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Effects of moss restoration on topsoil water dynamics in a temperate vineyard

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Abstract. Climate change is intensifying pressure on vineyard soil and water management, particularly under-vine, where vegetation is commonly suppressed to minimize competition with grapevines. Bryophytes represent a promising but little-tested alternative to bare soil or cover crops. We evaluated moss restoration as an under-vine ground cover in a temperate, rainfed vineyard in southwestern Germany, comparing it with bare soil and cover crop (grass) over a 22-month field experiment. Continuous topsoil moisture measurements using time-domain transmission sensors were used to analyse the initial response time (the time between the onset of precipitation and the first increase in topsoil moisture) and the peak response time (the time between the onset of precipitation and the maximum topsoil moisture). We additionally quantified mean topsoil moisture and drying rates and monitored treatment development during and after maintenance.

Moss restoration did not significantly delay topsoil moisture response times following precipitation compared to grass or bare soil. Initial response times followed the pattern grass > moss > bare soil; differences between treatments were most pronounced under light and moderate precipitation and declined with increasing intensity, with moss and bare soil converging under heavy events. Peak response times followed a similar pattern (grass > moss ≈ bare soil), with significant differences restricted to light and heavy precipitation events: grass exhibited longer peak response times than bare soil under light rainfall and longer times than both bare soil and moss under heavy rainfall. Mean topsoil moisture did not differ significantly among treatments, whereas drying rates were higher under moss and bare soil than under grass. Moss plots initially suppressed grass establishment and consistently exhibited the lowest variability in topsoil moisture response, although vegetation cover and functional differences between treatments gradually converged after maintenance ceased.

Overall, moss restoration maintained topsoil moisture dynamics comparable to bare soil while avoiding the delayed infiltration and higher variability associated with grass cover. These results suggest that mosses may provide a low-maintenance under-vine ground cover with stable hydrological functioning, warranting further investigation into their long-term persistence and performance under future climate and management scenarios.

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1 Introduction

Climate change is profoundly affecting viticulture worldwide. Most wine-producing regions now face shifts in phenology, declining yields and quality, and increasing vulnerability to pests, diseases, and extreme weather events (Mirás-Avalos and Araujo, 2021; van Leeuwen et al., 2024). Among these challenges, water scarcity has emerged as a central constraint (van Leeuwen et al., 2019), with water availability projected to decrease in many regions of the world (IPCC, 2021). The severity of this threat was illustrated during July 2022, when Europe experienced one of its most intense drought–heat episodes on record: precipitation in vineyards dropped by 46.5% and topsoil moisture by 29.8%, affecting nearly one-fifth of European vineyards (Straffelini et al., 2023). With such extremes projected to increase in frequency, water availability represents a critical bottleneck for the future of viticulture (Diago, 2023).

Conventional vineyard management often relies on mechanical tillage between rows and herbicide application beneath the vines to suppress vegetation and minimize competition for nutrients or avoid the spread of diseases (Celette et al., 2005; Steenwerth and Belina, 2010; Dittrich et al., 2021). While this approach can help maintain vine productivity, it affects runoff and topsoil water fluxes potentially also increasing soil evaporation and reducing infiltration, which might intensify water stress (Biddoccu et al., 2016).

To counter these negative effects, regenerative management strategies have been developed for both between-row and under-vine zones. Between-row approaches, such as allowing spontaneous vegetation to establish or sowing grasses and cover crops (Morvan et al., 2014; Kirchhoff et al., 2017), as well as under-vine practices including mulching (Prosdocimi et al., 2016) or planting aromatic herbs (Dittrich et al., 2021), can enhance soil water retention, reduce runoff, open new possibilities for weed and pathogen control, and improve overall soil health (O'Brien et al., 2025). However, these practices may affect each other on the topsoil, but also influence grape yield in some cases through competition for water and nutrients, depending on local conditions, climate, and species selection (Celette et al., 2005; Ruiz-Colmenero et al., 2011; Dittrich et al., 2021). The extent to which vines are affected is closely linked to root system architecture: vine rooting depth and distribution vary with species, plant age, soil type, and management, and although roots can extend to several metres, the majority are typically concentrated within the upper metre of soil (Smart et al., 2006; Lehnart et al., 2008; Lanari et al. 2025). Taken together, these considerations underscore the need for adaptive, site-specific water management strategies that balance ecological function with sustained vineyard productivity.

Against this backdrop, bryophytes represent a promising but largely underexplored option for under-vine ground cover in vineyards. Their traits offer practical advantages: minimal maintenance requirements, the ability to establish in soils unsuitable for vascular plants, high resilience and persistence under conditions where conventional cover crops often fail (Corbin and Thiet, 2020; Gall et al., 2022). Despite these advantages, their use in viticulture has scarcely been tested. Gall et al. (2025) pioneered this approach by evaluating moss restoration as a tool for erosion control and runoff reduction in temperate

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vineyards, where mosses significantly reduced surface runoff by 71.4% and sediment discharge by 75.8% compared with bare soil.

In parallel, studies from other ecosystems have examined the broader hydrological functions of bryophytes. As poikilohydric organisms, they can absorb and retain substantial amounts of water (Price et al. 1997; Proctor et al., 1998), thereby influencing soil hydrology (Turetsky et al., 2012; Thielen et al., 2021; Gall et al., 2024). But their role in regulating water fluxes remains debated: some studies report reduced evapotranspiration (Thielen et al., 2021; Liu et al., 2022), whereas others suggest enhanced rates (Bu et al., 2015; Fischer et al., 2023). Similarly, mosses have been shown to promote infiltration and increase soil water content (Gypser et al., 2016; Oishi 2018; Sun et al., 2021; Tu et al., 2022), to restrict water movement into deeper layers (Yair et al., 2011; Xiao et al., 2015; Li et al., 2016), or to exert seasonally variable effects (Siwach et al., 2021). These contrasting results highlight the strong context dependence of moss hydrological functions, shaped by community structure, climate, seasonality, and species identity (Belnap, 2006; Bu et al., 2015; Dollery et al., 2022; Tu et al., 2022).

Recent studies have begun to clarify the mechanisms underlying these hydrological effects. Hu et al. (2023) showed that moss layers enhance soil water retention by altering pore structure and promoting organic matter accumulation. Similarly, moss colonization has been found to reduce evaporation and increase soil water storage in karst landscapes (Lulu and Dongdong, 2025). Experimental work by Zeng et al. (2025) further revealed that moss cover increases surface roughness and substantially reduces runoff and erosion, particularly on steeper slopes, thereby enhancing the soil's water-holding capacity.

Consistent with these findings, studies using moss species similar to those applied here reported enhanced topsoil moisture without impeding infiltration (Thielen et al., 2021). Complementary work by Gall et al. (2021, 2022, 2024, 2025) highlighted that mosses improve soil water retention, promote infiltration, and mitigate surface runoff and erosion under both controlled and field conditions. Collectively, these results indicate that, under appropriate environmental conditions, mosses can act as conduits rather than barriers for water movement, underscoring their potential as vineyard ground cover (Gall et al., 2025). Mosses have been successfully cultivated under controlled greenhouse conditions and can be applied, for example, in the form of mats. Initial trials in vineyards demonstrated promising cultivation performance and potential for soil protection and restoration, making mosses a suitable starting point for further ecohydrological and microclimatic studies.

To evaluate whether moss restoration represents a viable under-vine soil surface management strategy, rather than herbicide-induced bare soil or cover crop (grass), several factors must be considered. While the effects on surface runoff and erosion have already been demonstrated by Gall et al. (2025), the influence of moss restoration on vineyard soil water dynamics remains unclear. In rainfed vineyards, it is crucial that water infiltrates rapidly into the soil and that the ground cover does not compete excessively with the vines. We therefore use the initial (IRT) and peak (PRT) response times of topsoil moisture to precipitation as metrics of soil moisture dynamics, and the topsoil drying rate as an indicator of desiccation processes. We hypothesize that:

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(1) Moss restoration does not significantly delay topsoil moisture response times after precipitation events, regardless of rain intensity.

(2) Moss restoration shows a higher mean topsoil moisture due to a slower drying rate compared to bare soil and cover crop (grass).

(3) Differences in topsoil moisture response between moss restoration, grass and bare soil decrease over time once maintenance ceases due to natural succession.

With this experimental study, we aim to provide insight into the effects of moss restoration on soil moisture dynamics in the under-vine area of temperate vineyards.

