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SpongeScapes: understanding the role of nature-based solutions in improving sponge functioning of landscapes – the case of regenerative agriculture

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Abstract. The SpongeScapes project aims to accelerate understanding Nature-based Solutions (NBS) that enhance the sponge functioning of soil, groundwater, and surface water ecosystems, improving landscape resilience against hydrometeorological extremes across diverse climates. One NBS being explored within SpongeScapes is the adoption of Regenerative Agricultural Practices (RAPs) such as reduced tillage and cover cropping. These practices can improve soil health and potentially increase water retention capacity, compared to conventional agriculture practices that degrade soil structure and porosity. However, quantifying RAP benefits is challenging due to the delayed soil response to management changes. This report discusses an exploratory approach of back-analysing long-term soil moisture datasets to assess the impacts of RAPs on soil water retention capacity. By inferring changes in saturated water content (proxy for porosity), findings from trend analyses on UK case studies provide insights into the potential of RAPs as an NBS for enhancing landscape water resilience through improved soil sponge functioning.

1 Introduction

The EU/UKRI funded SpongeScapes project (2024-2027) aims to study the water retention capacity of landscapes, providing resilience to droughts and floods. It includes in-depth research across 14 case studies in Europe, ranging from surface water (e.g., stream reconnection to floodplains) to soil/groundwater (e.g., Regenerative Agricultural Practices or RAPs), in diverse climate, physiography, vegetation and soil contexts. SpongeScapes taps into long(er) term monitoring records as well as new monitoring with innovative technologies. Here, we focus on initial work analysing some of these available longer datasets for selected UK sites.

Conventional intensive farming methods have contributed to widespread soil degradation, including increased compaction, depletion of soil organic matter, and reduced structural porosity [1]. These changes compromise the water retention capacity and resilience of agricultural soils, making them more vulnerable to extreme hydrological

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events like floods and droughts. RAPs, focused on fostering healthy soil ecosystems, offer a promising nature-based approach to enhance the resilience of agricultural systems to such extreme weather conditions [2]. Practices like reduced tillage, controlled traffic, reduced livestock density, cover cropping, and afforestation can improve soil organic matter content, alleviate compaction, promote better soil structure, and stimulate microbial activity, leading to increased soil porosity, water infiltration, and water retention capabilities [3, 4].

However, quantifying the potential effectiveness of RAPs in mitigating flood and drought risks faces a critical challenge due to the inherent time lag in soil responses to changes in agricultural management practices. Long-term monitoring of soil properties before and after the implementation of RAPs may require decadal timescales to reveal significant impacts [5]. This time lag presents a significant obstacle in assessing the immediate and medium-term benefits of RAPs, making it difficult for policymakers and land managers to make informed decisions about their implementation.

To address this research gap, we have adopted an exploratory approach that investigates the utility of back-analysing existing long-term soil moisture datasets to detect any changes in inferred soil porosity resulting from shifts in land use and management practices.

2 Materials and methods

2.1 Study sites and data

This study utilises long-term soil moisture datasets from various monitoring networks in the UK, including the COSMOS-UK network [6] and the UK Greenhouse Gases Flux Network [7]. We focused on five sites with varying characteristics and management practices, as detailed in Table 1. All sites measure precipitation in millimetres (mm) and soil moisture or volumetric water content (VWC) of soil in percentage. The VWC are measured using Time Domain Transmissivity (TDT) probes.

A) Chimney Meadows

B) Waddesdon


C) Alice Holt


D) ASSIST_EH

Fig.1. Study sites

In this study we use VWC measured at 10 cm depth below ground level because it's highly responsive to rainfall events and management practices. Further, VWC at this depth was available at all chosen sites.

