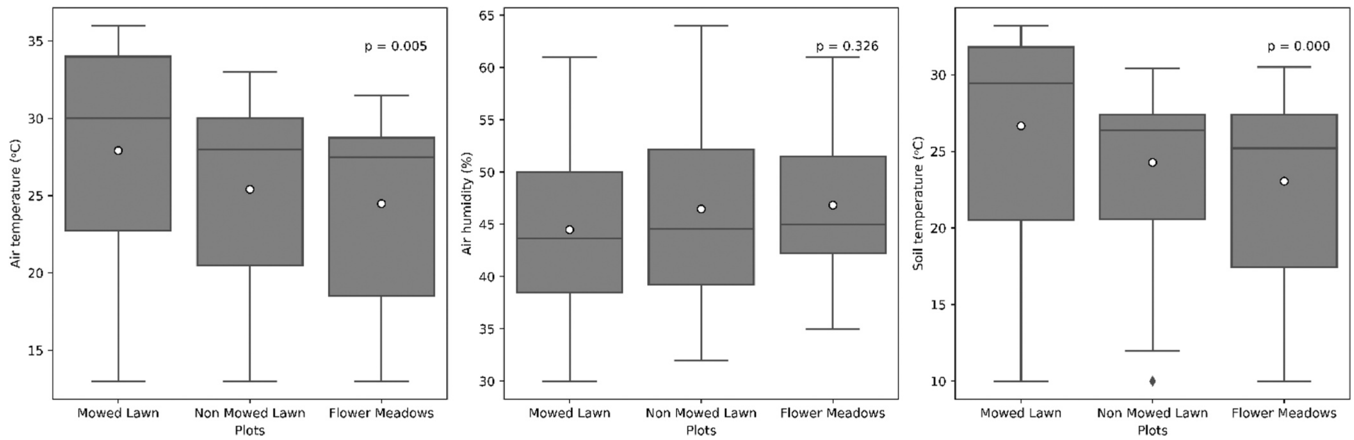

Fig. 2. Boxplots of air temperature (°C), air humidity (%), and soil temperature (°C) in different vegetation management. The middle line within the boxplot shows the median value, and the white circle represents the mean value.

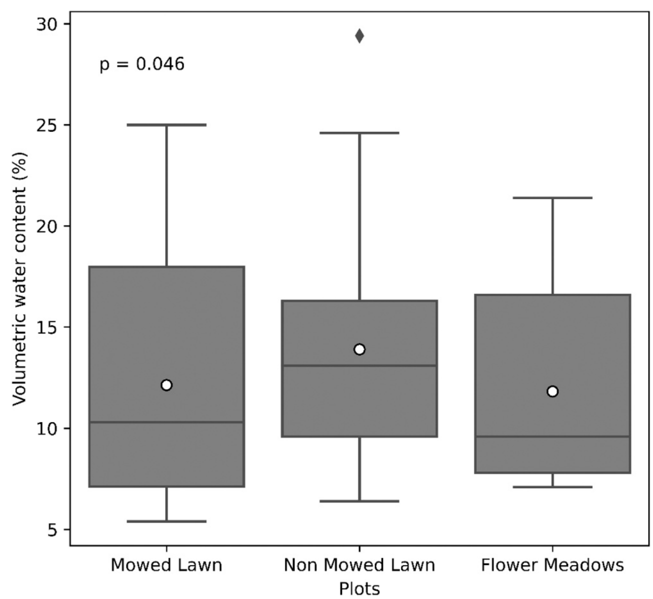

Fig. 3. Boxplots of soil volumetric water content [%] across different vegetation management. The middle line within the boxplot shows the median value, and the white circle represents the mean value.

and water storage capacity after 24 hours (S24). The soil temperature also shows a strong positive correlation with air temperature (0.90), while it shows a negative correlation with the volumetric water content (-0.64), infiltration (-0.20), and Sa (-0.27).

3.7. Principal component analysis

The biplot (Fig. 8) of the principal component analysis shows the 40.1 % variance on the x-axis and 26.2 % on the y-axis; altogether, it shows the 66.3 % variance in the measured variables. Soil temperature and air temperature lie in the same direction and exhibit a positive correlation with each other. However, they show a negative correlation with variables positioned on the opposite side in Principal Component 1 (PC1). The volumetric water content lies in the opposite direction of the air and soil temperature, indicating a negative correlation. The infiltration represents a negligible contribution to the variance in both PC1 and PC2. The water storage capacities of the soil (i.e., Sa, S24, and S4) all point in the same direction, indicating a strong correlation with each other and with the Principal Component (1).

4. Discussion

Extreme weather events, such as droughts, heat waves, and intense rainfall, result from complex interactions of physical processes across various spatial and temporal scales. In urban ecosystems, these phenomena often exceed the buffering capacity of natural and engineered systems, leading to critical disruptions (Zscheischler et al., 2018; Turner, 2010).

Our study demonstrates that different vegetation management practices significantly affect air and soil temperatures, soil moisture, and soil infiltration properties. Specifically, mowed lawns exhibited higher air and soil temperatures compared to non-mowed lawns and flower meadows. This is mainly due to reduced shading, lower vegetation diversity, and increased soil surface exposure, which intensify direct solar radiation. In contrast, non-mowed lawns and flower meadows, with taller and denser vegetation, provided better shading, which effectively mitigated soil heating. These findings are consistent with previous observations where higher soil temperatures were recorded under sparse vegetation compared to forested areas (Özkan and Gökbulak, 2017; Ni et al., 2019; Song et al., 2013). Jenerette et al. (2011) stated that at the local scale, urban green spaces help in mitigating the urban heat island by absorbing heat, increasing humidity, and also provide shade, which contributes to controlling nearby surface and air temperatures. Our study confirms that by simple interventions such as reduced mowing and thus controlling ground cover structure, it is possible to significantly influence soil temperature and moisture, ultimately improving the microclimatic conditions in urban environments.

Soil compaction caused by frequent mowing likely contributed to reduced soil porosity and infiltration in mowed lawns. Conversely, the diverse root systems in unmown lawns and flower meadows enhanced macroporosity, promoting water movement through the soil. Literature supports that vegetation types with extensive root systems, such as flower meadows, improve infiltration and water retention capacities (Wu et al., 2017; Niu et al., 2019). Furthermore, both lawns and meadows are highly efficient in enhancing water infiltration, which can contribute to reduced soil erosion and flood risk (Groffman et al., 2009; Monteiro, 2017). The changes in the physical and biological structure of soil due to management activities can directly or indirectly affect soil functions, such as water infiltration (Gregory et al., 2006).

Importantly, while our sampling period extended from spring to autumn, seasonal variations in soil and air temperature were relatively minor in the urban environment of Kraków. The primary fluctuations in soil moisture were driven by isolated rainfall events rather than gradual seasonal transitions. Short-term rainfall episodes significantly affected the volumetric water content, while overall temperature trends remained stable. Therefore, the study focused on the general trends in

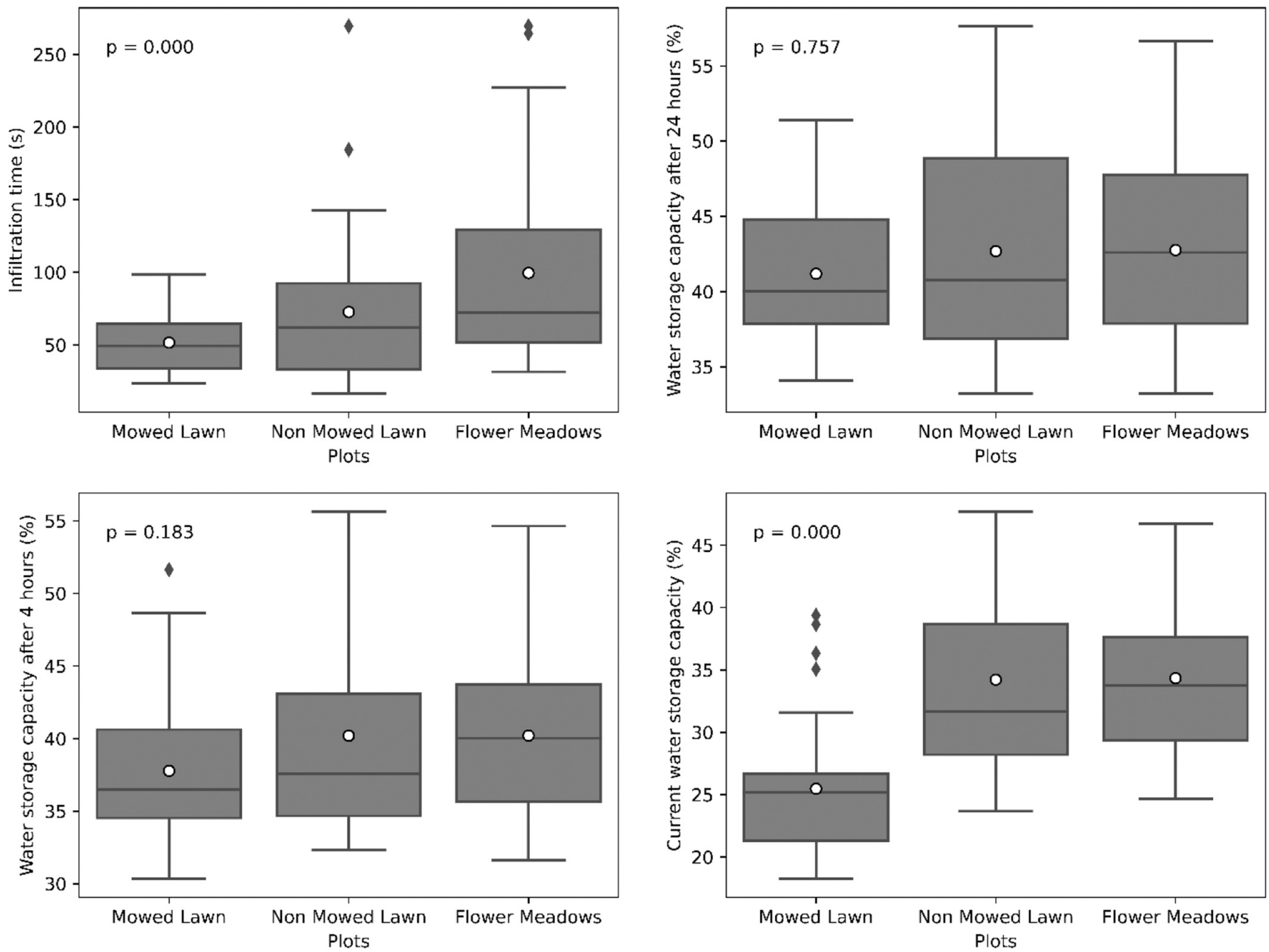

Fig. 4. Boxplots of soil infiltration (S), water storage capacity after 24 and 4 hours (S24 and S4), and current water storage capacity (Sa) across different vegetation management. The middle line within the boxplot shows the median value, and the white circle represents the mean value.

soil and microclimatic properties across different vegetation covers, rather than capturing detailed seasonal dynamics. This approach allowed us to highlight practical insights applicable to urban land management, showing that simple interventions such as reducing mowing frequency can have a measurable positive impact on urban microclimate and soil water retention.