2 Methodology

2.1 Study site

The study was conducted in a vineyard located on a slope south of Fellbach (48.80158° N, 9.28113° E) in southwestern Germany. The site is managed by the wine cooperative "Fellbacher Weingärtner" and the Lemberger grape variety is cultivated with continuous cover crops between vine rows. The soil is classified as a Mollic Anthrosol. This study builds on data collected concurrently with Gall et al. (2025); a detailed description of the site is provided there.

2.2 Experimental design and treatments

Experimental treatments were established on 17 February 2022 within the vine rows at the study site. Three treatments were applied, each on a surface of 40 cm x 40 cm: moss restoration (moss), bare soil (bare), and cover crops (grass), each replicated four times. The bare treatment was maintained by periodic weeding to keep vegetation cover below ~20%. The grass treatment retained the existing cover crop mixture dominated by the grasses *Lolium perenne* and *Trisetum flavescens*, with occasional occurrences of *Trifolium repens* and *Achillea millefolium* (identified using Jäger and Werner, 2005). The moss treatment involved installing pre-cultivated moss mats (produced by Reinhold Hummel GmbH+Co.KG, Stuttgart, Germany) with five species: *Amblystegium serpens (Hedw.) Schimp., Brachythecium rutabulum (Hedw.) Schimp., Funaria hygrometrica Hedw., Homalothecium lutescens (Hedw.) Robins, Oxyrrhynchium hians (Hedw.) Loeske* on weeded soil surfaces which were initially watered to promote establishment.

2.3 Monitoring of topsoil moisture

For this study, continuous topsoil moisture data was recorded with time-domain-transmission sensors by TMS-4 dataloggers (TOMST, Czech Republic) installed in all plots on 14 April 2022. Each device measures volumetric topsoil moisture to ~14 cm depth and air/soil temperature at three heights (15 cm above ground, 2 cm above ground, and 6 cm below ground; Wild et al.,

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2019). To synchronize measurements and avoid temporal offsets, all dataloggers were installed simultaneously. All TMS-4 measurements were logged in Coordinated Universal Time (UTC). Data were collected over a 22-month period for analysis at 5-minute intervals and cross-checked to ensure data validity and quality. Datalogger calibration was performed using soil parameters specific to the study site, including clay, sand, and loam fractions. Soil characteristics were derived from laboratory analyses reported in Gall et al. (2025), encompassing grain size distribution, soil pH, organic carbon content, and bulk density.

2.4 Monitoring natural succession of treatments

Monitoring the development of the treatments served to document how their conditions changed over time and to identify periods during which they remained functionally distinct. These observations were necessary for subsequent analyses but not part of the hypothesis testing.

The study was structured into distinct periods based on management practices and expected vegetation dynamics:

Maintenance period (April–October 2022): During this period, treatment conditions were actively maintained. Grass was manually removed from moss and bare soil plots using cutting or gentle hand-weeding, while avoiding disturbance of the soil.

First succession period (November 2022–February 2023): Maintenance ceased at the start of November 2022, allowing natural succession to proceed during the winter months, when limited vegetation growth was expected.

Second succession period (March 2023–February 2024): This period encompassed the full growing season and subsequent months, beginning in spring 2023. It allowed evaluation of whether moss treatments could maintain dominance over grasses throughout an entire growing season without intervention.

Target period (September–November 2022): During this three-month transition from maintenance to the first succession phase, moss cover was vigorous and green, mat material fully decomposed, and soil largely bare with minimal grass.

Ground vegetation cover was assessed using the quadrat method, following the approach of Belnap (2001) and as applied by Gall et al. (2022). For each plot, a digital grid of 100 squares was overlaid on a photograph, and each square containing more than 50% vegetation was counted. Importantly, the assessment considered only vegetation emerging directly from the surface within the grid square, rather than overhanging parts such as blades of grass extending from adjacent areas. For moss treatments, total vegetation cover was further distinguished between moss and grass (Table 2). Each vegetated grid square was carefully evaluated using field experience to determine whether moss or grass dominated the area. All values reported as absolute percentages of the total plot area (not relative to each other).

2.5 Meteorological data and precipitation analysis

Meteorological data was obtained from an agricultural weather station (Station Fellbach, data provided by Agrarmeteorologie Baden-Württemberg) located within the vineyard, approximately 10 m from the experimental plots. The station records

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precipitation (mm, 10-min intervals), global solar radiation (Wh m^{-2}), air temperature (2 m above ground), and relative humidity (%), among other variables. While long-term climate analyses usually rely on 30-year datasets, continuous records from the nearby Fellbach station (since 2006) provide an accurate reflection of the local microclimate, supporting interpretation of ecological responses in 2022 and 2023. The records of the reference period (2006–2021) show a mean annual temperature of 11.3 °C and precipitation of 666 mm (Table 1; Agrarmeteorologie Baden-Württemberg, 2025b). The study years 2022 and 2023 were warmer (+1.4–1.6 °C) and drier (−10–13%) than the long-term average, with slightly higher radiation in 2022 (+2%) but lower in 2023 (−9%) (Agrarmeteorologie Baden-Württemberg, 2025a, b).

At the national scale, 2022 and 2023 set new climate records in Germany: according to the German Meteorological Service (DWD, 2022, 2023), 2022 was among the warmest and sunniest years since 1881, characterized by multiple summer heatwaves and droughts, whereas 2023 was the warmest year on record but wetter overall, exceeding average precipitation by more than 20%. At the study site in Fellbach, summer (June–August) 2022 was hot and dry (21.9 °C, 157 mm), while summer 2023 had similar temperatures but substantially higher precipitation (21.3 °C, 211 mm). Winters (December–February) also differed, with 2022/23 being drier and slightly colder (4.6 °C, 62 mm) than 2023/24 (6.1 °C, 114 mm) (Figure 1; Agrarmeteorologie Baden-Württemberg, 2025b). These interannual differences provide essential context for interpreting topsoil moisture and vegetation dynamics observed during the experiment.

Table 1: Comparison of meteorological variables between the reference period (2006–2021) and the study years (2022–2023), showing absolute (Δ abs) and relative differences (Δ%).

Variable	2006–2021	2022	Δ2022 abs	Δ2022%	2023	Δ2023 abs	Δ2023%
Relative Humidity (%)	73,52	72,0	−1,52	−2,1%	73,1	−0,42	−0,6%
Temperature (°C)	11,27	12,7	+1,43	+12,7%	12,9	+1,63	+14,4%
Global Radiation (Wh m^{-2})	1126,52	1148,6	+22,1	+2,0%	1026,5	−100,0	−8,9%
Precipitation (mm a^{-1})	665,5	577,7	−87,8	−13,2%	599,5	−66,0	−9,9%

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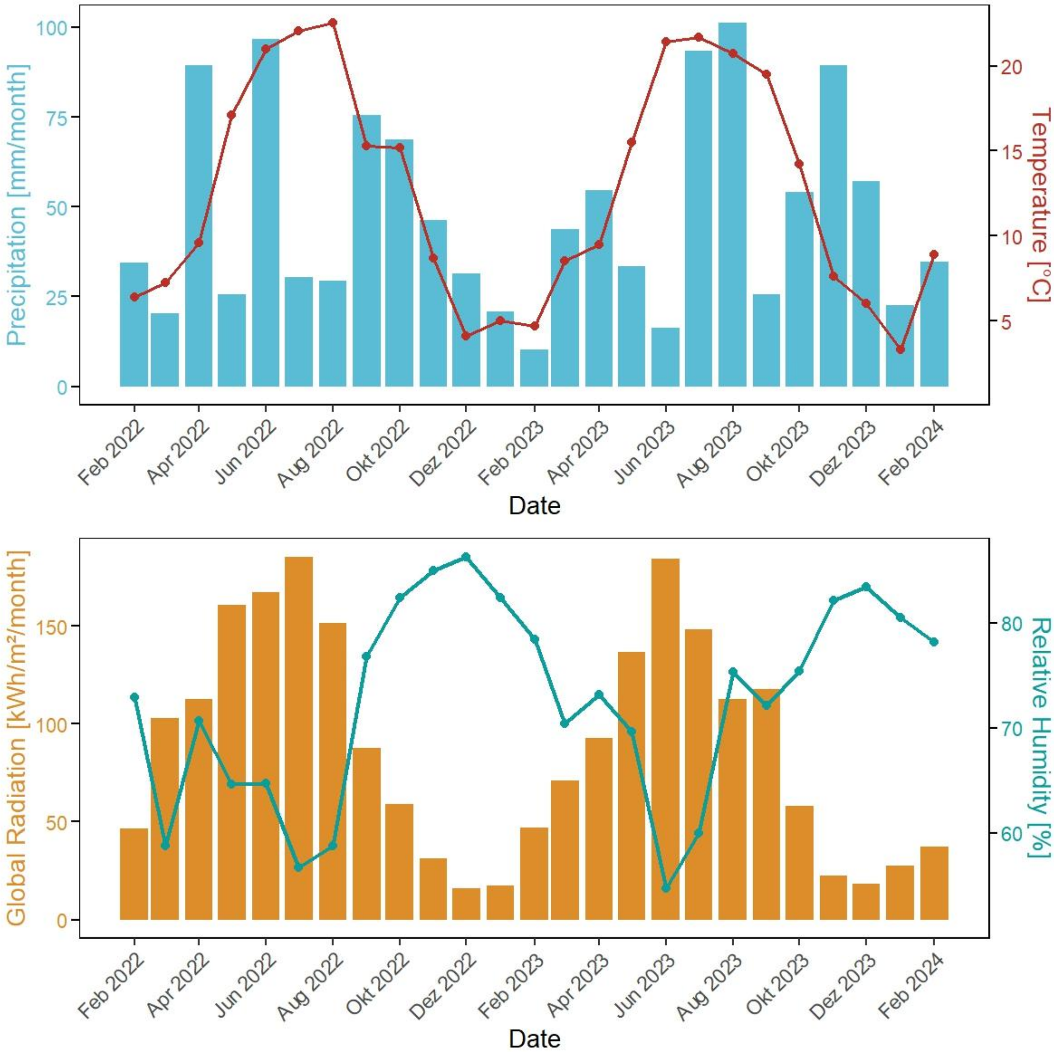