Table 1 : Characteristics of study sites

Site Name	Network	Data	Altitude (mAOD)	Landcover/ RAP	Soil Type	Reference Bulk Density (g/cm^3)
Chimney Meadows	COSMOS -UK	2013-2024	66	Improved grassland	Calcareous mineral soil	1.37 (loamy soil)
Alice Holt	COSMOS -UK	2015-2024	74	Broadleaf Woodland	Mineral soil	0.85 (loamy soil)
Waddesdon	COSMOS -UK	2013-2024	91	Improved grassland	Mineral soil	1.14 (clayey/loamy soil)
ASSIST_EH	UK Greenhouse Gases Flux Network	2018-2024	~72	Grass strips, plus low traffic, and cover crops in the rotation (RAPs)	Mineral soil	NA
ASSIST_EC	UK Greenhouse Gases Flux Network	2019-2024	~72	Traditional agricultural practice	Mineral soil	NA

mAOD = meters above Ordnance Datum

The ASSIST_EH and ASSIST_EC sites form a paired study, with ASSIST_EH receiving RAPs treatment while ASSIST_EC follows traditional agricultural practices. This pairing allows for comparison of the effects of RAPs on soil moisture dynamics. The COSMOS-UK sites have two TDTs located 1m apart from one another.

Additionally, we used land cover information from the UK Centre for Ecology & Hydrology (UKCEH) Land Cover Maps from 1990 onwards to track changes in land use over time.

2.2 Conceptual framework and analytical approach

Given that these UK sites fall under the 'humid temperate oceanic' Köppen climate classification, we anticipate that the annual maximum soil moisture content, representing saturated conditions, is attained during most winter seasons (excluding any 'dry' winters). We estimate soil porosity in a particular year by equating it to the maximum soil moisture content, effectively using this as a proxy measurement while considering potential air entrapment effects.

Our null hypothesis is that any change in land use or management has no significant impact on inferred soil porosity over time, testing the common assumption of static soil properties.

To test this hypothesis and identify long-term changes in soil porosity, we employ a combination of trend analysis. Changes in soil porosity are then linked to shifts in land use and management, identified using Land Cover Map data and local site knowledge.

2.2.1 Trend analysis

We employed the Mann-Kendall (MK) Trend test to assess long-term changes in soil moisture and associated precipitation patterns [8]. The analysis focused on three key variables:

1. Winter maximum soil moisture: The highest recorded soil moisture value for each winter season (defined herein as December, January and February).

2. Antecedent daily total precipitation: The cumulative precipitation over the 24-hour period immediately preceding the winter maximum soil moisture event.

3. Average weekly precipitation: The mean daily precipitation over the 7-day period leading up to the winter maximum soil moisture event.

These precipitation metrics were selected to capture both the immediate and short-term antecedent moisture conditions associated with peak soil moisture. The antecedent daily total provides insight into the direct impact of recent rainfall, while the average weekly precipitation offers a broader perspective on the moisture conditions leading up to the peak event.

The significance of trends was tested at a 90% confidence level ($\alpha = 0.1$). To account for potential soil disturbance and settling effects following the installation of Time Domain Transmissivity (TDT) probes, we excluded the first two years of soil moisture data from our analysis. This exclusion period allows for soil rehabilitation and ensures that our trend analyses reflect stabilised soil conditions.

2.2.2 Comparative analysis

For the paired UK Greenhouse Gases Flux Network sites (ASSIST_EH and ASSIST_EC), we conducted a comparative analysis of the soil moisture trends. This comparison allows us