Our results confirm that non-mowed lawns and flower meadows store more water per unit soil volume compared to mowed lawns. These surfaces benefited from higher soil porosity, greater organic matter content, and improved moisture retention conditions. Reduced volumetric water content in mowed lawns can be attributed to increased surface heating and soil compaction. Similar patterns were reported by Lozano-Parra et al. (2018) and Nguyen et al. (2020), linking vegetation structure to soil moisture dynamics. Boivin et al. (2009) and Panagea et al. (2021) reported that carbon content has a considerable influence on the soil's water storage capacity in the long-duration experiments. Flower meadows exhibited longer infiltration times compared to non-mowed and mowed lawns, likely due to denser root networks partially obstructing soil pores. Previous studies have demonstrated that vegetation type and root architecture strongly influence infiltration processes (Niu et al., 2019). Furthermore, both lawns and meadows are highly efficient in enhancing water infiltration, which can contribute to reduced soil erosion and flood risk (Groffman et al., 2009; Monteiro, 2017).

In terms of soil chemical properties, the percentage of organic carbon was highest in non-mowed lawns, likely due to the accumulation of undecomposed plant material. Nitrogen contents across all vegetation types remained low but were slightly higher in non-mowed lawn soils, suggesting initial stages of organic matter enrichment. Urban turf lawns have the potential to sequester carbon at a rate of 0.1 kg C m^{-2} per year in the long term (25–30 years) (Qian and Follett, 2002; Townsend-Small, Czimczik,2010). Cardinale et al. (2011) suggested that urban meadows may considerably enhance carbon sequestration, due to their high plant diversity and species richness, enabling more carbon assimilation into aboveground biomass. Another research conducted by Pouyat et al. (2006) reported that well-managed urban lawns can store more organic carbon than urban meadows in a dry climate. Petrovic (1990) concluded that properly well-managed urban lawns are capable of retaining nitrogen up to 90 %, thereby considerably decreasing nitrogen loss in groundwater.

This study contributes to the growing body of ecohydrological research promoting nature-based solutions for enhancing urban water retention. Despite the short period since flower meadow establishment, significant improvements in soil moisture retention and microclimate regulation were already observed. We anticipate that longer-term soil formation processes, including root decomposition and organic matter accumulation, will improve soil properties in the coming years.

Future studies should include extended monitoring over multiple years to capture long-term changes in soil chemistry and structure. Additionally, using larger-scale infiltration tests, beyond point-based

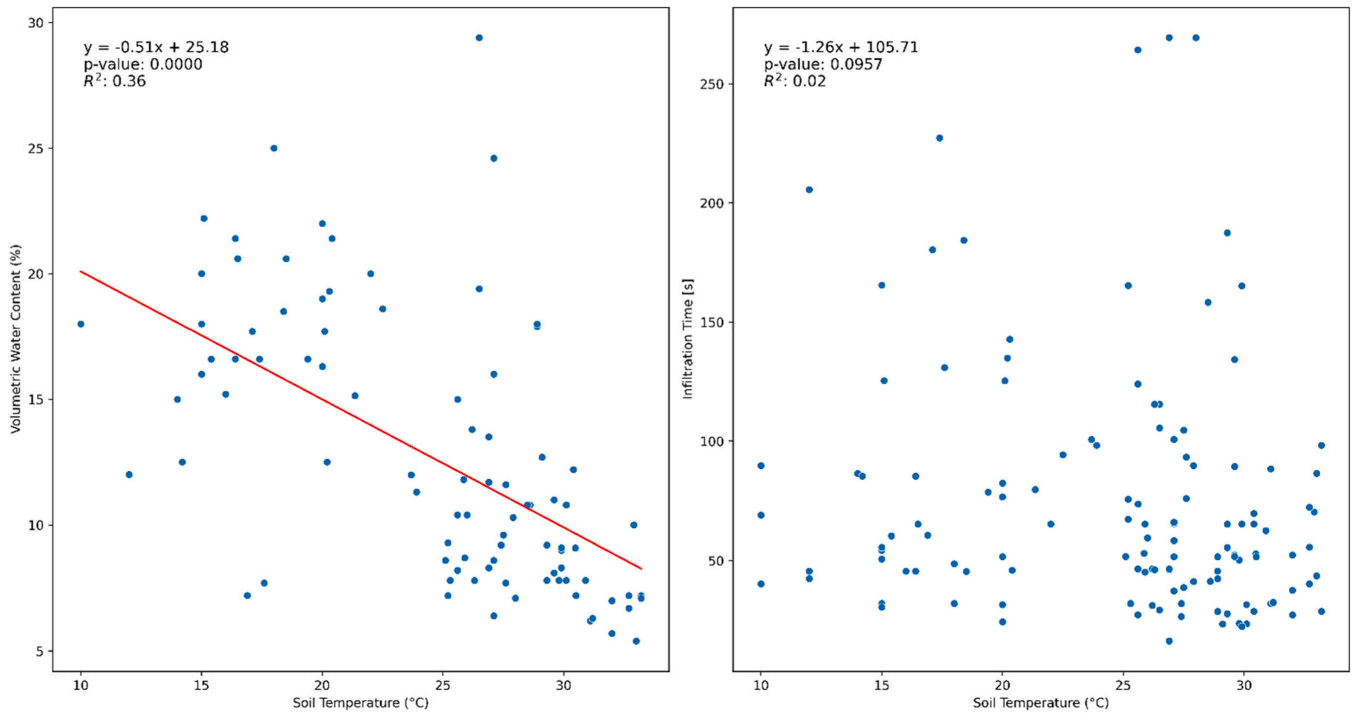

Fig. 5. Influence of soil temperature (°C) on volumetric water content (%) and infiltration time (s).

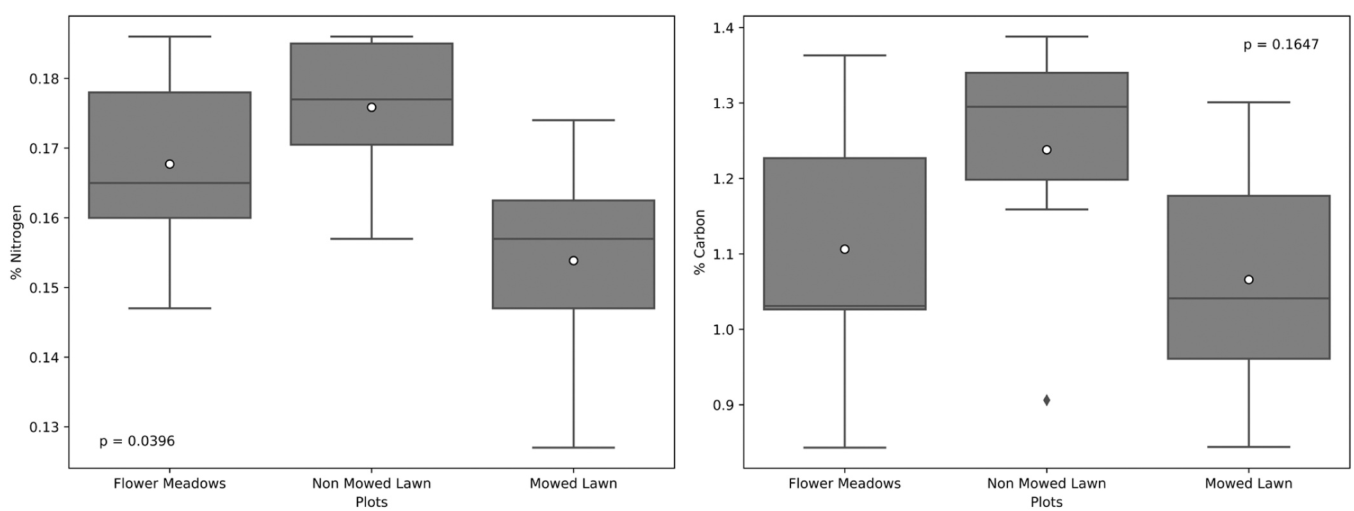

Fig. 6. Boxplots of soil % Nitrogen and % Carbon across different vegetation covers. The middle line within the boxplot shows the median value, and the white circle represents the mean value.

wettability assessments, could help better simulate real-world water dynamics during extreme rainfall events.