Figure 1: Weather conditions for Fellbach with monthly data from February 2022 till February 2024, showing monthly sum of precipitation (mm), monthly average air temperature (°C), monthly sum of global radiation (kWh m-2), monthly relative air humidity (%).

To characterize precipitation dynamics during the experiment, precipitation data from April 2022 to February 2024 were analysed and classified according to German Meteorological Service (DWD, 2026) intensity thresholds using both 10-min and 60-min precipitation records: violent: ≥ 50 mm h^{-1} and/or ≥ 8.3 mm (10 min^{-1}); heavy: ≥ 10 mm h^{-1} and/or ≥ 1.7 mm (10 min^{-1}); moderate: ≥ 2.5 mm h^{-1} and/or ≥ 0.5 mm (10 min^{-1}); light: below the above thresholds.

A total of 422 precipitation events were identified, comprising 285 light, 101 moderate, 34 heavy, and 2 violent events, their distribution over the study periods is shown in Table 2. Of all events, 313 met both the 10-min and 60-min criteria, while 109

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were classified based on the 10-min threshold only. For each event, duration, peak timing, and mean precipitation rate were calculated. Event durations ranged from < 1 h to > 10 h (median = 1.3 h, mean = 2.7 h), with peak intensities typically occurring within the first hour. Maximum hourly precipitation reached 17.6 mm, and mean event intensities ranged from 0.07 to 10.8 mm h^{-1} (median = 0.43 mm h^{-1}), indicating that short, low-intensity events dominated the study period.

Table 2: Number of precipitation events by event intensity category for each period

	Maintenance Apr–Oct 2022	**First Succession** Nov 2022–Feb 2023	**Second Succession** Mar 2023–Feb 2024	**Target** Sep–Nov 2022
Light	23	20	56	19
Medium	27	14	54	14
Heavy	13	0	19	3
Violent	1	0	1	0
Total	**64**	**34**	**130**	**36**

2.6 Data analysis

All analyses were performed in R version 4.3.1 (R Core Team, 2025). Shapiro–Wilk and Levene's tests were used to assess normality and homoscedasticity. As the data did not meet these assumptions, non-parametric methods were applied where appropriate. Statistical significance was set at $p < 0.05$, and mean values are reported ± standard error. Data visualization was conducted with the R packages ggplot2 (Wickham, 2016) and based on wesanderson (Karthik et al., 2018).

2.6.1 Topsoil moisture response times

As a preliminary step, we assessed how consistently precipitation events triggered measurable topsoil moisture responses by quantifying the proportion of sensors that showed no increase in topsoil moisture ("non-response") across all events between April 2022 and February 2024.

Building on this assessment, we tested whether moss restoration affects topsoil-moisture response dynamics following precipitation events by quantifying two metrics: the initial response time (IRT) and the peak response time (PRT). These metrics are based on established approaches for soil moisture response analysis (Kim, 2009; Singh et al., 2021; da Silva-Dias et al., 2024). The IRT represents the interval between the onset of precipitation and the first non-random increase in topsoil moisture, whereas the PRT denotes the time elapsed from precipitation onset to the subsequent peak topsoil moisture value. For each sensor, a reference topsoil moisture (SM_{ref}) was defined as the median value within the 60 minutes preceding precipitation onset (t_{e_onset}). The initial topsoil moisture response was identified as the first increase exceeding 0.005 m^3 m^{-3} relative to SM_{ref}, occurring during precipitation or within three hours after the event. The threshold of 0.005 m^3 m^{-3} was chosen

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to exceed background fluctuations arising from natural variability or measurement noise. The initial response time (IRT, in minutes) was calculated as:

$$IRT = t_{e,ir} - t_{e,onset}$$

where $t_{e,onset}$ is the time of precipitation onset, and $t_{e,ir}$ is the time of the initial response in topsoil moisture.

IRT values were set to NA if any of the following criteria were met: all six 10-minute measurements of the reference topsoil moisture (SM_{ref}) were missing, the first 30 minutes of the precipitation contained only missing values, or no response above the threshold occurred within the precipitation event and subsequent three-hour period.

Preliminary data inspection revealed that precipitation events with < 2 mm within the first 60 min did not produce a measurable increase in topsoil moisture in that hour. Such "slow-start" events distort initial response time (IRT) and were therefore excluded from the IRT analysis. In addition, precipitation events with an intensity below 0. 5 mm h^{-1} (light drizzle) did not generate detectable topsoil moisture changes and were likewise filtered out prior to analysis. The peak response time (PRT, in minutes) was defined as:

$$PRT = t_{peak} - t_{e,onset}$$

Where t_{peak} is the timestamp of the maximum topsoil moisture observed during the precipitation or within the following 600 minutes, or until the next precipitation event if it occurred sooner.

Precipitation events with intensities below 0.5 mm were excluded from the analysis, consistent with the IRT filtering criteria. However, "slow-start" events were retained, as their influence on PRT is minimal given that the topsoil moisture peak typically occurs after the precipitation maximum. To test the effects of moss restoration on IRT and PRT, linear mixed-effects models (LMMs) were applied. In the base model, treatment was included as a fixed effect and date as a random effect to account for repeated measures. Extended models included precipitation intensity as an additional fixed effect, as well as its interaction with treatment, to assess whether the effect of moss restoration varied with precipitation intensity. Pairwise comparisons were performed using estimated marginal means (emmeans) with Bonferroni correction to adjust for multiple testing.

2.6.2 Daily topsoil moisture and drying rate

To assess whether moss restoration maintains higher topsoil moisture by slowing post-precipitation drying compared to bare soil and grass, daily topsoil moisture (SM) dynamics were analysed and drying rates were calculated. Daily SM values were modelled using a generalized additive mixed model (GAMM) with treatment as a fixed effect and a random intercept for each sensor to account for repeated measurements. Non-linear smooth terms were included for each treatment to capture seasonal and long-term temporal trends across the study period. Data were aggregated to daily means per sensor to reduce temporal autocorrelation and computational demand.

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Drying rates were calculated individually for each replicate over the 24-hour period following the topsoil-moisture peak (from precipitation onset to the SM maximum). If another precipitation occurred within this 24-hour window, the drying rate for that replicate was set to NA. For each event, the median drying rate across the four replicates per treatment was calculated. Only events with valid medians for all treatments were retained, resulting in 135 events. Differences among treatments were assessed using pairwise comparisons following a Kruskal–Wallis test, with significance determined via Dunn's test and Benjamini–Hochberg correction.

2.6.3 Topsoil moisture response under natural succession

To test whether differences in topsoil moisture response among moss restoration, grass, and bare soil diminish over time as natural succession progresses, we analysed changes in vegetation cover and temporal patterns of initial response time (IRT). Temporal dynamics in IRT were visualized using locally weighted regression (LOESS) smooths to capture non-linear seasonal and interannual variation. We used generalized additive models (GAMs) to analyse treatment effects on topsoil moisture response across discrete precipitation events. The models included treatment as a fixed factor and a non-linear smooth of month (numeric) for each treatment, allowing for treatment-specific monthly trends in IRT. Models were fitted using restricted maximum likelihood (REML).