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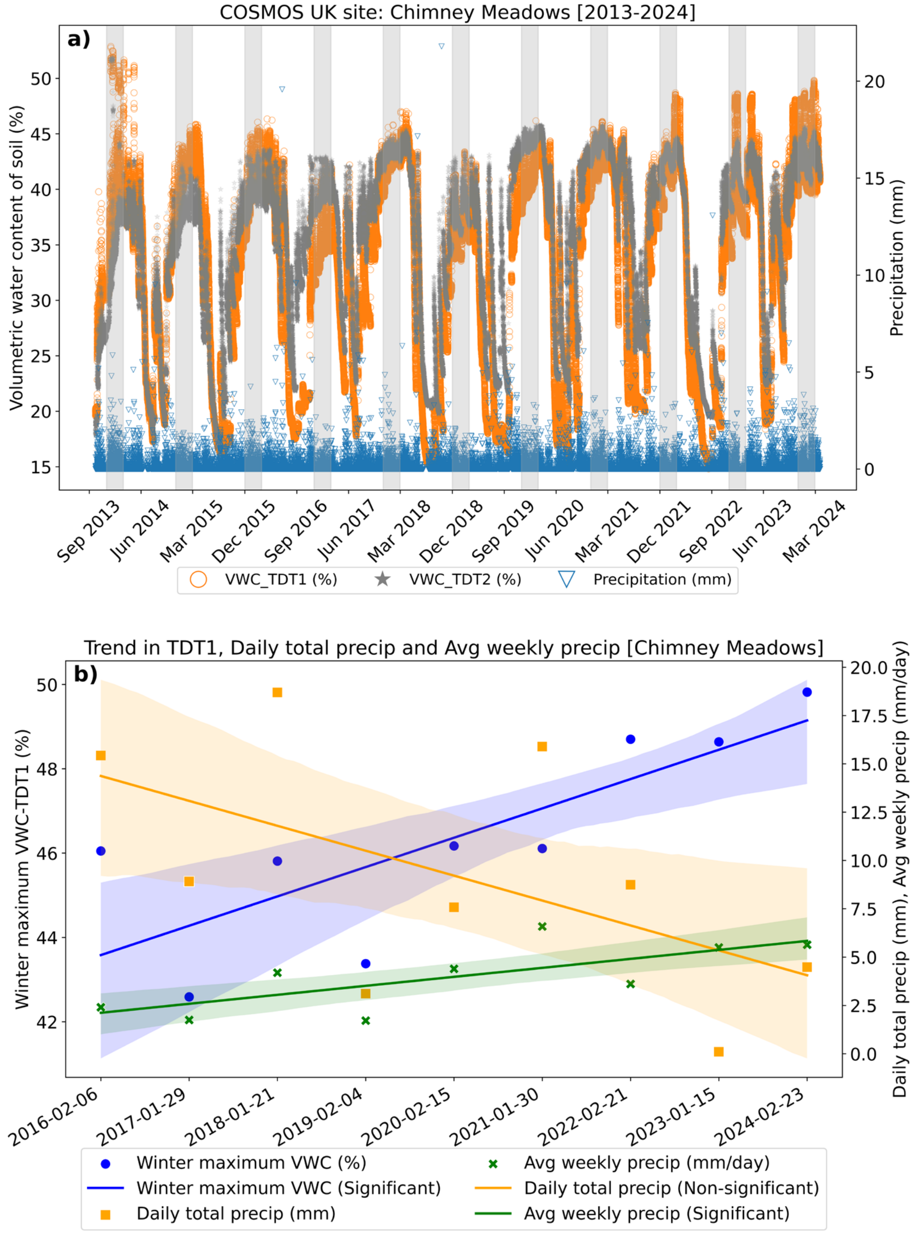
to isolate the effects of the RAPs implemented at ASSIST_EH by contrasting its soil moisture dynamics with those of the traditional agricultural practice site ASSIST_EC.