Our findings support the initial hypothesis that soil hydrological properties and micrometeorological conditions significantly differ among various vegetation types and are strongly influenced by simple management interventions, such as reducing mowing activities. By reducing mowing frequency and allowing for the natural development of vegetation cover, it is possible to decrease soil and air temperatures while enhancing soil moisture retention in urban environments (Yao et al., 2015). This microclimatic improvement, achieved through relatively simple actions, demonstrates that sustainable management of urban green spaces can effectively increase the soil's capacity to retain water, particularly during extreme weather events such as heavy rainfall (Zhuang et al., 2025).

The outcomes of this research provide valuable scientific evidence to inform municipal decision-making, suggesting that limiting mowing activities could be an effective nature-based strategy for enhancing urban soil water retention and mitigating flood risks in cities facing increasing climate variability.

While this research's findings offer important insights into the influence of urban vegetation management on soil water retention and microclimate, several limitations should be acknowledged to contextualize findings. The study was conducted within a single urban location, which may limit the generalizability of the findings to regions with different climatic conditions, soil types, or vegetation management practices. The relatively small plot sizes and the six-month observation period provide valuable insights into seasonal dynamics, but do not capture long-term trends or interannual variability. These limitations should be considered when generalizing the results to broader urban settings.

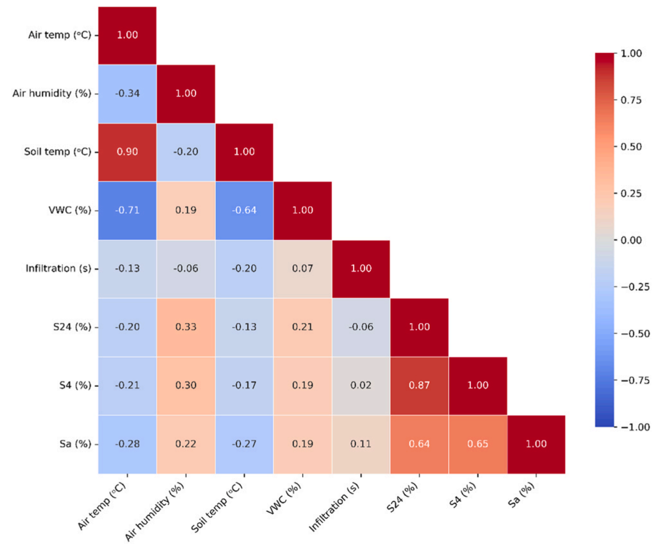

Fig. 7. Heatmap (Spearman's rank correlation matrix); vwc; volumetric water content, Sa; current water storage capacity, S4 and S24; water storage capacity after (4 and 24 hours).

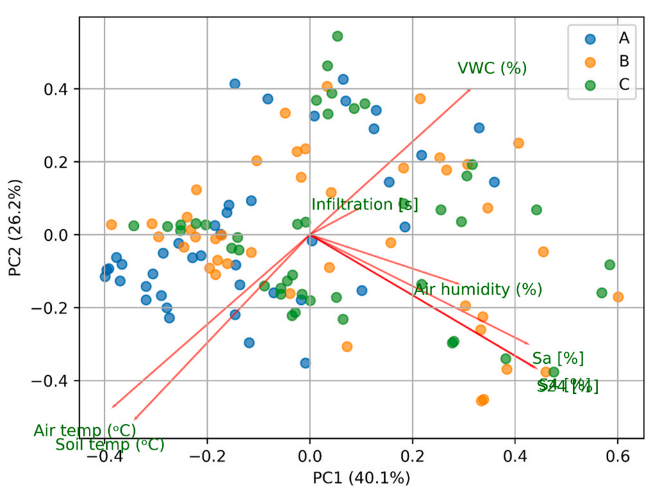

Fig. 8. Biplot of the principal component analysis of all measured variables across different vegetation management (A: mowed; B: non-mowed lawn; C: flower meadows, vwc; volumetric water content, Sa; current water storage capacity, S4 and S24; water storage capacity after (4 and 24 hours).

5. Conclusions

This study confirms that the different vegetation covers and mowing strategies, such as reduced mowing or establishing flower meadows, significantly influence soil water retention properties and microclimatic conditions in urban environments. Practices such as reducing mowing frequency or establishing flower meadows enhance soil moisture availability, lower soil surface temperatures, and increase air humidity, contributing to improved soil health and reduced flood risk. The results showed that flower meadows reduced the urban heat island (UHI) effects. It has to be noted, though, that flower meadows cannot compete with urban trees in mitigating the UHI effect. Furthermore, flower meadows offer benefits for biodiversity and localized cooling, but they cannot match the broader ecological functions and cooling effects provided by urban trees. Regularly mowing lawns during the summer season might lead to the formation of hydrophobic soil layers that resist water absorption. The obtained results recommend urban green space managers to reduce mowing frequency in conventional lawns, integrate flower meadows to diversify vegetation structure and support soil processes, and prioritize tree planting and preservation as a core strategy to promote sustainable water retention, improve urban soil health, and mitigate the UHI effect. Long-term studies are recommended to evaluate the sustained impacts of these practices on urban soil hydrology and microclimate regulation.

Ethical acceptance

N/A.

Funding

N/A.

CRediT authorship contribution statement

Anna Klamerus-Iwan: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Muhammad Owais Khan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Consent to participate

N/A.

Permission for publication

All authors have carefully read and given their approval for this article to be published.

Data availability

The data can be obtained from the corresponding author upon submission of a formal request.

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ORIGINAL PAPER

Impact of climate change on root zone soil moisture in two Polish cities

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ABSTRACT

Climate change has a significant effect on the perpetual state of soil moisture conditions. The objective of the study was to evaluate the effect of climatic parameters on status of root zone soil moisture. The research study has investigated the implications of various environmental variables such as earth skin temperature [°C], wind speed [m/s], relative humidity [%], maximum and minimum temperature [°C], and precipitation [mm] on root zone soil moisture of Polish cities namely Kraków and Warsaw. Kraków is characterized by a temperate climate zone, located in the central Europe. Warsaw is the capital of Poland, located in the central part of the country. It is essential to ascertain the stationarity nature of variables before the application of the autoregressive distributed lag (ARDL) model of Jordan and Phillips (2018). The findings of unit root tests by Augmented Dickey Fuller (ADF) and Phillips Perron (PP) illustrate the stationary status of variables at both levels 1 (0) and the first difference 1 (1). The results revealed improvement in the rhizosphere's moisture levels as affected by relative humidity, precipitation, and minimal temperature at two meters, both in short- and long-term periods. The earth's skin temperature, wind speed, and maximum temperature at two meters has a negative influence on soil moisture content. The results have depicted that a 10% increase in precipitation, minimum temperature, and relative humidity have enhanced the soil moisture content by 1.294%, 1.019%, and 0.193%, respectively, at Krakow, and 0.993%, 0.794%, 0.873% improvement at Warsaw in the long run. The long-term influence of maximum temperature, wind speed, and earth skin temperature has negatively affected soil moisture by –0.744%, –0.468%, –0.3875% in Kraków, and –1.472%, –0.761%, –1.614%, in Warsaw. This study has emphasized the significant effect of climate change on agriculture, forestry, and ecosystems, which has accentuated the requirement for adopting water conservation and smart agriculture practices. It is feasible to mitigate the detrimental effects of wind gusts and high temperatures by cultivating drought invulnerable plant varieties and practicing soil conservation methods. The adoption of these measures is pivotal in diminishing the influence of climate change on soil moisture and contributes significantly to sustainable agriculture practices, forestry, and ecosystems.

KEY WORDS

dynamic ARDL model, precipitation, relative humidity, root zone soil moisture, soil temperature, urban forestry

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Introduction

Soil moisture plays a vital role in the water and energy balance of the earth's surface, having significant impacts on agriculture productivity and runoff processes (Torres Rua *et al.*, 2016; Toronquo *et al.*, 2022). Crops germination and biomass yield have been significantly affected by soil moisture due to climate change and hydrology (Le and Bae, 2022). Soil moisture scrutiny through water balance methodologies is necessary for determining the water requirement of present and successional crops (Fries *et al.*, 2020). Soil moisture plays a decisive part in the conveyance of constituents and the quantity of energy used in the soil-plant-atmosphere continuum (SPAC). It is a critical eco-hydrological element that associates rainfall, groundwater, plant water, and the surface water inside an ecosystem (Wang *et al.*, 2018, 2019; Zhang *et al.*, 2020). Efficient planning and management of hydrological variables are crucial, particularly due to the worsening of impact assessments and mitigation actions caused by climate change. Plants rely primarily on soil water storage during rainfall events, which affects crop yields.

Several regions on the earth have faced consistent wetting or drying drifts, which have caused environmental, social, and ecological problems in recent decades (Dai, 2013; Greve *et al.*, 2014; Donat *et al.*, 2016). The identification of these forces and their contributions would be effective in the management of the water resources and climatic adaptations. Different factors cause these trends, but the most important one is climate change (Trenberth *et al.*, 2014). Climate change impacts the supply and demand of water resources (Haddeland *et al.*, 2014). Numerous environmental scientists explained the ideas that climate change controls the water's dynamic forces (Wentz *et al.*, 2007). There are many factors affecting soil moisture availability, including soil density, soil structure, soil texture, climatic factors, and soil-plant-atmosphere interactions (Liu *et al.*, 2020). In general, soil moisture is determined mainly by rainfall, and the initial soil moisture is estimated by using the precipitation antecedents (Hagen *et al.*, 2020; Chen *et al.*, 2022). The effect of climate change on soil water content (SWC) trends is essential for demonstrating crop water requirements efficiently because SWC is an important variable in regional hydrology (Barnett *et al.*, 2005). The variations in temperature levels and precipitation patterns are the key indications of the influence of climate change on soil water content. Feng *et al.* (2015) have studied changes in rainfall as influenced by water storage, snow accumulation, and surface runoff. The water cycle was significantly influenced by the effect of air temperature (Bouslihim *et al.*, 2016).