3 Results

3.1 Natural succession of cover treatments

The following observations document the development of treatments and provide context for interpreting subsequent hypothesis-driven analyses.

During the **maintenance period** (April–October 2022), treatments remained functionally stable, with grass plots maintaining full (100%) vegetation cover, bare soil plots exhibiting a mean cover of 7.16%, and moss plots averaging 81.58% cover (Table 3). Moss plots experienced drying during April and June, with parts of the underlying jute fleece still visible and a temporary reduction in moss cover (Figure 2). By the end of the period, only one moss plot contained any grass (4% cover), indicating that, despite seasonal stress, mosses effectively prevented grass establishment.

Despite low temperatures and low global solar radiation during the **first succession period** (November 2022–February 2023; Figure 1), clear signs of colonization by grasses were visible in both moss and bare plots. Between October and December, vegetation cover in bare soil plots increased sharply from a mean of 11.25 % to 57.5 %. Moss plots remained more resistant, with grass cover reaching only 12,25% while mosses still occupied a mean of 61% of the surface (Table 3). Functional differences between treatments were still apparent at this stage.

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Over the 11 months of the **second succession period** (March 2023–February 2024), vegetation cover in bare soil plots increased from 67.5 % to 91.5%, dominated by grass but also encompassing mosses (Figure 2). In moss plots, grass cover expanded from 19.25 % to 45.5%, while moss cover declined from 61.5 % to 29.75 % (Table 3). By this stage, functional differences between treatments had largely disappeared, and vegetation structure in moss and bare plots had converged towards that of the grass treatment. Monitoring was therefore concluded.

The **target period** (September–November 2022) captured the phase in which treatments were functionally most distinct. During this period, moss plots exhibited high vitality, as indicated by their green colouration (Figure 2), while vegetation cover in bare soil plots remained minimal (Table 3), providing optimal conditions for assessing treatment effects.

Table 3: Vegetation cover (in %) for all replicates (Rep.) and treatments (bare, grass, moss) across the study period from February 2022 to February 2024. For moss treatments, total vegetation cover (value outside brackets) is differentiated between moss (first value in brackets) and grass (second value in brackets), where the values indicate the percentage of the total plot area.

			2022		2023	2024
Rep.	**April**	**June**	**October**	**December**	**March**	**February**
			bare			
1	4	6	10	46	65	79
2	3	2	8	47	45	90
3	10	6	20	78	79	97
4	6	4	7	59	81	98
Mean	**5.75**	**4.5**	**11.25**	**57.5**	**67.5**	**91.5**
			grass			
1	100	100	100	100	100	97
2	100	100	100	100	100	90
3	100	100	100	100	100	97
4	100	100	100	100	100	98
Mean	**100**	**100**	**100**	**100**	**100**	**95.5**
			moss			
1	91	81	(78 + 4) 82	71	(77 + 6) 83	(21 + 44) 65
2	83	67	82	(45 + 20) 65	(46 + 33) 79	(38 + 54) 92
3	91	87	94	(86 + 10) 96	(73 + 23) 96	(30 + 46) 76
4	96	60	65	(42 + 19) 61	(50 + 15) 65	(30 + 42) 72
Mean	**90.25**	**73.75**	(79.75 + 1) **80.75**	(61 + 12.25) **73.25**	(61,5 + 19.25) **80.75**	(29,75 + 45.5) **75.5**

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Figure 2: Example of the cover treatment development over the study period (April 2022–February 2024). Photos show replicate number 3 of bare, grass and moss treatments.

3.2 Topsoil moisture response times

Topsoil-moisture responsiveness varied strongly with precipitation intensity and surface treatment. Non-response rates declined markedly with increasing precipitation intensity across all treatments. During light precipitation, non-response was most frequent under grass (36.7%), compared with bare soil (11.1%) and moss (11.1%). Under moderate precipitation, non-response occurred in 19.5% of grass sensors, 5.9% of bare soil sensors, and 6.8% of moss sensors. Heavy precipitation further reduced non-response to 14.1% in grass, 0.9% in bare soil, and 0% in moss. During violent precipitation events, non-response was observed only in grass (12.5%), while both bare soil and moss exhibited complete responses (0%). Pairwise contrasts of estimated response probabilities from the binomial GLMM confirmed that grass differed significantly from both moss ($p < 0.0001$) and bare soil ($p < 0.0001$), whereas moss and bare soil did not differ significantly ($p = 0.10$).

Initial response time (IRT) differed significantly among treatments across the full dataset (Figure 3), following the pattern grass > moss > bare soil, with grass showing the longest IRT, moss intermediate, and bare soil the shortest (grass vs. moss $p < 0.0001$; grass vs. bare soil $p < 0.0001$; moss vs. bare soil $p = 0.253$). When analysed by period, significant treatment effects were detected during the maintenance period (Apr–Oct 2022) between bare soil and grass ($p = 0.022$) and between grass and moss ($p = 0.048$). In the first succession period (Nov 2022–Feb 2023), grass again exhibited longer IRT than both moss and bare soil ($p < 0.0001$ for both), with moss also exceeding bare soil ($p = 0.044$). During the second succession period (Mar 2023–Feb 2024), grass maintained significantly higher IRT than moss and bare soil ($p < 0.0001$ for both), while moss and bare

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soil did not differ (p = 1). In the target period (Sep–Nov 2022), grass again exceeded both moss and bare soil (p < 0.0001 for both), with no significant difference between moss and bare soil (p = 1).

IRT generally declined with increasing precipitation intensity, with light events producing the slowest responses, followed by moderate and heavy events. This pattern was most pronounced during the maintenance period, when all event categories were present. IRT during light events was significantly longer than during heavy events (p = 0.0002), and moderate events also responded more slowly than heavy ones (p = 0.01). In the first succession period, only light and moderate events occurred, and their IRTs did not differ significantly (p = 0.162). During the second succession period, when all event categories were recorded, IRTs were significantly longer during moderate events than during heavy events (p = 0.005). In the target period, when light, moderate, and heavy events occurred, light precipitation events again showed significantly slower responses than moderate ones (p = 0.009). Differences involving violent events were not significant in any period, likely due to their low frequency (Table 2).

The difference between grass and moss or bare soil was most pronounced under light and moderate events (all p < 0.001), and remains significant, but less strong, under heavy events (grass > bare p = 0.0022; grass > moss p = 0.0004). The IRT of moss and bare soil converged with increasing intensity but never differed significantly (light: p = 0363, moderate p = 0.592, heavy p =1).

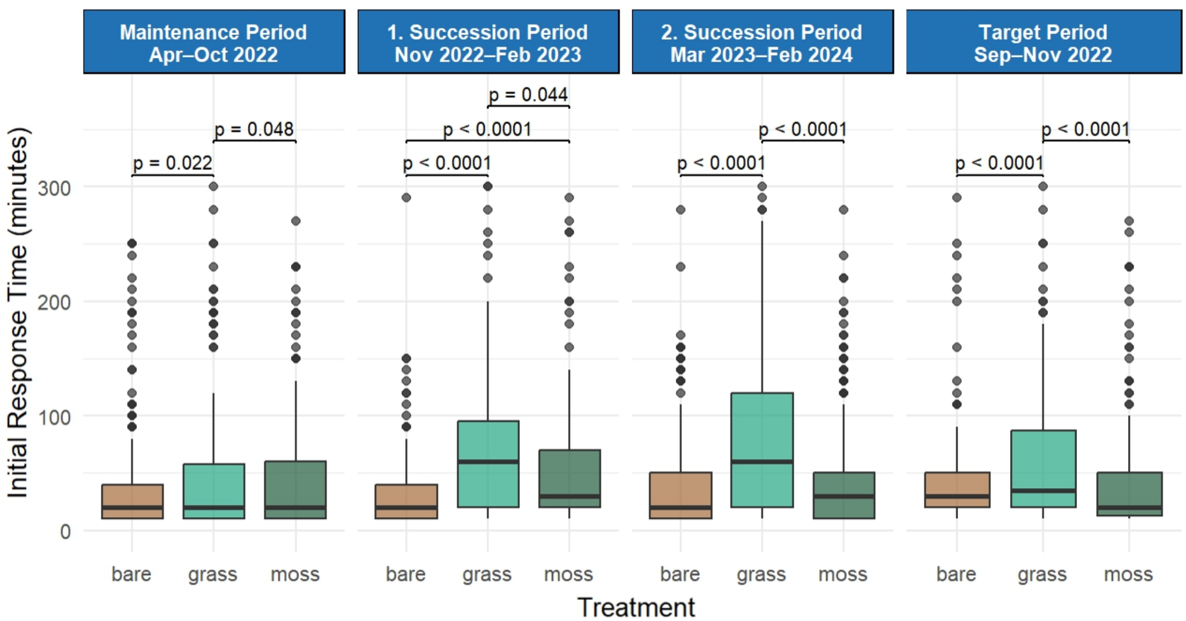

Figure 3: Initial response time (IRT) by treatment and period during the study. Results are from a linear mixed model (LMM) with treatment as fixed effect and date as random effect. Boxplots display the median (central line), interquartile range (boxes), and 1.5× IQR whiskers; outliers beyond this range are shown as individual points. Values above 300 were excluded from the figure for visualization purposes but were retained in all statistical analyses. Significant pairwise differences based on emmeans with Bonferroni fitting are indicated in the figure.