3 Results and discussions

3.1 Trend analysis

3.1.1 COSMOS-UK sites



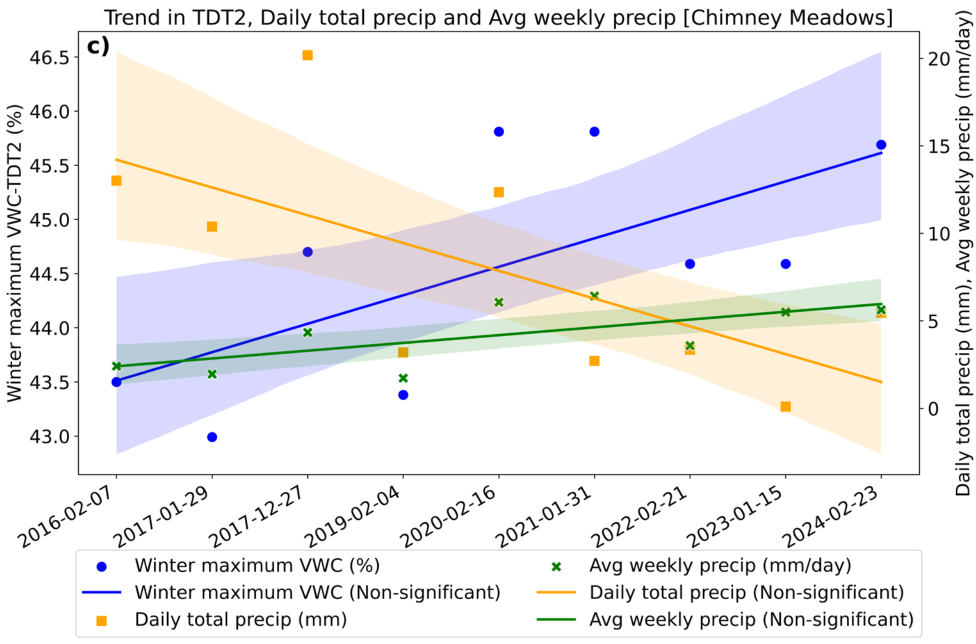


Fig. 2. (a) Soil moisture from Time Domain Transmissivity (TDT) probes-TDT1 and TDT2, along with precipitation measured at 30-minute intervals at Chimney Meadows, COSMOS-UK site (b) Results of the MK Trend Test at a 90% significance level for TDT1, and c) same as b but for TDT2. Vertical shadings in (a) indicate Winter months (DJF); the anticipated annual peak in soil moisture during winter seasons is evident. It can also be inferred that near-surface soil moisture capacity has increased by ~4% in 11 years. Panel (b) and (c) shows a strong correlation between weekly antecedent rainfall and maximum soil moisture.

Analysis of the COSMOS-UK TDT data revealed consistent increasing trends in winter maximum soil moisture across multiple sites, with variations in the magnitude of increase. At Chimney Meadows and Waddesdon (figures not included because of space limitations and, they are similar to Chimney Meadows), significant increases in soil moisture capacity of approximately 4% and 4.5% respectively were observed over the decade-long study period (2013-2024). Alice Holt (figures not included because of space limitations), characterised by broadleaf woodland, showed the most substantial increase, with winter maximum soil moisture rising by 7%.

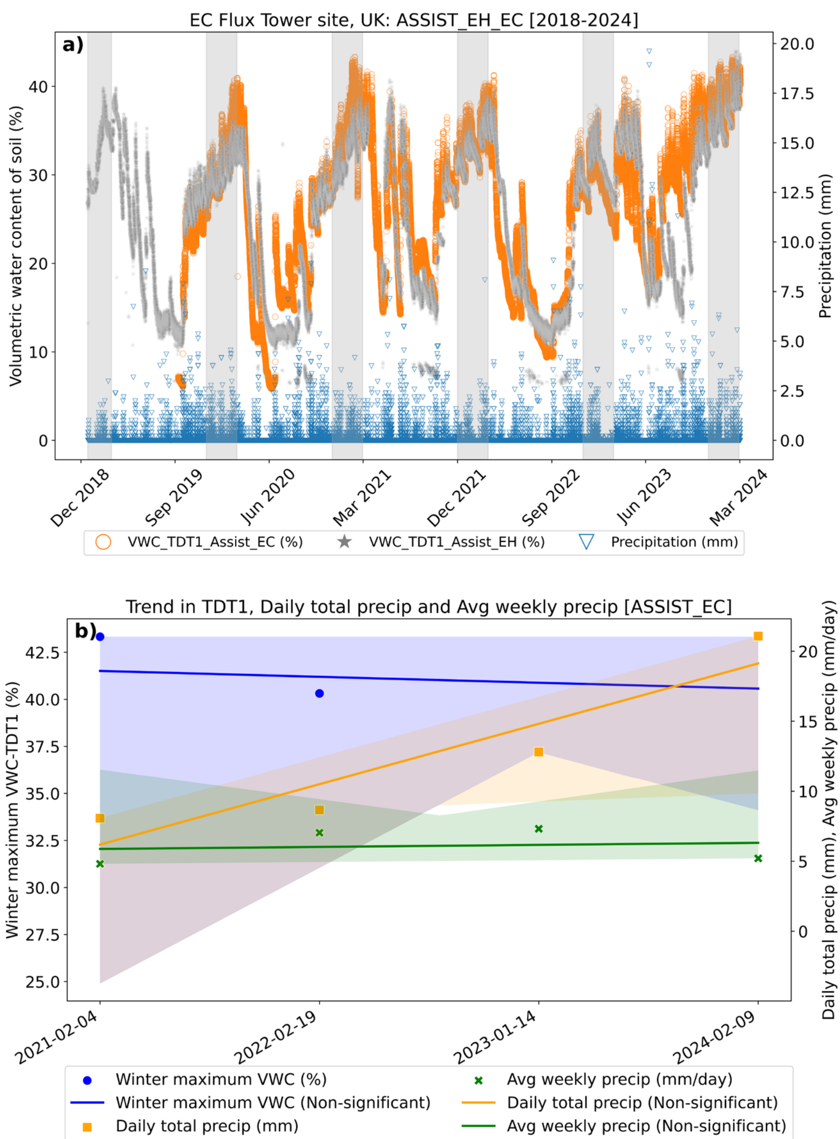
It's crucial to note that these COSMOS-UK sites were fenced off when sensors were installed in 2013, effectively excluding vehicular traffic, agricultural practices, and stock grazing. Since then, vegetation within these enclosures has grown relatively naturally, with only occasional trimming for site access, essentially creating small-scale re-wilding scenarios [9].