The rhizosphere soil water contains less than (0.001%) of water on the earth's surface (Shiklamonov, 1993). However, it has a considerable impact on energy and mass exchanges that are essential for climate change, crop production, ecosystem, and ecohydrology services (Schwingshackl *et al.*, 2017; Zhou *et al.*, 2019). Rhizosphere moisture has the potential to shape hydro-climatic conditions, prompting cloud formations and precipitation patterns on timescales ranging from days to months. When soil moisture preserves at higher levels, the relative humidity of surrounding air escalates while vapour pressure deficit decreases. This permutation generates favourable conditions for condensation, cloud formation, and enhanced precipitation (Corona *et al.*, 2022).

The complex interaction between rhizosphere moisture and atmospheric phenomenon across various time intervals is crucially important for the examination of ecological, hydrological, and climatic activities (Senevirente *et al.*, 2010). Rhizosphere moisture variability has been demonstrated in different scientific models, and the studies have indicated that it is susceptible to variations in the composition of rhizosphere moisture over time (Lozano Parra *et al.*, 2018; Oorschot *et al.*, 2021). The analysis of variance of rhizosphere moisture during various time intervals comprises a critical focus in climate and water science (Oglesby *et al*., 2002; Albertson and Monttaldo, 2003; Koster *et al*., 2004; Senevirente *et al*., 2010; Dirmeyer, 2011; McColl *et al*., 2017).

All these hydrological and climatic conclusions regarding climate change and significant dependencies are based on long-term and expensive measurements. Therefore, the study has used the dynamic Auto Regressive Distributed Lag (ARDL) model to investigate the impact of climate change on root zone soil moisture. Prior to employing dynamic models for understanding and predicting the root zone soil moisture (RZSM) content in Kraków and Warsaw, it is required to highlight existing research gaps by comparing patterns in climate change variables as influenced by climatic shifts. This has helped to understand and predict the root zone soil moisture activity across the two cities (Kraków and Warsaw). Based on our assessment and outcomes, we expected in terms of the main disruptions causing climatic variations in the moisture levels of the root zone. Early studies have used traditional regression models for results analysis, while this is the first study in which we used the dynamic ARDL simulations model (Jordan and Philips, 2018). This model predicts both positive and negative changes in the independent variables and their effects on the dependent variable in graphs in the short and long terms, as compared to the simple ARDL model. Further, the traditional ARDL model was used repeatedly, whereas the dynamic ARDL simulation model was applied for the first time to predict the actual changes (± changes) in graphs. The main aim and objective of this research was to use the dynamic ARDL model to simulate 10% positive and 10% negative changes in the independent variables (precipitation [mm], maximum and minimum temperature [°C], wind speed [m/s], earth skin temperature [°C], and relative humidity [%]), and their impact on the root zone soil moisture in the short and long run by predicting graphs. Therefore, the changes in soil moisture levels due to climate change in urban areas could help in providing useful insights for urban forest management and planning.

Methodology and variables description

This study has used data for Kraków, a southern Poland city (50°03'52.75"N, 19°56'41.93"E) and Warsaw (52°13'23.83"N, 21°01'32.27"E) (Fig. 1). Kraków is characterized by temperate climate zone, located in central Europe, and the area of Kraków is 327 km^2 with population of 750,000.

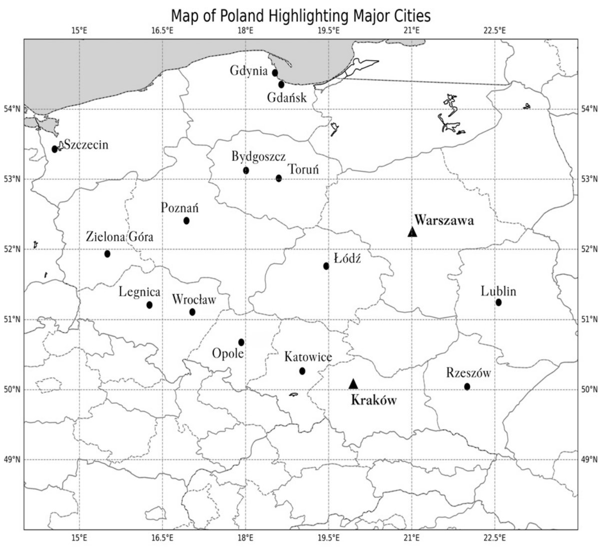

Fig. 1.
Map of Poland with marked locations (▲) of places for which the analysis was carried out

CO_2 is the main greenhouse gas emitted by car traffic, natural gas, household coal burning, and industries, which causes climate change in the city (Jasek-Kamińska *et al.*, 2020). The mean annual temperature is 9°C, and the mean annual rainfall is about 650 mm in Kraków. Warsaw is the capital of Poland, located in the central part of the country. The temperature progressively increased by approximately 0.4°C per decade (Kostka and Zając, 2022). The climate of Warsaw is cold in winter and hot in summer, with a mean annual temperature of 8-9°C and annual rainfall is 500-600 mm. Besides temperature changes in both Krakow and Warsaw, they have almost the same soil conditions that play an important role in urban forestry. The soil types that are dominant in Kraków are sandy loam and clay loam (Podwika *et al.*, 2020), which in turn affect water retention and tree growth in urban forests. However, the soil type (sandy soils) is present in Warsaw, which provides better drainage for trees in urban areas. The selected cities are typical places for the temperate climate zone, and the relationships between the analysed factors are universal and may indicate the consequences of climate change globally.

The study used a dataset sourced from the Power NASA website (). We have used six variables to examine the influence of important climatic drivers on the root zone soil moisture of Kraków and Warsaw: annual average earth skin temperature [°C]; annual average relative humidity at 2 meters [%]; annual average wind speed at 2 meters [m/s]; annual temperature at 2 meters maximum [°C]; annual temperature at 2 meters minimum [°C]; annual average precipitation [mm] and root zone soil moisture (100 cm). Based on early research, this study has used variables in the following time series regression model (Eq. 1). Variables descriptions are presented in Table 1.

$$RZSM_t = \sigma_0 + \sigma_1 EST_t + \sigma_2 RH2M(\%)_t + \sigma_3 WS2M(m/s)_t + \sigma_4 T2M\_MAX(°C)_t + \sigma_5 T2M\_MIN(°C)_t + \sigma_6 PCS(mm)_t + \varepsilon_t \quad (1)$$

Econometrics methodology. The Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) unit root tests were used in this study to confirm the stationarity of the used series (Dickey and Fuller 1979; Philips and Perron, 1988). It is essential to evaluate each series' stationarity before using the dynamic ARDL simulation model and to make sure that none of the used variables exhibit stationarity at I (II). Failure to do so would render the findings invalid. If the ADF or PP test statistic has a significance level of 5%, the series are considered to be a stationary series; on the other hand, if the P-value is higher than the 5% significance level, the series are considered non-stationary. According to the findings of the ADF and PP tests, the under-consideration series display stationarity at both the level and the first difference. This finding supports the use of a dynamic ARDL simulation model.

Bounds test. The presence of cointegration in the studied variables was measured with bound tests. If the estimated F-statistics value surpasses the upper bound, cointegration exists, and it

Table 1.
Variables description

Variable	Description	Data source and resolution
RZSM	Root Zone Soil Moisture	Power NASA website (https://power.larc.nasa.gov/beta/data-access-viewer/) Resolution: 0.5°×0.625° latitude/longitude
EST	Annual Average Earth Skin Temperature [°C]	
RH2M	Annual Average Relative Humidity at 2 Meters [%]	
WS2M	Annual Average Wind Speed at 2 Meters [m/s]	
T2M_MAX	Annual Average Temperature at 2 Meters Maximum [°C]	
T2M_MIN	Annual Average Temperature at 2 Meters Minimum [°C]	
PCS	Annual Average Precipitation [mm]	

does not exist if it is below the lower bound. On the other hand, the outcome of cointegration will be uncertain, if the F-statistics value is among the I (I) and I (0) bounds (Pesaran *et al.*, 2001; Narayan, 2005). The following are the null and alternative hypotheses of the Bounds test. According to the null hypothesis, there is no long-term association Ho=d1=d2=d3=d4=d5=d6=0 and H1≠δ1≠δ2≠δ3≠δ4≠δ5≠δ6≠0. The bounds testing equation for the study variables is as follows (Eq. 2; Table 1).

$$\Delta RZSM_t = \sigma_0 + \sigma_1 EST_{t-i} + \sigma_2 RH2M(\%)_{t-i} + \sigma_3 WS2M(m/s)_{t-i} + \sigma_4 T2M\_MAX(°C)_{t-i} + \sigma_5 T2M\_MIN(°C)_{t-i} + \sigma_6 PCS(mm)_{t-i} + \sum_{l=1}^{q}\theta_1 EST_{t-i} + \sum_{l=1}^{q}\theta_1 RH2M(\%)_{t-i} + \sum_{l=1}^{q}\theta_1 WS2M(m/s)_{t-i} + \sum_{l=1}^{q}\theta_1 T2M\_MAX(°C)_{t-i} + \sum_{l=1}^{q}\theta_1 T2M\_MIN(°C)_{t-i} + \sum_{l=1}^{q}\theta_1 PCS(mm)_{t-i} + \varepsilon_t \quad (2)$$

This study has used the Akaike information criterion (AIC) lag selection criteria for variables. In the above equation *Δ*, demonstrates the change; the number of optimal lag selections is indicated by *t-i*. This study has investigated sigma and theta in the equation above Akaike (1974) of the used variable in the short and long run while ε_t show the error term.