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Peak response time (PRT) differed among treatments across the full dataset regardless of precipitation intensity (Figure 4). Grass reached peak topsoil moisture significantly faster than bare soil (p = 0.0005) and moss (p < 0.0001), whereas moss and bare do not differ significantly. When analysed by defined periods, treatment differences were only evident during the second succession period. In this period, grass exhibited significantly faster PRT than bare soil (p = 0.0001) and moss (p < 0.0001), while moss and bare soil again did not differ significantly.

PRT generally varied with precipitation intensity, though temporal patterns were less consistent than for IRT. Over the entire study period, light and moderate events showed the longest PRTs, with no significant difference between them, and both were significantly longer than heavy events (light > heavy, p = 0.0002; moderate > heavy, p < 0.0001). Violent events had the shortest PRTs, but observed differences to light (p = 0.0036) and moderate (p = 0.0014) events should be interpreted cautiously due to low number of events (Table 2). During the maintenance period, moderate events had the longest PRT of all intensity categories. It was significantly longer than under light (p < 0.0001) and heavy events (p < 0.0001). Other pairwise comparisons were not significant. During the first succession period, light events had significantly longer PRT than moderate events (p < 0.0001). During the second succession period, there was no significant difference between the PRT of light and moderate events. Light events had longer PRT than heavy (p = 0.008) and violent events (p = 0.002), while moderate events had longer PRT than heavy (p = 0.027) and violent events (p = 0.0064). During the target period, the PRT of moderate events was again significantly longer than that of light and heavy events (both p < 0.0001), the latter two were no different from each other.

Differences between treatments within precipitation event categories were only found under light and heavy events. During light events, grass showed significantly longer PRT than bare soil (p = 0.0049) and moss (p = 0.007), whereas bare and moss did not differ significantly (p = 1). During moderate events, no significant differences between treatments were observed (all p > 0.1). For heavy events, grass again had the longest PRT, differing significantly from moss (p < 0.0001) and bare soil (p = 0.0032), while moss and bare soil remained similar (p = 1). No significant differences between treatments were detected during violent events, likely reflecting the limited number of violent events recorded (n = 2).

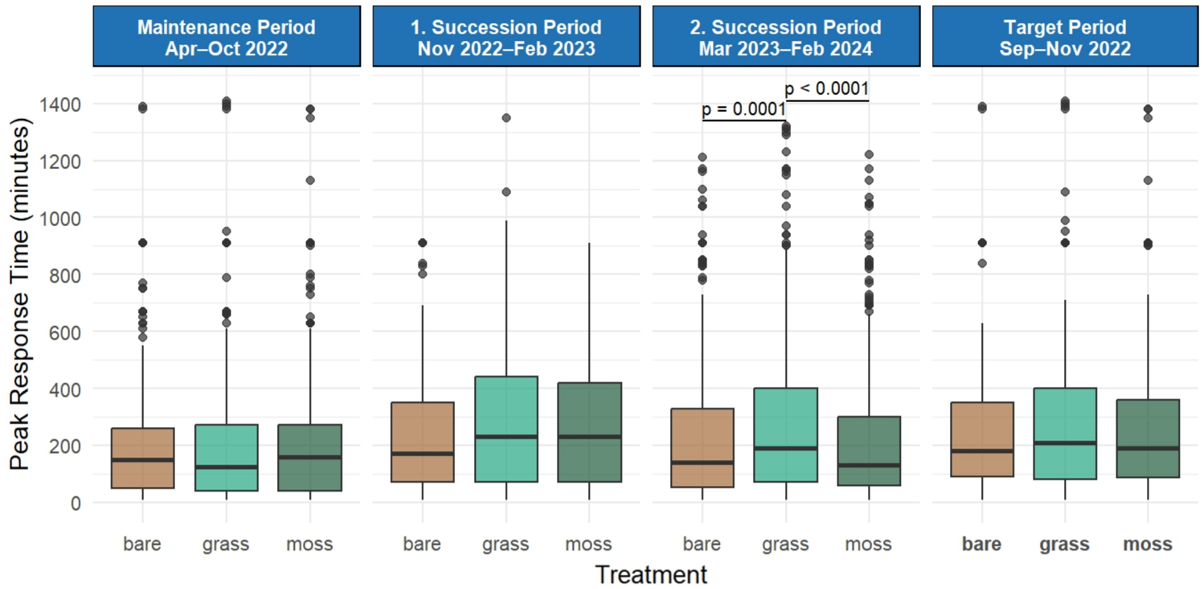

Figure 4: Peak response time (PRT) by treatment and period during the study. Results are from a linear mixed model (LMM) with treatment as fixed effect and date as random effect. Boxplots display the median (central line), interquartile range (boxes), and 1.5× IQR whiskers; outliers beyond this range are shown as individual points. Values above 1400 were excluded from the figure for visualization purposes but were retained in all statistical analyses. Significant pairwise differences based on emmeans with Bonferroni fitting are indicated.

3.3 Mean topsoil moisture and drying rate

To assess whether moss restoration maintains higher topsoil moisture through slower drying compared to bare soil and grass, we analysed topsoil moisture dynamics across the three treatments, focusing on both mean moisture and drying rates. Topsoil moisture exhibited strong seasonal patterns, with lower values in summer and higher values in autumn and winter, and pronounced non-linear temporal variation across all treatments (Figure 5). GAMM results indicated no significant differences between treatments over the full study period from April 2022 to February 2024 (all $p > 0.1$). Using bare soil as a reference, significant differences were observed only during the maintenance period (April–October 2022), when grass plots had slightly lower topsoil moisture than bare soil ($p = 0.03$). Although not statistically significant, the trend continues in the second succession period (March 2023–February 2024), with bare soil maintaining the highest mean soil moisture (Figure 6).

Across all periods, between-sensor variability was consistently significant (random effect, $p < 2 \times 10^{-16}$), indicating systematic differences among measurement locations, while the GAMM models explained 84–92 % of the deviance. Overall, temporal variation and seasonal trends had a much stronger influence on topsoil moisture than treatment effects, and differences between treatments were relatively minor.

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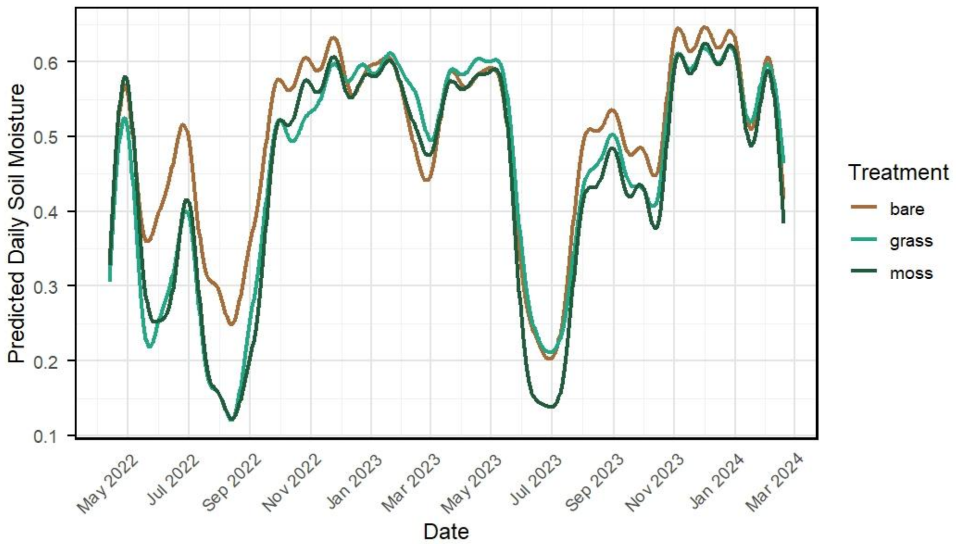

Figure 5: Predicted daily mean volumetric soil moisture over study period (April 2022 – Feb 2024) for each treatment (bare, grass, moss), estimated from a generalized additive mixed model (GAMM). Random effects of individual sensors were excluded in the visualization to show population-level trends.

