Effects of moss restoration on surface runoff and initial soil erosion ~~and soil water content~~ in a temperate vineyard

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Abstract.

Soil erosion threatens soil fertility and food security worldwide, with agriculture being both a cause and a victim. Vineyards are particularly at risk due to the often steep slopes, and detrimental management practices such as fallow interlines and bare soil under the vines. ~~Soil erosion is a serious problem worldwide, as it jeopardizes soil fertility and thus food security. At the same time, agriculture itself is one of the biggest drivers of soil erosion, and vineyards in particular are vulnerable due to often steep slopes, fragile soils, and management practices.~~ Therefore, the search for alternative management practices becomes vital, and vegetation covers, including mosses, have the potential to reduce soil erosion. ~~. Since soil erosion is reduced by vegetation cover, this also applies to moss cover.~~ However, research on moss ~~the~~ restoration ~~and protection of bare soil using mosses~~ as erosion control is still in its infancy, and has never been applied in vineyards. It is thus unclear whether moss restoration can be implemented in vineyards. In this study, the restoration of mosses was investigated by applying artificially cultivated moss mats in a temperate vineyard. The effects of moss restoration on surface runoff and sediment discharge were examined compared to bare soil and cover crops using rainfall simulation~~s~~ experiments (45 mm h^{-1} for 30 minutes) with small-scale runoff plots at three measurement times during one year (April, June, and October). ~~Additionally, soil water content was monitored for each treatment during all rainfall simulations.~~

Mosses initially showed considerable desiccation in summer, whereupon their growth declined. In October, the mosses recovered and re-established themselves in the vineyard, showing a high level of resistance. Moss restoration significantly reduced surface runoff by 71.4% and sediment discharge by 75.8% compared to bare soils. While moss restoration ~~had~~ reduced~~a slightly~~ surface~~better effect on reducing~~ runoff slightly more, and ~~a slightly lower effect on reducing erosion~~sediment discharge slightly less ~~than~~ compared to cover crops (68.1% and 87.7%, respectively), these differences were not statistically significant. Sediment discharge varied seasonally for moss restoration, especially from April to June, which is most likely due to the decline in moss cover and the foliage of the vines in June, as concentrated canopy drip points have formed on the leaves and woody surfaces of the vines, increasing erosion. ~~In April and June, the different treatments do not significantly impact soil water content, while in October, bare soil had the highest and moss restoration the lowest soil water content. According to this, the influence of soil cover varies seasonally, with moss restoration not having a detrimental effect on the soil water content in~~

~~the drier summer months, but retaining the least water in October.~~ Overall, moss restoration proved to be an appropriate and low-maintenance alternative for erosion control, as it requires no mowing or application of herbicides. However, future research should address challenges such as preventing moss mats from drying out in summer, developing methods for large-scale application, and evaluating whether mosses significantly impact soil water content, potentially reducing water availability for vines. ~~and does not reduce near-surface soil water content during summer.~~

1 Introduction

Soil erosion poses a serious threat to global soil fertility and, consequently, to food security (Amundson et al., 2015). As one of the primary drivers of this issue, agricultural activities exacerbate soil degradation (Borrelli et al., 2017), thus resulting in soils that ~~are no longer able to~~can no longer provide important ecosystem services such as filtering and storing water, providing nutrients, storing carbon, providing habitat for biological activity, and producing biomass (Vogel et al., 2019; FAO and ITPS, 2015). With progression of land use changes and climate change, soil erosion will intensify in the future, which requires the rapid development of effective soil conservation strategies (Olsson et al., 2019; Borrelli et al., 2020).

Vineyards are particularly susceptible to soil erosion due to their typically steep slopes, fragile soils characterized by an extremely basic or acidic pH, loamy or clayey textures, and low soil organic carbon ~~(SOC)~~ contents as well as specific management practices such as fallow interlines (Rodrigo-Comino, 2018; Prosdocimi et al., 2016a; Rodrigo Comino et al., 2016). For instance, conventional farming in vineyards usually involves practices to control weed by ~~means of~~ application of herbicides and tillage that leave the soil bare (Biddoccu et al., 2016), which is the most relevant anthropogenic factor for increased soil erosion in viticulture (Rodrigo-Comino et al., 2018; Rodrigo Comino et al., 2015). As a result of soil erosion in viticulture, the grape yield can decrease by up to 50% according to Costantini et al. (2018), who conducted a multidisciplinary study in nineteen European and Turkish vineyards. In addition, this study emphasizes that soil erosion has degraded essential parameters of soil fertility such as available water capacity, chemical fertility, total nitrogen, and cation exchange capacity, among others. Given the critical role of vineyards in agriculture and their vulnerability to erosion, it is imperative to explore alternative management practices that can mitigate soil erosion effectively.