Auto Regressive Distributed Lags (ARDL) approach. Pesaran *et al.* (2001) have introduced the ARDL Model and this model is reliable for relatively little data as compared to other time series traditional models. This model can employ variables with integration orders of I (1), I (0), or a combination of both. Instead of assuming one co-integrating vector. The long-term relationship between the used variables is calculated in Equation 3:

$$RZSM_t = \sigma_0 + \sum_{l=1}^{q}\theta_1 EST_{t-i} + \sum_{l=1}^{q}\theta_2 RH2M(\%)_{t-i} + \sum_{l=1}^{q}\theta_3 WS2M(m/s)_{t-i} + \sum_{l=1}^{q}\theta_4 T2M\_MAX(°C)_{t-i} + \sum_{l=1}^{q}\theta_5 T2M\_MIN(°C)_{t-i} + \sum_{l=1}^{q}\theta_6 PCS(mm)_{t-i} + \varepsilon_t \quad (3)$$

Short-run elasticities were estimated using the following error correction model (Eq. 4):

$$RZSM_{2t} = \sigma_0 + \sum_{l=1}^{q}\theta_1 EST_{t-i} + \sum_{l=1}^{q}\theta_2 RH2M(\%)_{t-i} + \sum_{l=1}^{q}\theta_3 WS2M(m/s)_{t-i} + \sum_{l=1}^{q}\theta_4 T2M\_MAX(°C)_{t-i} + \sum_{l=1}^{q}\theta_1 T2M\_MIN(°C)_{t-i} + \sum_{l=1}^{q}\theta_1 PCS(mm)_{t-i} + \gamma ECT_{t-i} + \varepsilon_t \quad (4)$$

The error correction term (ECT_{t-1}) is used to gauge aftershock adjustment speed toward equilibrium, and *γ* displays the short-run outcomes between 0 and –1 (Stock and Watson, 1992). Further, this study has used different diagnostic techniques, including the Ramsey RESET test for model fitness, the Breusch Godfrey LM (Lagrange multiplier) test for serial correlation, and the Jarque Berra test for residual normality.

Dynamic ARDL simulations. Khan *et al.* (2020) used the dynamic ARDL simulation model and indicated that this model has removed the drawbacks of the traditional ARDL model, that is used again and again. The ARDL simulations model has demonstrated the ability to simulate and forecast both positive and negative change graphs compared to pre-existing ARDL models. The dynamic ARDL simulation model has used multivariate normal distributions, and 5000 vector simulations (Jordan and Philips, 2018).

$$\Delta RZSM_{2t} = \sigma_0 RZSM_{2t-1} + \beta_1 EST_t + \sigma_1 \Delta EST_{t-1} + \ldots + \beta_2 RH2M_t + \sigma_2 \Delta RH2M_{t-1} + \beta_3 WS2M_t + \sigma_3 \Delta WS2M_{t-1} + \beta_4 T2M\_MAX_t + \sigma_4 \Delta T2M\_MAX_{t-1} + \beta_5 T2M\_MIN_t + \sigma_5 \Delta T2M\_MIN_{t-1} + \beta_6 PCS(mm)_t + \sigma_6 PCS(mm)_{t-1} + \varphi ECT_{t-1} + \varepsilon_t \quad (5)$$

The above equation σ and β depicts the short-run and long-run coefficients of the variables, respectively. The ECT_{t-1} (error correction term) is used to measure the pace of adjustment towards equilibrium aftershocks φ shows the ECT coefficient that ranges between 0 and –1 (Eq. 5; Table 1).

Results

Unit root tests. The results of unit root tests for both ADF and PP are presented in Table 2. The ADF test and the PP test are time series tests used for checking the stationarity. The ADF and PP were conducted to figure out the stationarity of a time series. Stationarity is an important notion in time series analysis, and it refers to the property that the statistical features of a time series (such as its mean and variance) do not change during analysis of time series. The non-stationarity can lead to misleading correlations and incorrect predictions, and it can make it difficult to model a time series. The findings of both tests, *i.e.*, ADF and PP have demonstrated that the used series are stationary at the level and first difference (Table 2).

Lag selection criteria. ARDL allows the use of different lags for both independent and dependent variables and distinguishes it from other time series models. The findings of the vector autoregressive (VAR) lag selection criteria for both regions, *i.e.* (Kraków and Warsaw) have demonstrated that lag one is the most appropriate lag for both models (Table 3). This study has used the Akaike information criterion (AIC) for lag selection criteria and selected lag one for both models.

ARDL F-bounds test. Table 4 reveals the results of the ARDL bound test. The ARDL bound test is utilized to examine the presence of cointegration among variables. The findings of the ARDL bound test shows that cointegration exists in the study variables for both cities. The study's models for both regions provide evidence of cointegration, as indicated by the observed F statistic value, which exceeds the upper bound.

Table 2.
Results of unit root tests

Cities	Kraków				Warsaw			
	ADF		PP		ADF		PP	
	Level	1st Diff	Level	1st Diff	Level	1st Diff	Level	1st Diff
Root Zone Soil Moisture								
	–4.9385***	–7.4986***	–4.9504***	–11.7115***	–5.5060***	–6.7758***	–5.8263***	–9.7262***
Precipitation Corrected Sum [mm]								
	–5.7133***	–8.3041***	–5.7527 ***	–20.2362***	–5.4560***	–8.7664***	–5.5076***	–19.2397***
Relative Humidity at 2 Meters [%]								
	–5.9338***	–8.0151***	–5.9338***	–26.8653***	–5.5999***	–9.9051***	–5.6073***	–8.1561***
Temperature at 2 Meters Maximum [°C]								
	–6.1503***	–12.2810***	–6.1503***	–30.0455***	–5.8073***	–10.4005***	–5.8106***	–15.8168***
Temperature at 2 Meters Minimum [°C]								
	–5.7243***	–10.6652***	–5.6925***	–19.2649***	–5.6312***	–7.1578***	–5.6394***	–19.7869***
Earth Skin Temperature [°C]								
	–3.8358***	–6.6660***	–3.8607***	–16.0263***	–3.6306***	–7.2847***	–3.6937***	–13.8329***
Wind Speed at 2 Meters [m/s]								
	–6.5018***	–7.2247***	–6.5018***	–22.0070***	–5.5115***	–5.6461***	–5.7308***	–18.4314***

*10% level of significance; **5% level of significance; ***1% level of significance

Results of the dynamic ARDL model simulation. Table 5 reveals that rainfall had a favourable effect on root zone soil moisture content in the cities of Kraków and Warsaw both in the short and long term. The study demonstrated that in the cities of Kraków and Warsaw, a 10% rise in precipitation showed a long-term rise in root zone soil moisture of 1.294% and 0.993%, respectively. This upsurge is 1.157% and 0.866%, respectively, in a short period of time.

The result depicted that a 10% rise in minimum temperature has caused an upsurge to RZSM content for about 1.019 and 0.794% in the long run, and 0.881 and 0.585% in the short run basis at Kraków and Warsaw. The maximum temperature at 2 meters has negatively affected

Table 3.
Lag selection criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
			Kraków			
0	–403.5342	NA	3.280429	21.05303	21.35162*	21.16017*
1	–346.5984	90.51323*	2.275642*	20.64607*	23.03478	21.50312
			Warsaw			
0	–370.4609	NA	1.001307	19.86636	20.16802*	19.97369*
1	–320.0593	79.58144*	0.972577*	19.79259*	22.20588	20.65122

* Show lag selection: LR – Likelihood ratio, FPE – Final prediction error, HQ – Hannan-Quinn criterion, SC – Schwarz criterion, AIC – Akaike information criterion

Table 4.
ARDL F-bounds test

Test Statistic	Value	Signif. [%]	I (0)	I (1)
			Asymptotic: n=1000	
F-statistic for Kraków	9.926816	10	1.99	2.94
F-statistic for Warsaw	10.32878	5	2.27	3.28
K	6	2.5	2.55	3.61
		1	2.88	3.99

Table 5.
Dynamic ARDL Simulation Regression Results

Variable	Variables Coefficient and their t values	
	Kraków	Warsaw
ECT	–1.432*** (–2.869)	–1.761*** (–3.528)
D_Precipitation	1.294*** (5.056)	0.993*** (3.879)
L1_ Precipitation	1.157*** (6.024)	0.866*** (4.510)
D_Temp_min	1.019* (1.897)	0.794* (1.979)
L1_Temp_min	0.881*** (7.050)	0.585*** (4.682)
D_ Temp_max	–0.744** (–2.655)	–1.472*** (–5.256)
L1_Temp_max	–0.606*** (–2.035)	–0.958*** (–3.636)
D_Wind_speed	–0.468*** (–3.421)	–0.761*** (–5.561)
L1_Wind_speed	–0.330** (–2.328)	–0.646*** (–4.555)
D_Relative_humidity	0.193*** (2.238)	0.873*** (2.079)
L1_Relative_humidty	0.855*** (3.202)	0.835*** (3.127)
D_Earth_skin_temp	–0.387 (–1.879)	–1.614*** (–7.835)
L1_Earth_skin_temp	–0.224*** (–4.058)	–0.552*** (–10.000)
_cons	0.761*** (5.209)	1.610*** (11.020)

D with variables shows long, and L shows short run. *10% level of significance. **5% level of significance. ***1% level of significance root zone soil moisture by –0.744 and –1.472% in the long run in Kraków and Warsaw, while in the short run, the impact of maximum temperature is negative and significant. These findings have demonstrated that maximum temperature has reduced RZSM by –0.606 and –0.958 % in Kraków and Warsaw, respectively. The long-term impact of wind speed has reduced the RZSM by about –0.468 and –0.761%, and –0.330 and –0.646% in the short term in the cities of Kraków and Warsaw. Wind speed has a negative impact on root zone soil moisture content. Furthermore, the long-term effect of relative humidity has predicted that a 10 percent rise has caused an increase of about 0.193 and 0.873% of soil moisture in Kraków and Warsaw, respectively. The short-run impact of relative humidity has escalated the soil moisture by about 0.855 and 0.835% in Kraków and Warsaw. The effect of earth skin temperature was recorded as negative, about –0.387 and –1.614 in long-term effect at Kraków and Warsaw. The short term has depicted –0.224 and –0.552 reduction in soil moisture content, respectively. The ECT values for both cities were significant and negative which reveals that the model has captured the dynamics and adjustments about 14 and 17%, respectively.