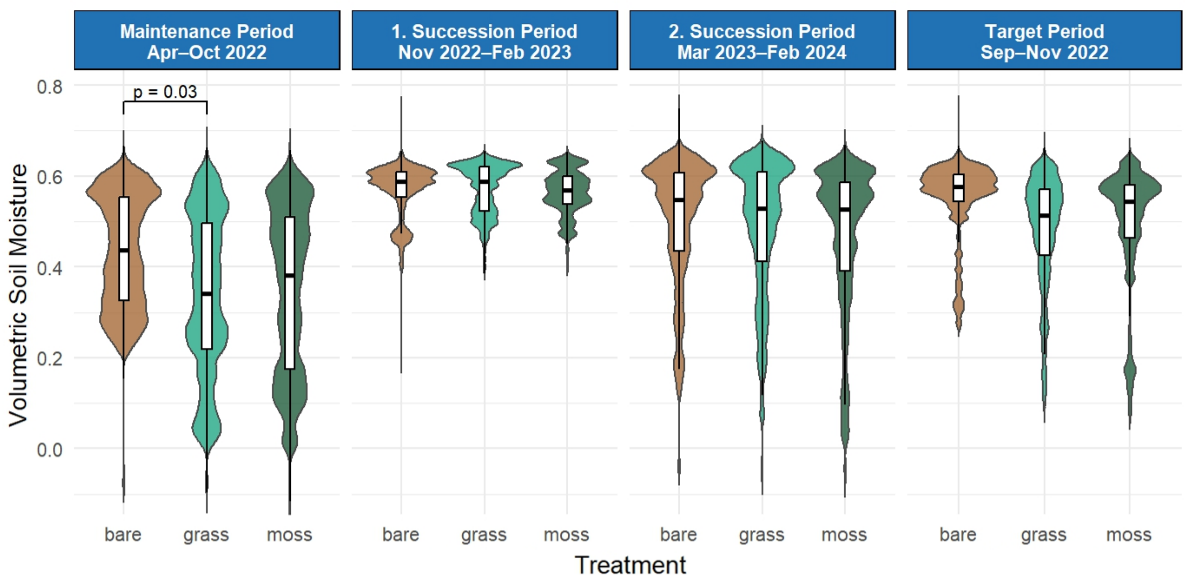

Figure 6: Volumetric topsoil moisture of the three treatments across four periods: maintenance (April–October 2022), first succession (November 2022–February 2023), second succession (March 2023–February 2024), and target period (September–November 2022. Significant differences between treatments derived from a generalized additive mixed model (GAMM), are indicated with p-values for selected pairwise comparisons.

To test whether moss slows topsoil drying compared to bare soil and grass, drying rates were calculated over 24 h following the topsoil moisture peak. Pairwise comparisons of median 24 h drying rates (Figure 7) revealed significant differences among

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treatments, following the pattern moss ≈ bare > grass. Drying rates were higher in moss than in grass ($p < 0.0001$) and higher in bare soil than in grass ($p = 0.0009$), while drying rates did not differ significantly between bare soil and moss ($p = 1$).

When extended to a 72-h drying window, the overall pattern (moss ≈ bare > grass) persisted, but differences were no longer statistically significant. The reduced number of events with a full 72-h drying period (65 events) likely limited statistical power compared to the 24-h analysis (135 events).

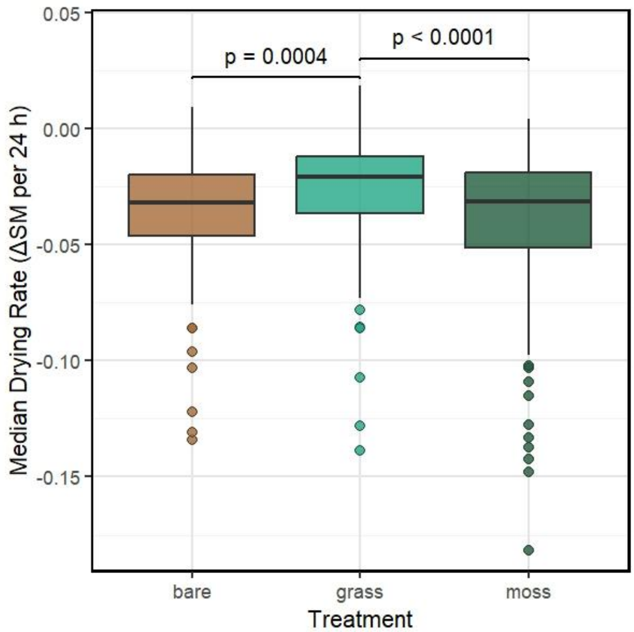

Figure 7: Median 24 h topsoil moisture drying rates by treatment across the study. Boxplots show the median (central line), interquartile range (boxes), and 1.5× IQR whiskers; outliers beyond this range are shown as individual points. Only events with valid data for all treatments (135 events) are included. Significant pairwise differences were assessed using Kruskal–Wallis followed by Dunn's tests with Benjamini–Hochberg correction; p-values are indicated in the figure.

3.4 Topsoil moisture response under natural succession

The generalized additive model (GAM) revealed strong nonlinear seasonal patterns in initial response time (IRT), which differed among treatments and aligned with the LOESS visualization (Figure 8). Across the full dataset, grass showed the longest overall IRT, while bare soil and moss responded faster (parametric terms: grass > moss > bare, all $p < 0.0001$). Temporal variability of IRT was most pronounced in grass $p < 0.0001$), followed by moss ($p < 0.009$), while bare soil exhibited weaker but still significant seasonal fluctuations ($p = 0.017$). Overall, the model explained about 11% of the variation in IRT, suggesting that treatment and seasonality together contributed modest but significant effects to the timing of topsoil moisture responses.

The most pronounced difference occurred between grass and bare soil, emerging in September 2022 (p = 0.004) and remaining highly significant from October 2022 to December 2023 (p < 0.0001), before gradually declining in early 2024 (January p = 0.0008; February p = 0.0453). The grass–moss contrast followed a similar pattern, becoming significant in September 2022 and persisting until January 2024 (September 2022 – December 2023 p = 0.0009, January (p = 0.0018). Differences between bare and moss were limited, occurring only in December 2022 (p = 0.035) and January 2023 (p = 0.0317). It should be noted that data from April 2022 and February 2024 represent only partial months, resulting in a reduced number of observations.

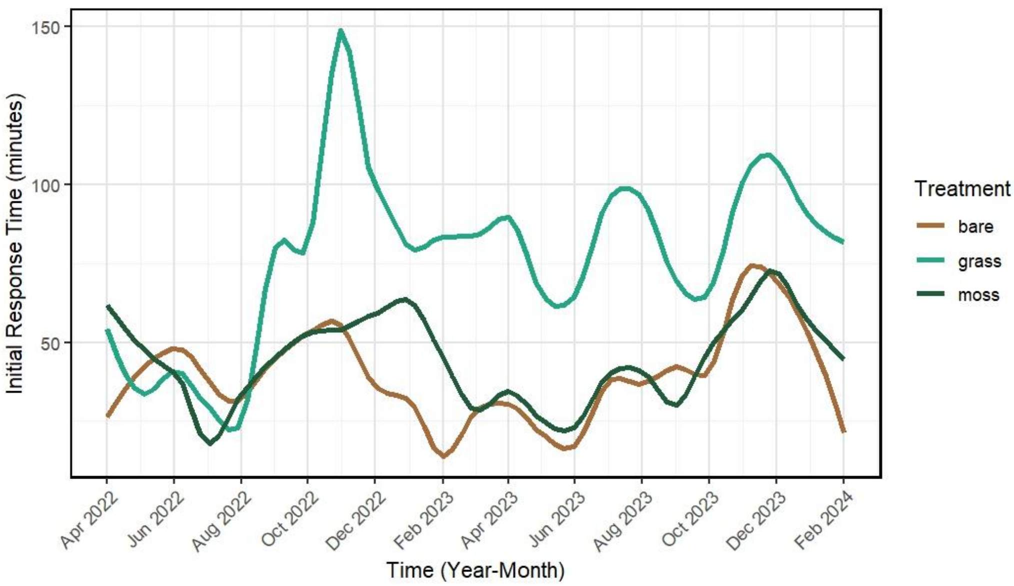

Figure 8: Monthly initial topsoil moisture response time (IRT) for the three treatments (bare, grass, and moss) over the study period (14 April 2022 – 20 February 2024). Lines represent locally weighted regression (LOESS) smooths (span = 0.2) of the mean IRT per month.