The observed improvement in soil water retention capacity under these conditions aligns with the theory that undisturbed soil tends to increase its water holding capacity over time. This process is often associated with the accumulation of organic matter, improved soil structure, and enhanced biological activity [10, 11]. The consistent trends at both agricultural sites, with their transition from managed and grazed to lightly managed and ungrazed grassland, highlight the potential for passive restoration approaches to improve soil hydrological functioning.

The higher increase observed at Alice Holt compared to the transitioned agricultural sites underscores the likely sensitivity of woodland soils to compaction (due to their high soil organic matter content and wider range of soil pore sizes due to macrofaunal and root processes) and resultant lower starting soil water retention capacity. It suggests that woodland soils may have a greater potential for further enhancing their water retention properties [12, 13].

These findings have important implications for land management strategies aimed at improving soil hydrological functioning. They highlight the value of both conserving existing high-organic matter soils (such as woodlands) and implementing practices that reduce trafficking, increase organic matter and improve structure in agricultural soils. Furthermore, the results from Chimney Meadows and Waddesdon demonstrate the potential benefits of reducing disturbance and allowing natural vegetation growth, even in previously intensively managed agricultural lands [14].

3.1.2 Paired UK greenhouse gases flux network sites



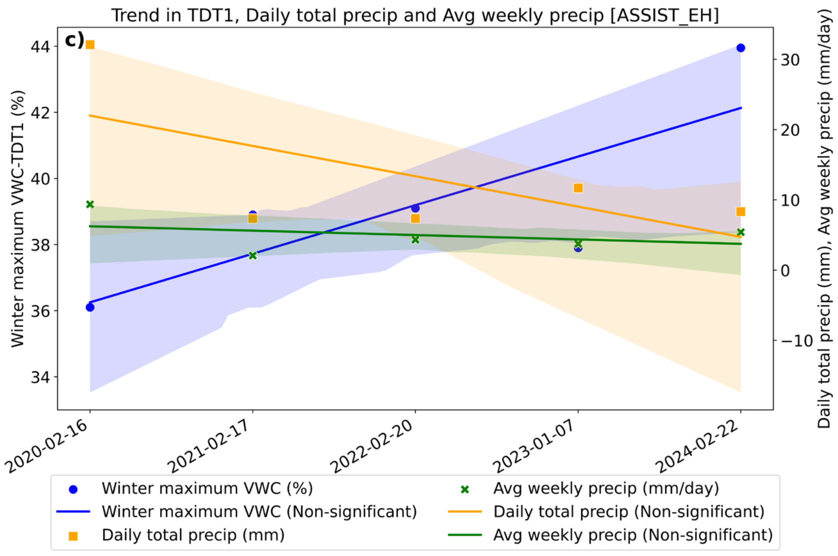


Fig. 3. (a) Soil moisture from Assist_EC and Assist_EH, along with precipitation measured at 30-minute intervals (b) Results of the MK Trend Test at a 90% significance level for Assist_EC (c). Same as (b) but for Assist_EH. Vertical shadings in (a) indicate Winter months (DJF); the anticipated annual peak in soil moisture during winter seasons is evident. It is noteworthy that although antecedent precipitations have decreasing trend in Assist_EH (Panel c), winter maximum soil moisture have an increasing trend. However, antecedent rainfall condition in Assist_EC has an increasing trend, but the winter maximum soil moisture has a decreasing trend.

Analysis of the paired sites from the UK Greenhouse Gases Flux Network (ASSIST_EH and ASSIST_EC) revealed contrasting trends in soil moisture dynamics. At ASSIST_EH, where RAPs were implemented, including cover cropping, we observed a significant increasing trend in winter maximum soil moisture over the study period (2018-2023), despite a decreasing trend in antecedent precipitation. In contrast, ASSIST_EC, which maintained traditional agricultural practices, exhibited a slight decreasing trend in winter maximum soil moisture, even with an increasing trend in antecedent rainfall [15].

The stark difference between these sites suggests that the implementation of RAPs, particularly cover cropping, has positively impacted the soil's water retention capacity. This finding aligns with previous research, which has shown that land with cover crops is less susceptible to compaction during extreme rainfall events and less prone to cracking during dry periods, creating a network of pores that enhance water retention capacity [16, 17].