Effects of positive and negative changes in independent variables and their impact on RZSM in Kraków and Warsaw. The study has examined the effects of both (±) changes in climatic parameters and their subsequent influence on the root zone soil moisture (SM) content in Kraków (Fig. 2, 3). Fig. 2A reveals that a 10% positive changes in predicted precipitation has caused enhanced soil moisture in the root zone at Kraków in the short and long term. Fig. 2B indicates that 10% negative changes in precipitation has a tendency to reduce soil moisture content

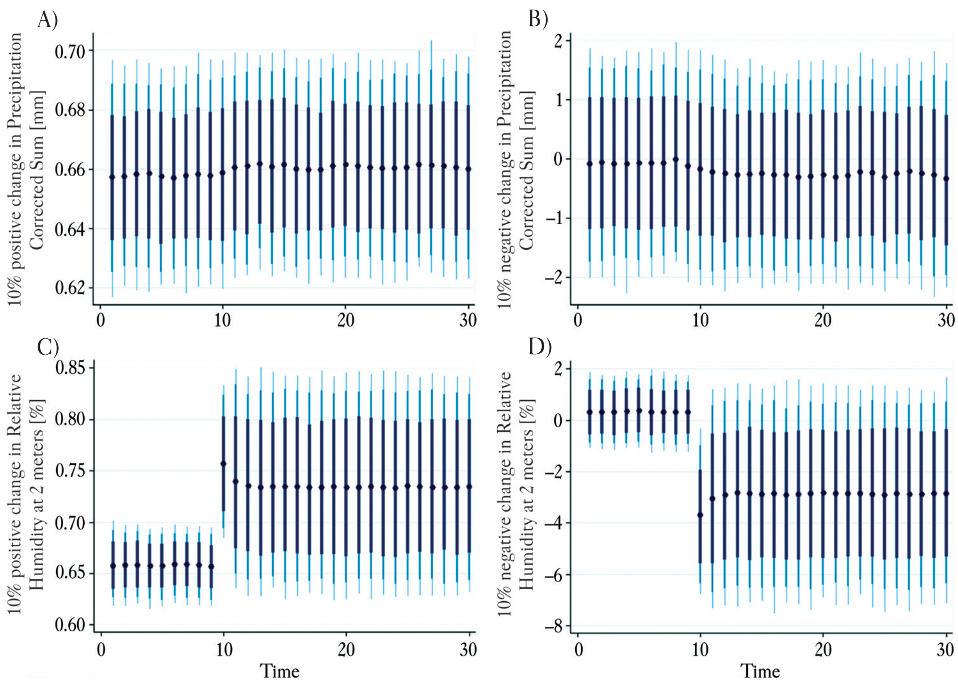

Fig. 2.

Plots (Kraków) from a dynamic simulated ARDL model displaying the impact of: (A, B) 10% positive and negative change in Precipitation Corrected Sum [mm] on root zone soil moisture. (C, D) 10% positive and negative change in Relative Humidity at 2 Meters [%] on root zone soil moisture. The dark blue to light blue lines show the 75, 90, and 95% confidence intervals, while the dots reflect the average predicted value

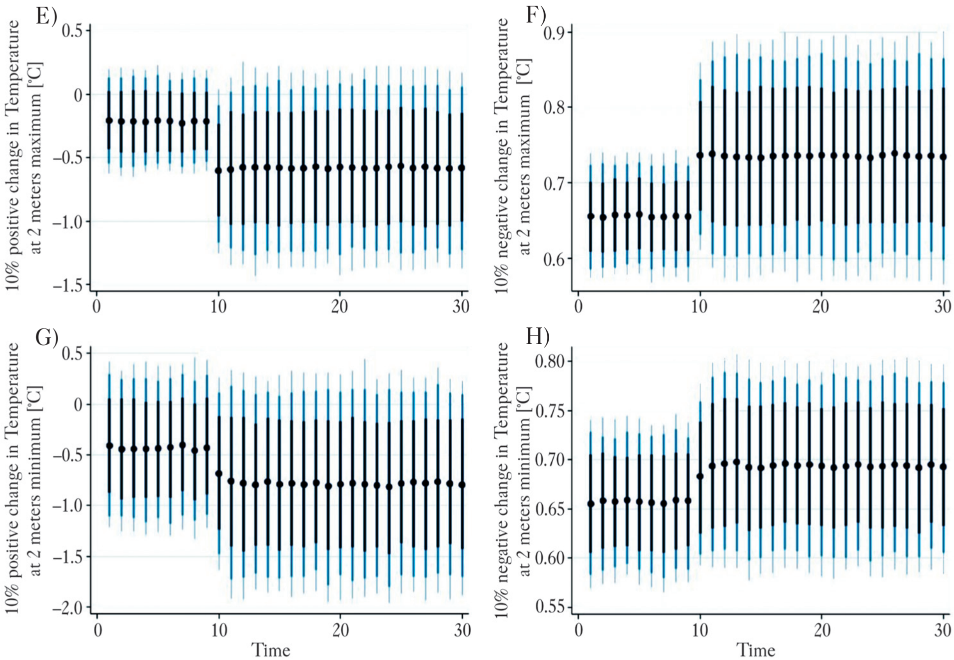

Fig. 3.

Plots (Kraków) from a dynamic simulated ARDL model displaying the impact of: (E, F) 10% positive and negative change in temperature at 2 meters maximum [°C] on root zone soil moisture. (G, H) 10% positive and negative change in temperature at 2 meters minimum [°C] on root zone soil moisture. The dark blue to light blue lines shows the 75, 90, and 95% confidence intervals, while the dots reflect the average predicted value

in both the short and long term, respectively. The figures (2C, 2D) show both the (± changes) of expected relative humidity, and how it affected the amount of RZSM. The 10% positive changes in relative humidity tends to boost RZSM in the short and long term. The influence of a 10% negative changes in relative humidity has shown a positive impact in the short run, while moisture content in the root zone decreased in the long run. The influence of 10% +ive and –ive changes in maximum temperature and how it affects the SM in the root zone is presented in (3E, 3F). The 10% positive rise in predicted maximum temperature has declined the root zone SM content during the short and long term. It is revealed that 10% negative changes in maximum temperature has caused an upward trend in RZSM content both in the short and long term basis. The RZSM was significantly affected by 10% (± changes) in the predicted minimum temperature (Fig. 3G, 3H). The 10% positive changes in predicted minimum temperature tends to decrease the RZSM content on a short- and long-term basis. The 10% negative changes in minimum temperature has caused enhancement in the RZSM during the short and long term. Fig 4A and 4B show 10% +ive changes in the predicted maximum temperature at 2 meters with a tendency to decline the root zone soil moisture in Warsaw. The 10 percent negative shock in maximum temperature has caused enhancement of RZSM, in a short- and long-term basis. The ten percent positive and negative changes in predicted minimum temperature lean towards an downward and upward trend in soil moisture content in the short and long term, respectively (Fig. 4C, D). The 10% positive changes in earth skin temperature has caused a reduction in soil moisture content, whereas the 10% negative change has improved the root zone SM content in both the short and long term (Fig. 5E, F). The identical outcomes were recorded for (10% +ive and

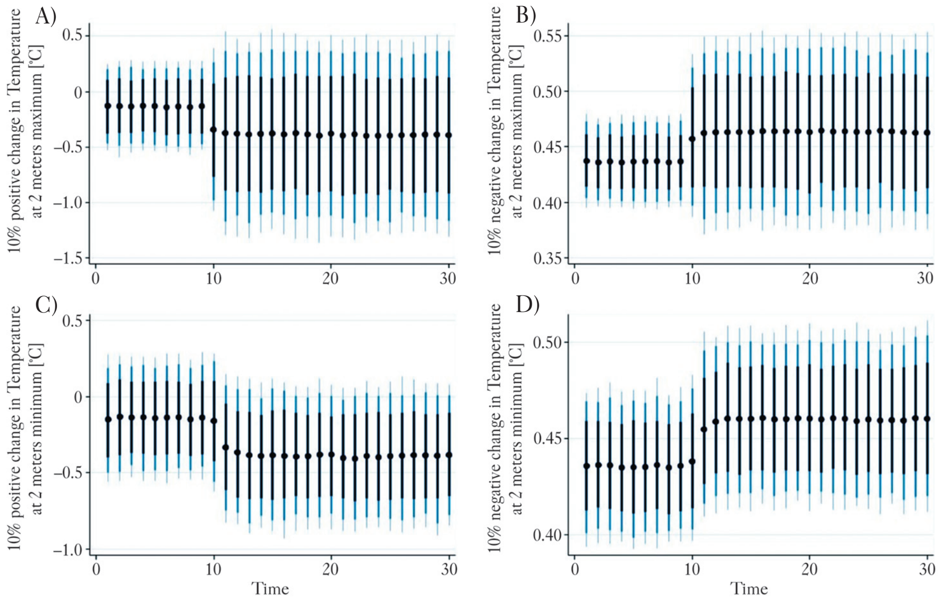

Fig. 4.