Variability in IRT remained low and similar among treatments during the early study period but diverged in later periods. Across the maintenance period (April–October 2022), variability did not differ among treatments (Levene's p = 0.424). In the first succession period (November 2022–February 2023), grass exhibited greater dispersion than moss and bare soil, with variance differences reaching significance (p = 0.020). Variability further diverged during the second succession period (March 2023–February 2024), with significant differences among treatments (p < 0.001) and grass showing the highest variance. In the target period (September–November 2022), differences in variability were also significant (p = 0.017), primarily driven by the higher dispersion under grass. These temporal patterns suggest that the heterogeneity of IRT increased over time, particularly under grass cover.

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4 Discussion

4.1 Natural succession of cover treatments

Discussing the natural succession of treatments provides essential context for interpreting topsoil moisture responses.

Grass establishment in bare-soil plots resumed rapidly after maintenance ceased, likely reflecting favourable late-autumn conditions, including mild temperatures and high humidity, as well as reduced disturbance following the harvest. Similar growth responses of *Lolium perenne*, the dominant species in our grass treatment, under moist and mild conditions have been reported by Celette et al. (2008), although primarily for spring growth.

Moss plots initially suppressed grass colonization, consistent with findings summarized by Qu et al. (2023), who reported that mosses can inhibit seed germination and early seedling establishment. Grass gradually expanded over subsequent months, while moss cover declined; however, mosses persisted for over a year, highlighting their ability to maintain dominance under limited disturbance. These dynamics indicate that mosses can delay grass colonization during early succession but are ultimately outcompeted over time.

Seasonal and environmental conditions further shaped these patterns. Mosses remained green and vigorous throughout winter, likely supported by persistently high relative humidity, moderate temperatures and limited solar radiation exposure, which reduce desiccation stress (Figure 1 and 2). This underscores the importance of moisture availability and microclimatic buffering for moss persistence under field conditions.

By the end of the experiment, functional differences between all treatments had largely converged, with bare-soil plots recolonized by grasses and moss plots containing a mixed cover. This convergence demonstrates that moss restoration can persist for extended periods but may require occasional interventions, such as selective grass removal or seasonal trimming, to maintain long-term dominance and achieve desired under-vine management outcomes.

4.2 Topsoil moisture response times

Our results support the hypothesis that moss restoration does not significantly delay topsoil moisture response times after precipitation events. While grass cover slowed both initial and peak response times, moss treatments showed only minor delays compared to bare soil, indicating that moss did not impede infiltration under the conditions of this study.

To analyse response times accurately, it was necessary to exclude non-response events. Such thresholds are common: Silva-Dias et al. (2024) reported topsoil moisture responses only above 1.2 mm h^{-1}, whereas in our study the threshold was much lower (< 0.5 mm h^{-1}). This highlights the importance of determining site-specific thresholds in future studies to ensure meaningful interpretation of topsoil moisture dynamics.

Initial response times (IRT) differed consistently among treatments, indicating that vegetation structure modulates the onset of infiltration. This supports our hypothesis that moss restoration does not significantly delay topsoil moisture response, even though vegetation cover per se can slow infiltration. Similar observations under high-intensity precipitation have been reported in experimental studies, where mosses did not act as a barrier to infiltration (Li et al., 2016; Thielen et al., 2021). The delayed response under grass likely reflects an interception effect, where dense vegetation prevents precipitation from reaching the soil surface, thereby delaying infiltration (Bodner et al., 2008; Huang et al. 2023; Silva-Dias et al., 2024).

At the same time, the influence of moss on infiltration is context dependent. Previous work has demonstrated that infiltration responses reflect not only surface cover but also underlying soil structure, with well-developed, stable topsoil horizons promoting rapid infiltration irrespective of vegetation type (Leonard and Andrieux, 1998). Reviews of biocrusts further emphasize that moss-dominated surfaces can either enhance or inhibit infiltration depending on coverage, thickness, and developmental stage, with early or less dense crusts generally facilitating water entry (Ya et al., 2025). In the present study, the moss was applied as cushion-like mats rather than compact crusts, which may partly explain the absence of infiltration delays observed here. Experimental and modelling studies confirm this complexity, identifying crust thickness, organic matter content, and biocrust maturity as key controls, with infiltration rates often declining as moss-dominated crusts become more developed (Yang et al., 2025; Zhao et al., 2025).

Precipitation intensity further modulated IRT across treatments, with faster responses under higher intensities, consistent with threshold-like infiltration behaviour. Similar intensity-dependent effects have been reported for biocrusts, where moss-dominated surfaces can enhance infiltration during prolonged, low-intensity precipitation but reduce it during short, high-intensity events (Ju et al., 2024). More generally, precipitation characteristics often outweigh vegetation effects in controlling soil moisture response, particularly under variable antecedent conditions (Zhang et al., 2022). Together, these findings indicate that while moss restoration does not delay initial topsoil moisture response under the conditions studied here, its hydrological role is contingent on both precipitation and plant development.

Peak response times (PRT) were generally longest under grass, while moss and bare soil exhibited similarly rapid peaks, further supporting the hypothesis that moss restoration does not substantially delay topsoil moisture responses following precipitation. These differences indicate that vegetation structure influences not only the onset but also the temporal evolution of topsoil moisture dynamics.

The delayed peak observed under grass likely arises from mechanisms similar to those influencing initial response times. Although grass has been shown to reduce surface runoff compared to bare soil (Rodrigo Comino et al., 2016; Duan et al., 2022; Gall et al., 2025) it can also impede infiltration, and its root system plays an important role by increasing the soil porosity and infiltration rates (Duan et al., 2022). Moss restoration has likewise been shown to reduce surface runoff (Xiao et al., 2015; Tu et al., 2022; Gall et al., 2025), but due to mosses' poikilohydric characteristics and lack of deep rooting systems (Proctor et al., 1998), infiltration processes differ fundamentally from those under grass cover.

PRT generally varied with precipitation intensity, but temporal patterns were less consistent than for IRT, partly due to unexpectedly high estimates for moderate events during the maintenance period. This variability may also reflect the inherent complexity of soil moisture response dynamics, as emphasized by Silva-Dias et al. (2024), who showed that the magnitude and timing of soil moisture responses can represent partly independent processes. To our knowledge, studies explicitly focusing on peak response times in moss-dominated systems are lacking, which limits broader generalization of the observed patterns.

Across both IRT and PRT, our ability to assess extreme precipitation is limited because only two violent events occurred during the study. This is an inherent constraint of field experiments relying on natural precipitation. Targeted precipitation simulations could help determine whether extreme storms override vegetation effects or amplify differences between treatments.

4.3 Mean topsoil moisture and drying rate

Results show that moss restoration does not increase topsoil moisture through slower drying and our second hypothesis was thus rejected. Mean topsoil moisture did not differ significantly among treatments, except during the maintenance period, when grass plots exhibited slightly lower values than bare soil. Although not significant, this pattern re-emerged during the second succession period (March 2023–February 2024).

Although bare soil lacks protective cover and would therefore be expected to dry more rapidly, the absence of vascular vegetation and associated plant water uptake may counterbalance enhanced evaporative losses, resulting in higher mean topsoil moisture. This interpretation is consistent with findings by Capri et al. (2023), who showed that grasses generally exhibit the highest daily water uptake due to evapotranspiration, but that mowing can substantially reduce water use, in some cases to levels below those of bare soil. Similarly, Monteiro and Lopes (2007) observed higher topsoil moisture in tilled vineyard soils compared to plots with resident vegetation or sown cover crops, which they attributed to reduced transpiration and interception losses. Together, these results highlight that vegetation effects on topsoil moisture reflect a balance between surface protection and plant water uptake rather than vegetation cover alone.

Comparisons with other studies show that the hydrological role of mosses is highly site-dependent, influenced by soil structure and climate. Hu et al. (2023) found that in alpine forest soils, bare surfaces retained more moisture than moss cover in the upper 0–10 cm, whereas moss increased retention at 10–30 cm depth, raising the question of whether the higher surface moisture in our bare plots might invert at greater depths. In contrast, Lulu and Dongdong (2025) reported that in karst soils, moss establishment reduced surface evaporation by 48–72% and increased water storage by 11–22%, partly through surface sealing within the top 5 cm.