The ability of ASSIST_EH to maintain higher soil moisture levels even with less rainfall underscores the potential of RAPs in enhancing soil water retention capacity. It suggests that practices such as cover cropping and reduced tillage may be effectively countering the impacts of reduced rainfall by improving the soil's ability to capture and retain available water.

Moreover, these findings emphasise that the quantity of rainfall alone does not determine soil moisture levels. Instead, the soil's capacity to absorb and retain water, heavily influenced by management practices, might play a crucial role. This has important implications for agricultural resilience in the face of changing precipitation patterns due to climate change [18].

4 Conclusions

This study demonstrates the potential of long-term soil moisture monitoring in revealing changes in soil hydrological functioning. Our findings from both the COSMOS-UK sites and the paired UK Greenhouse Gases Flux Network sites provide evidence for the positive impact of reduced disturbance and RAPs on soil water retention capacity.

At COSMOS-UK sites, continuous improvement in soil water retention over 11 years of minimal disturbance highlights the potential for soil recovery when agricultural land is allowed to regenerate naturally. The more pronounced improvement at Alice Holt underscores the high potential to enhance soil water retention capacity in some woodland soils.

The clear difference observed between the RAP-treated (ASSIST_EH) and traditionally managed (ASSIST_EC) sites reinforces the effectiveness of practices such as cover cropping in enhancing soil water retention capacity, even when precipitation trends was decreasing.

However, it's important to acknowledge some limitations of this study. Firstly, our focus on soil moisture measurements at 10 cm depth using TDT probes, while providing valuable near-surface data, may not fully represent changes occurring in deeper soil layers crucial for long-term water storage and drought resilience. Secondly, the lack of control for confounding variables such as changes in local climate patterns or variations in vegetation cover limits our ability to isolate management effects from other potential influences on soil moisture trends. Lastly, while we used winter maximum soil moisture as a proxy for soil porosity, direct measurements of soil physical properties over time would provide more robust evidence of changes in soil structure.

Our future research plan aims to address these limitations by incorporating soil moisture measurements at multiple depths and expanding the spatial scale to include a wider range of soil types and climatic conditions. We plan to employ wavelet analysis to identify periodic patterns and dominant frequencies in soil moisture time series, potentially revealing how different processes contribute to overall soil moisture variability. This approach, along with wavelet coherence analysis between soil moisture and precipitation data, will help elucidate the relationship between rainfall patterns and soil moisture dynamics under different management practices.