Plots (Warsaw) from a dynamic simulated ARDL model displaying the effect of: (A, B) 10% positive and negative change in temperature at 2 meters maximum [°C] on root zone soil moisture. (C, D) 10% positive and negative change in temperature at 2 meters minimum [°C] on root zone soil moisture. The dark blue to light blue lines shows the 75, 90, and 95% confidence intervals, while the dots reflect the average predicted value

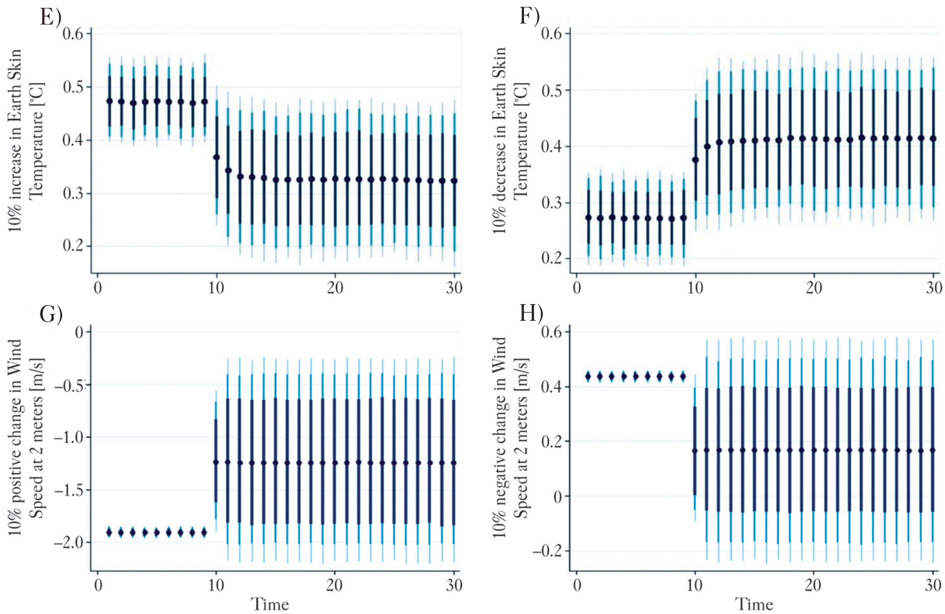

Fig. 5.

Plots (Warsaw) from a dynamic simulated ARDL model displaying the effect of: (E, F) 10% positive and negative change in earth skin temperature [°C] on root zone soil moisture. (G, H) 10% positive and negative change in wind speed at two meters [m/s] on root zone soil moisture. The dark blue to light blue lines shows the 75, 90, and 95% confidence intervals, while the dots reflect the average predicted value

–ive changes) in predicted wind speed and its influence on the root zone soil moisture content (Fig. 5G, H). The ten percent positive and negative changes in wind speed at 2 meters tend to diminish and boost up the root zone soil moisture content both in the short and long run, respectively.

CUSUM of Squares. The cumulative sum (CUSUM) plots of Squares of both cities (Kraków and Warsaw) exhibits that coefficients are stable based on blue line inside the upper and lower bounds red lines (Fig. 6). The recursive CUSUM of Squares are statistical methods for tracking changes over time in a process or set of numbers.

Discussion

Extreme weather and climate phenomena (such as droughts, heat waves, and storms) arise from complex interactions between various physical processes on many spatial and temporal scales. Many adverse phenomena are linked via weather systems that reinforce each other, such as drought and heat waves; dry soil becomes hydrophobic and less permeable, and in the event of heavy rains, it can contribute to local flood episodes (Zscheischler *et al.*, 2018).

In many cases, especially in urban ecosystems, these extreme events may exceed the capacity of natural, human, and engineering systems (Turner, 2010).

Understanding, analysing, quantifying, and the ability to predict such complex reactions should be based both on field studies but also on attempts to model and transfer these dependen-

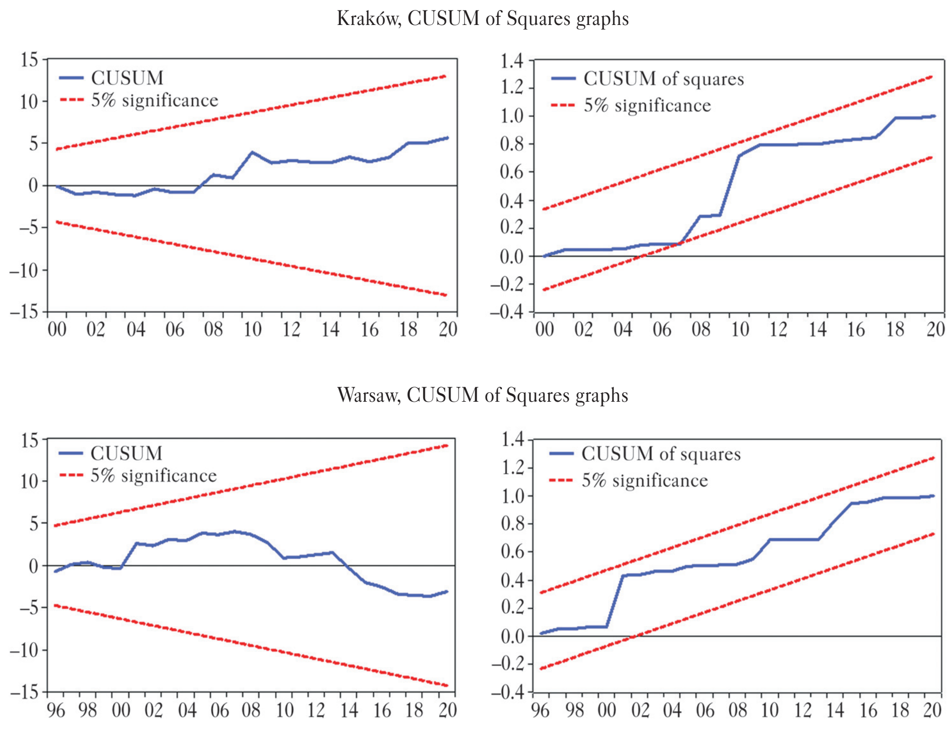

Fig. 6.

Recursive CUSUM plots of Kraków and Warsaw. The ARDL bounds testing model is supported by residuals for all variables falling within the limits, which illustrates the consistency of coefficient variances through time cies and correlations to larger areas thanks to remote sensing tools. Our research has shown that the possibility of using a dynamic ARDL model will allow for faster forecasting of changes in the soil based on atmospheric data.

We could conclude that a 10% increase in minimum temperature has caused an upsurge to RZSM content for an average of 0.9065% for both cities. The maximum temperature at 2 meters has negatively affected root zone soil moisture by an average –1.108%. Wind speed also has a negative impact on root zone soil moisture content. Furthermore, the long-term effect of relative humidity has predicted that a 10 percent rise has caused an increase of about 0.193 and 0.873% in soil moisture in Kraków and Warsaw, respectively.

Higher temperatures and less water in the root zone observed in the city may also have a fundamental impact on soil processes related to the resources of dissolved carbon and organic nitrogen fractions and thus affect the hydrophobicity and water capacity of soils (Staszel-Szlachta *et al*., 2022). Insufficient soil moisture and increasingly frequent spring droughts weaken trees, making them more susceptible to strong winds, insect pests, and a range of diseases (Sławska and Sławski, 2017; Boczoń and Zachara, 2022). Joseph *et al*. (2020) noted the small temporary increases in soil water content due to short rainfall events, which quickly enhanced the carbon levels belowground in non-irrigated plots compared to trees in irrigated plots. The research shows how minor changes in soil moisture can impact trees, emphasizing the significance of maintaining optimum moisture levels in urban forestry. The long period of tree growth makes them particularly vulnerable to adverse environmental conditions (Pardos *et al*., 2021). Different tree species respond to drought in various ways, depending on their physiology, root system, survival strategies, and adaptation to stress conditions. Trees can exhibit a range of defence mechanisms, such as reducing transpiration by closing stomata, developing deeper root systems, storing water in tissues, or shedding leaves to minimize the evaporative surface. For example, Rohde *et al*. (2024) stated that Isohydric trees have deep-rooted systems and they close their stomata when their root systems sense a change in soil water. In contrast, anisohydric plants have shallow root systems and they even transpire when the soil moisture level decreases. Therefore, anisohydric trees have a greater risk of hydraulic failure under drought stress due to stomatal conductance. The amount and magnitude of drought varies for different tree species under a single extreme drought or longer dry periods (5 years). The examined species revealed that Scots pine *Pinus sylvestris* L. shows higher resistance to drought (–13 growth); however, Norway spruce *Picea abies* (L.) H.Karst. shows higher sensitivity to drought (–30 growth) (Jiang *et al*., 2024). Furthermore, the drought resistance for the three broad leaved species was higher than the two coniferous species for the recent two droughts in the Czech Republic. Therefore, we see that the problem of the distribution of water and listing the factors influencing it, in both the spatial and temporal aspects, is extremely important today (Seidl *et al*., 2017). This is even more important because all four stages of drought occurred more often in all areas of the Earth: atmospheric, soil, hydrological, and socioeconomic. The availability of soil moisture affects forest resilience to drought stress, and forests with greater moisture levels had higher resistance to drought and were better capable from recovering drought stress. This can also be relevant to urban forest management, where soil moisture plays an important role in tree growth and health (Gazol *et al*., 2017). Another study conducted by (Meineke and Frank, 2018) concluded that due to water stress, urban trees grow less than rural trees in temperate cities worldwide. They further explored that water stress intensifies warming and insect pests affect the growth of trees. The results identify the importance of soil moisture in urban trees growth and health.