Drying rates followed the pattern moss ≈ bare > grass. Contrary to our expectations, grass did not exhibit the fastest drying despite its active root system; instead, moss and bare soil dried more rapidly. This pattern suggests that grass primarily accesses water from deeper soil layers beyond the 14 cm measurement depth, while its dense vegetation cover reduces direct soil evaporation. This interpretation is consistent with findings by Liu et al. (2020), who identified root length density at 5–30 cm depth and root surface area at 10–20 cm depth as key factors influencing infiltration rates, indicating that root effects on soil hydraulic processes are strongly depth-dependent. Similar depth-dependent root activity has been observed in vineyards by Celette et al. (2008), who reported that a perennial cover including *Lolium perenne*, the dominant species in our cover crop (grass), concentrates most of its roots within the upper 0.5 m but can extend down to 1 m. This rooting strategy enables efficient water uptake from deeper layers while simultaneously limiting near-surface drying through shading and reduced evaporation.

In contrast, the higher drying rates observed under moss and bare soil indicate a stronger coupling between the soil surface and the atmosphere. Rice et al. (2018) showed that moss layers are thermally structured, with cooler shoot tips creating vertical temperature gradients. Moreover, coupling with the atmosphere is strong when mosses are wet but weak when dry, and the structural characteristics have a greater influence on these dynamics than species identity. The size and surface roughness of moss cushions may create a threshold beyond which further increases in roughness either enhance or restrict water loss, with the leaf area-to-volume ratio reflecting the balance between evaporative surface and water storage capacity (Rice and Schneider, 2004). In our study, this suggests a high fluctuation in water storage within the moss treatments over time, as mosses were visibly dry in early 2022 (April and June; see 3.2), yet topsoil moisture beneath moss remained similar to that under grass and lower than bare soil. Controlled laboratory experiments could help disentangle the specific mechanisms by which moss traits, such as structure, roughness, and vitality, affect topsoil moisture, independent of other environmental factors.

In parallel, interactions between ground vegetation and grapevine root systems further complicate soil moisture dynamics. Although grapevines generally develop deeper root systems, grasses can still compete for water in superficial soil layers (Smart et al., 2006; Lehnart et al., 2008; Lanari et al., 2025). Grass cover has been shown to reduce vine root density near the surface while promoting deeper rooting, resulting in vertical root stratification that may partially alleviate competition in upper soil horizons (Lanari et al., 2025). However, because grapevines access water across all soil compartments, competition for shallow soil moisture can still be substantial (Celette et al., 2008). These interactions are likely to become most critical during drought periods or at sites with limited deep soil water reserves, underscoring the need to integrate both above- and below-ground processes when evaluating vegetation-mediated soil moisture regulation in vineyards.

4.4 Topsoil moisture response under natural succession

The hypothesis that differences in topsoil moisture response between moss restoration, grass, and bare soil diminish over time after maintenance ended is only partially supported. While vegetation cover clearly converged, as discussed in 4.1, topsoil moisture dynamics tell a more nuanced story, with treatment-specific responses persisting in certain periods.

Monthly comparisons of initial response time (IRT) showed that significant treatment differences only emerged after September 2022. At first, this may seem counterintuitive, since all treatments were actively maintained from April to October 2022, and the strongest contrasts might have been expected during this period. However, as detailed in Gall et al. (2025), moss establishment progressed more slowly than anticipated due to unusually hot and dry conditions during summer 2022, which delayed jute mat disintegration and hindered moss development.

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The delayed divergence of IRT between bare soil and grass prior to September remains unclear, as both were expected to be fully established from the outset. Bare soil plots were prepared through careful weeding and cutting of existing vegetation, suggesting that residual grass roots might have persisted. However, all treatments were installed two months before the start of the experiment to minimize such legacy effects. While a longer establishment period might have further reduced residual influences, this alone does not fully explain the absence of early-season differences. A more likely factor is the hot and dry weather (see 2.1), which generated high evaporative demand and may have masked treatment-specific topsoil moisture responses. Seasonal variation in vineyard soil moisture is also strongly influenced by vine phenology: Monteiro & Lopes (2007) reported that soil moisture declines sharply from budbreak to harvest due to increasing vine water uptake. This pattern aligns with our volumetric topsoil moisture data (Figure 7), which declined across all treatments from May to July/August, potentially obscuring early-season differences and explaining why significant treatment effects in response times only appeared after September.

Variability in topsoil moisture response revealed a clear pattern: moss plots consistently exhibited the lowest dispersion in IRT throughout the study, reflected in narrow standard deviations and interquartile ranges. In contrast, grass plots displayed higher variability, reaching significance during the first succession period (November 2022–February 2023) and remaining elevated thereafter. This likely reflects seasonal fluctuations in grass root water uptake driven by growth dynamics, mowing, and environmental conditions (Capri et al., 2023; Celette et al., 2008), whereas mosses, being poikilohydric and lacking true roots, maintain more consistent water absorption and release via rhizoids (Proctor et al., 1998). For vineyard management, this suggests that moss restoration not only imposes minimal infiltration barriers but also promotes more stable and predictable soil moisture dynamics, highlighting its potential as a reliable under-vine ground cover.

To summarize, vegetation cover clearly converged, and by February 2024, bare soil and moss treatments no longer exhibited their distinct characteristics, justifying the termination of the experiment. However, topsoil moisture responses only began to show signs of hydrological convergence toward the end of the study. Extending the experiment by several months could have clarified whether these differences would have continued to diminish, providing a more definitive test of the hypothesis and offering deeper insight into the temporal dynamics of vegetation-mediated topsoil moisture under natural succession.

5 Conclusion

This study evaluated moss restoration as an under-vine soil management strategy in a temperate vineyard, focusing on soil moisture dynamics, drying behaviour, and vegetation succession.

1. Moss restoration did not significantly delay initial or peak topsoil moisture response times following precipitation. Across the full dataset, IRT followed the pattern grass > moss > bare soil and generally declined with increasing precipitation intensity. Peak response times showed a similar trend (grass > bare ≈ moss), though the influence of precipitation intensity was less consistent.

2. Mean topsoil moisture did not differ significantly among treatments, with a tendency toward slightly higher moisture in bare soil plots. Drying rates followed the pattern moss ≈ bare > grass, indicating that moss and bare surfaces were more strongly coupled to atmospheric evaporative demand than grass-covered soils.
3. Moss plots initially suppressed grass establishment more effectively than bare soil, but this advantage diminished during the second growing season. Vegetation cover indicated progressive convergence of treatments, bare soil plots reached over 90% coverage by the end of the study, yet convergence in topsoil moisture response dynamics had only begun to emerge, reflecting a temporal lag between vegetation development and hydrological effects.

Overall, moss restoration did not impede infiltration and maintained topsoil moisture dynamics comparable to bare soil, while simultaneously providing continuous soil cover and reducing the need for chemical or mechanical weed control. This combination highlights its potential as a low-maintenance and ecologically compatible under-vine management option.

Future research could focus on optimizing moss restoration strategies for vineyard conditions. The species mix used in this study comprised taxa from diverse habitats, ranging from shaded forests to open grasslands (Atherton et al., 2010; Nebel et al., 2000). While moderately tolerant to desiccation, these species are not among the most drought-resistant bryophytes (Proctor et al., 2007). Incorporating more stress-tolerant species (Proctor et al., 2007; Li et al., 2024) could enhance persistence under the increasingly frequent temperature and moisture extremes expected with climate change. Species selection, however, must remain aligned with local ecological and soil conditions to ensure successful establishment. The jute-mat approach proved viable but may not represent the most efficient installation technique. Refining substrate selection and maintaining the structural integrity of moss fragments could improve establishment success, promote soil aggregation, and accelerate canopy development (Doherty et al., 2020). Finally, future work should explore adaptive management measures, such as temporary irrigation, shading, or microhabitat selection, to buffer newly restored mosses against climatic variability and enhance their functional stability in vineyard ecosystems (Bu et al., 2018; Antoninka et al., 2020; Glime, 2021). With optimized implementation methods, moss restoration could provide a low-maintenance, ecologically compatible under-vine groundcover that reduces herbicide use, protects soil, supports biodiversity, and promotes sustainable vineyard management.

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Statements and Declarations

Competing interests. The contact author has declared that none of the authors has any competing interests.

Code availability. The codes used in this study are available on figshare: https://doi.org/10.6084/m9.figshare.31439944

Data availability. The dataset compiled and analysed in this study is available on figshare: https://doi.org/10.6084/m9.figshare.31438390

Author contribution. CG, StS and MN designed the experiment. SO, CG, and StS carried out field measurements. SO conducted data analyses and prepared the manuscript with contributions from all other co-authors.

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