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References

1. R. Lal, “Restoring Soil Quality to Mitigate Soil Degradation,” *Sustainability*, **vol. 7**, no. 5, pp. 5875–5895, May (2015). doi: 10.3390/su7055875.
2. R. Khangura, D. Ferris, C. Wagg, and J. Bowyer, “Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health,” *Sustainability*, **vol. 15**, no. 3, p. 2338, Jan. (2023). doi: 10.3390/su15032338.

3. L. Schreefel, R. P. O. Schulte, I. J. M. de Boer, A. P. Schrijver, and H. H. E. van Zanten, “Regenerative agriculture – the soil is the base,” *Glob Food Sec*, **vol. 26**, p. 100404, Sep. (2020). doi: 10.1016/j.gfs.2020.100404.
4. E. K. Bünemann *et al.*, “Soil quality – A critical review,” *Soil Biol Biochem*, **vol. 120**, pp. 105–125, May (2018). doi: 10.1016/j.soilbio.2018.01.030.
5. P. C. Baveye, J. Baveye, and J. Gowdy, “Soil ‘Ecosystem’ Services and Natural Capital: Critical Appraisal of Research on Uncertain Ground,” *Front Environ Sci*, **vol. 4**, no. JUN, Jun. (2016). doi: 10.3389/fenvs.2016.00041.
6. H. M. Cooper *et al.*, “COSMOS-UK: National soil moisture and hydrometeorology data for environmental science research,” *Earth Syst Sci Data*, **vol. 13**, no. 4, (2021). doi: 10.5194/essd-13-1737-2021.
7. UK Greenhouse Gases Flux Network, “Soil moisture data,” (2024). *Wallingford*.
8. Md. Hussain and I. Mahmud, “pyMannKendall: a python package for non parametric Mann Kendall family of trend tests.,” *J Open Source Softw*, **vol. 4**, no. 39, (2019). doi: 10.21105/joss.01556.
9. G. L. Harvey and A. J. Henshaw, “Rewilding and the water cycle,” *Wiley Interdisciplinary Reviews: Water*, **vol. 10**, no. 6, (2023). doi: 10.1002/wat2.1686.
10. J. Six, H. Bossuyt, S. Degryze, and K. Denef, “A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics,” (2004). doi: 10.1016/j.still.2004.03.008.
11. L. Wang, P. B. M. Pedersen, and J.-C. Svenning, “Rewilding abandoned farmland has greater sustainability benefits than afforestation,” *npj Biodiversity*, **vol. 2**, no. 1, (2023). doi: 10.1038/s44185-022-00009-9.
12. R. Lal, “Forest soils and carbon sequestration,” *For Ecol Manage*, **vol. 220**, no. 1–3, (2005). doi: 10.1016/j.foreco.2005.08.015.
13. T. G. Huntington, “Soil: Organic Matter and Available Water Capacity,” in Landscape and Land Capacity, **vol. 49**, no. 2, Second edition. | Boca Raton: CRC Press, [2020] | Revised edition of: Encyclopedia of natural resources. [2014].: CRC Press, (2020), pp. 273–281. doi: 10.1201/9780429445552-36.-36.
14. S. G. Baer, D. J. Kitchen, J. M. Blair, and C. W. Rice, “Changes in ecosystem structure and function along a chronosequence of restored grasslands,” *Ecological Applications*, **vol. 12**, no. 6, (2002). doi: 10.1890/1051-0761(2002)012[1688:CIESAF]2.0.CO;2.
15. C. M. Pittelkow *et al.*, “Productivity limits and potentials of the principles of conservation agriculture,” *Nature*, **vol. 517**, no. 7534, (2015). doi: 10.1038/nature13809.
16. H. Blanco-Canqui *et al.*, “Cover crops and ecosystem services: Insights from studies in temperate soils,” *Agron J*, **vol. 107**, no. 6, (2015). doi: 10.2134/agronj15.0086.
17. A. D. Basche *et al.*, “Soil water improvements with the long-term use of a winter rye cover crop,” *Agric Water Manag*, **vol. 172**, (2016). doi: 10.1016/j.agwat.2016.04.006.
18. R. Lal, “Regenerative agriculture for food and climate,” (2020). doi: 10.2489/jswc.2020.0620A.