The effect of precipitation on rhizosphere soil moisture might depend upon various factors such as climate, vegetation covers and soil type (Pająk *et al*., 2022; Banach *et al*., 2023). Precipitation has a significant impact on soil moisture spectrum, which illustrates varying effects across multiple frequency bands (Nakai *et al*., 2014). The standardized precipitation and evapotranspiration index (SPEI) indicates that not only meteorological droughts but also soil droughts will be even more severe in the near future (Dukat *et al*., 2022). High temperatures have a notable effect on the process of evapotranspiration, leading to reduction in soil moisture content due to high water loss from both soil and plants. Deng *et al*. (2020) observed negative trends in soil moisture with increasing temperature between 1979 and 2017. They also noticed that about 82% wetting trend was impacted by the combined action of vegetation, precipitation, and temperature. Furthermore, this research discovered global soil drying in seven land covers, in which urban area had the highest proportion of 80% soil drying. Increasing temperature leads to high evapotranspiration, and causes reduction in the soil water infiltration and soil water storage capacity (Varallyay, 1990). He further explained that anthropogenic activities (industrialization and energy usage) tended to increase in the atmospheric gas composition (*e.g.* CO_2) which impacts soil moisture conditions. Another study (van Groenigen *et al*., 2011) explained that the higher CO_2 concentration in the atmosphere can lead to reduced transpiration from the plants, which in turns result in higher soil moisture content. The increasing global temperatures significantly causes changes in the soil moisture (Dai, 2013; Seager *et al*., 2013). The soil moisture variation was considerably affected by precipitation and temperature, which are crucial determinants. The examined results are consistent with findings of (Hauser *et al*., 2016) which revealed that escalation in heat wave risk was due to consequence of SM, which has emphasized SM's role as a prerequisite to record-breaking temperatures. During the year 2003, when temperatures across Europe were exceptionally warm, the average simulated soil water availability was significantly reduced (Holsten *et al*., 2009). The soil moisture was declined significantly in Switzerland and throughout Europe in summer due to high temperature (Jasper *et al*., 2006; Fischer *et al*., 2007). High wind speed has raised evaporation from the soil which has reduced SM content due to drying effect. According to Wang *et al*. (2021), the soil moisture variations were not only positively dependent on-air temperature but also affected by humidity, vapour pressure deficit, wind speed, and solar radiation. The soil moisture content and relative humidity are positively correlated. In general, the evaporation rate from the soil tends to slow down in conditions of high relative humidity in the air. That's why high relative humidity tends to enhance the RZSM content. The influence of earth skin temperature was negative on the soil moisture content in root zone soil, because it has raised transpiration from trees and has escalated evaporation from the soil surface. The assessment of soil moisture content was greatly influenced by normalized difference vegetation index (NDVI) and the land surface temperature. Xu *et al*. (2013) conducted meta-analysis and found that higher soil temperature decreased soil moisture content across all studies. Zhan *et al*. (2007) reported importance of surface temperatures and vegetation indices in identifying the features of wet or dry land. Cai *et al*. (2019) studied autocorrelations of moisture data with SPSS and reported that it was not a stationary series and other climatic factors have influenced the soil water content. The negative correlation parameter indicates that increasing soil and air temperature, wind speed, and light will speed up soil surface water evaporation, which decreased soil moisture. Peretti *et al*. (2023) reported that wind speed enhanced potential evapotranspiration, due to which soil moisture reduced in Argentina between 1990 and 2019. The soil moisture is positively correlated with soil/air humidity, atmospheric pressure, and precipitation. Rainfall is one of the variables that directly affect soil moisture, and heavier rainfall can completely saturate it. The current study observed different soil moisture content both in Kraków and Warsaw. Urban forests being situated in highly anthropogenic areas, share some common ecological functions with traditional forest stands, such as regulating microclimate and enhancing water retention of the urban soil. However, it is important to note that all urban trees, parks, and vegetation in urban areas are significantly more vulnerable to the effects of high temperatures and drought.

The relationships between the meteorological factors examined in this study and their impact on the retention properties of the soil may be a specific predictor of climate changes affecting forests and other natural environments (Chang, 2006; Choat *et al*., 2012).

Conclusions and recommendations

The results of this study concluded the enhancement of soil moisture content in Kraków and Warsaw by simulating 10% positive changes in the relative humidity [%], minimum temperature [°C], and precipitation [mm] in the short and long term. In contrast, the effect of a 10% negative change in these variables reduced the soil moisture content both in short- and long-term conditions. Further, the analysis revealed that 10% positive changes in the maximum temperature [°C], earth skin temperature [°C], and wind speed [m/s] decreased the soil moisture concentration in Kraków and Warsaw, respectively. Conversely, the 10% negative change in these variables tends to increase the soil moisture content. Differences in soil moisture content depend upon geomorphological conditions and the type of plant habitat. The soil moisture retention in Kraków was highly sensitive in these increases of variables, particularly (precipitation and minimum temperature) compared to Warsaw. This suggests that soil moisture content was directly affected by these variables, showing differences in local climate, soil types, or land uses. The increase in maximum temperature and wind speed has highly decreased the soil moisture content in Warsaw compared to Kraków. The result has emphasized the importance of considering the above-mentioned criteria for development of sustainable land management techniques which may successfully adapt as well as reduce the influence of changing climates. Soil moisture (SM) is crucial for the sustainable development of agriculture, forestry, and ecosystems as it directly affects plant growth, fertility of soil, and availability of water.

To expand understanding, further research is recommended to examine the effect of climate change, different soil properties, soil types, and land uses on soil moisture levels of different regions. Because only the climatic variables cannot evaluate very well the exact scenario of the soil moisture content.

Authors' contributions

Conceptualization – M.O.K. and A.K.-I.; methodology – M.O.K.; supervision – M.O.K. and A.K.-I.; visualization – M.O.K.; writing-original draft – M.O.K.; writing-review and editing, M.O.K., A.K.-I., T.M. This article has been read and approved by all authors.

Conflicts of interest

The authors declare no potential conflicts.

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STRESZCZENIE

Wpływ zmian klimatycznych na wilgotność gleby w strefie korzeniowej w dwóch polskich miastach

Lasy i parki miejskie są żywymi systemami zintegrowanymi z obszarami wysoce antropogenicznymi: zachodzą między nimi ścisłe interakcje fizyczne, chemiczne i biologiczne. Jednocześnie w miastach obserwujemy generalnie wyższe temperatury niż np. w lasach i to może przekładać się na ilość i szybkość obiegu wody w strefie korzeniowej dostępnej dla roślin. Długi okres wzrostu drzew powoduje, że są one szczególnie narażone na wystąpienie niekorzystnych warunków środowiskowych. Zrozumienie, analiza, kwantyfikacja i możliwość przewidywania takich złożonych

reakcji powinna opierać się na badaniach terenowych, ale także próbach modelowania i przenoszenia tych zależności na większe powierzchnie dzięki narzędziom teledetekcyjnym.

W prezentowanej pracy wykorzystano dynamiczny model ARDL do analizy wpływu zmiennych klimatycznych, takich jak temperatura powierzchni ziemi [°C], prędkość wiatru [m/s], wilgotność względna na wysokości 2 m [%], maksymalna i minimalna temperatura oraz opady [mm], na wilgotność gleby w strefie korzeniowej – użyto danych z Power NASA (tab. 1). Model ten przewiduje zarówno dodatnie, jak i ujemne zmiany zmiennych niezależnych oraz ich wpływ na zmienną zależną w krótkim i długim okresie. W badaniu wykorzystano dane dla Krakowa i Warszawy. Wybrane miasta są typowymi miejscami dla strefy klimatu umiarkowanego, a powiązania pomiędzy analizowanymi czynnikami są uniwersalne i mogą wskazywać na skutki zmian klimatycznych w skali globalnej. Wykorzystano test rozszerzonej metody Dickey-Fullera (ADF) i Phillipsa-Perrona (PP) do sprawdzenia stacjonarności zmiennych (tab. 2 i 3). Testy granic zastosowano do oceny współintegracji zmiennych (tab. 4), co pozwala na ocenę długoterminowych związków między zmiennymi. Symulacje dynamicznego ARDL wykorzystano do generowania prognoz dotyczących wpływu pozytywnych i negatywnych szoków w zmiennych niezależnych na wilgotność gleby. Wyniki wykazały, że 10-procentowy wzrost opadów, minimalnej temperatury i wilgotności względnej spowodował poprawę wilgotności gleby w długim okresie: odpowiednio o 1,294, 1,019 i 0,193% w Krakowie oraz 0,993, 0,794 i 0,873% w Warszawie. Długotrwały wpływ temperatury maksymalnej, prędkości wiatru i temperatury powłoki ziemi wpłynął negatywnie na wilgotność gleby: o –0,744, –0,468 i –0,3875% w Krakowie oraz –1,472, –0,761 i –1,614% w Warszawie (ryc. 1 i 2; tab. 5). Natomiast w krótkim czasie 10-procentowy wzrost opadów spowodował wzrost wilgotności gleby w strefie korzeniowej: o 1,157% w Krakowie i 0,866% w Warszawie (tab. 5). Długoterminowe symulacje pokazały, że pozytywne zmiany wartości opadów, minimalnej temperatury i wilgotności względnej zwiększały wilgotność gleby w obu miastach. Negatywne zmiany tych samych zmiennych prowadziły do spadku wilgotności gleby, co podkreśla wrażliwość systemów hydrologicznych na zmiany klimatyczne (ryc. 3). Spadki wartości tych samych zmiennych prowadziły do spadku wilgotności gleby, co pokazuje wrażliwość systemów hydrologicznych na zmiany klimatyczne.

Badanie wskazuje znaczenie zarządzania zasobami wodnymi i adaptacji klimatycznej w kontekście rosnących zagrożeń związanych ze zmianami klimatu. Zaleca się dalsze badania nad wpływem różnych właściwości gleby, typów użytkowania ziemi oraz lokalnych warunków klimatycznych na wilgotność gleby. Wyniki mogą służyć jako podstawa do opracowania strategii zarządzania wodą w mieście, co jest kluczowe dla zrównoważonego rozwoju rolnictwa, leśnictwa i ekosystemów. Badania wykazały, że możliwość zastosowania dynamicznego modelu ARDL pozwoli na szybsze prognozowanie zmian w glebie w oparciu o dane atmosferyczne.

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