Vegetation cover is well-documented as a natural barrier against soil erosion due to its ability to stabilize the soil and reduce surface runoff (Morgan, 2005). In viticulture, organic management practices that cover the soil surface with vegetation are regularly used, which has been proven in several studies to substantially reduce surface runoff and soil erosion (Seeger et al., 2019; Kirchhoff et al., 2017; Biddoccu et al., 2017; Bagagiolo et al., 2018). These practices include allowing spontaneous vegetation to grow, seeding grasses and cover crops (Morvan et al., 2014; Kirchhoff et al., 2017), applying mulching techniques (Prosdocimi et al., 2016b), or planting aromatic herbs (Dittrich et al., 2021). In this way, vegetation covers not only prevent soil loss but also preserve soil organic matter (López-Vicente et al., 2020). Additionally, the vegetation cover beneath the vines can positively influence~~s~~ soil fertility~~, for example, it~~ by increasing~~es~~ the ~~SOC~~ soil organic carbon content (Fleishman et al., 2021; Marks et al., 2022), which can improve aggregate structure, though the extent of this effect varies by further soil properties that control the mechanisms of aggregate formation (Bonifacio et al., 2024). These factors in turn reduce soil erodibility, which also supports organic management practices in viticulture.

~~The~~ An argument against organic management practices in vineyards is that the soil-covering vegetation might compete~~s~~ with the vines for water and nutrients (Celette et al., 2009; Dittrich et al., 2021)~~, which can also negatively impact grape yields~~. For example, Celette et al. (2005) found that vine vigour was reduced in a vineyard intercropped with tall fescue grass~~, resulting in a 30% lower grape yield~~ compared to a conventional vineyard using chemical weed control~~. Although the cover crops in~~

this study led to a reduction in available water for the vines, Celette et al. (2005), attributinged this not only to the competition for water competition, but also to competition for other soil resources, such as nutrients, or allelopathy effects. Similarly, Ruiz-Colmenero et al. (2011) demonstrated that permanent vegetation covers that are not mowed can even reduce grape yield by up to 54% (with an average reduction of 40%). The extent of competition likely depends on the climatic conditions of the vineyard location and is probably more pronounced in arid regions than in humid ones, thus Trigo-Córdoba et al. (2015) showed that grape yield and quality in intercropped vineyards even improved compared to a conventional vineyard in humid and sub-humid climates. Regardless of whether through soil erosion or planting vegetation, there is a potential risk that the grape yield will be reduced. Nevertheless, in their review on cover crop management and water conservation in vineyards, Novara et al. (2021) recommended the use of cover crops not only in humid but also in drier areas due to their numerous benefits, such as erosion control, increased organic matter, and improved soil fertility, while emphasizing that in dry areas, the choice of cover crop species and the timing of termination should be adapted to the average rainfall. Therefore, in their review on cover crop management and water conversation in vineyards, Novara et al. (2021) recommended the use of cover crops not only in humid but also in drier areas due to their numerous benefits such as erosion control, increase of organic matter and improvement of soil fertility. In dry areas, however, the choice of cover crop species and the timing of killing crops should depend on the average rainfall (Novara et al., 2021).

An alternative to cover crops to combat soil erosion is a moss cover. As poikilohydric plants, mosses cannot actively regulate their water content, relying instead on ambient water availability (Green and Lange, 1994). Attributed in particular to their numerous capillary spaces, which depend on the respective species and its life form, mosses are capable of absorbing very high amounts of water, over 2000% of their dry weight in some species (Proctor et al., 1998; Wang and Bader, 2018; Thielen et al., 2021). In this way, mosses can act as a runoff sink that delays surface runoff (Rodríguez-Caballero et al., 2012). Various studies have already shown that mosses reduce surface runoff (Tu et al., 2022), Research in forests has shown that mosses reduce soil erosion and surface runoff and also effectively mitigate soil erosion (Gall et al., 2022a; Gall et al., 2024a; Juan et al., 2023). Unlike cover crops, they do not require mowing, thereby reducing maintenance efforts and costs. Furthermore, mosses thrive in conditions where vascular plants struggle, such as low pH soils, steep slopes, or managed soils (Gall et al., 2022b; Corbin and Thiet, 2020). Additionally, sSome studies, have shown demonstrated that they mosses can also enhance infiltration (Gall et al., 2024a), which depends on rainfall intensity and moss species (Tu et al., 2022), and prevent soil evaporation (Thielen et al., 2021; Liu et al., 2022). However, there are also indications of opposite effects; for example, in some cases, mosses have prevented infiltration (Li et al., 2022a), especially with low rainfall intensities (Tu et al., 2022), and have increased soil evaporation (Li et al., 2022a). However, there are also indications of opposite effects; for example, in some cases, mosses have prevented infiltration (Li et al., 2022a), especially with low rainfall intensities (Tu et al., 2022), and have increased soil evaporation (Li et al., 2022a), which could be detrimental to grape yields. Due to their potential beneficial effects on the soil, planting restoring mosses can be a promising new way for sustainable soil management in agricultural settings (Gall et al., 2022b).

However, moss restoration over large areas is demanding and a growing research field. In recent years there have been successful efforts to establish mosses in the field under different environmental conditions (Antoninka et al., 2020). For instance, Bu et al. (2018) conducted a plot experiment (1 × 1 m) in a warm temperate environment in China and achieved a moss cover of 85% using two dispersal methods (broadcast and spray), whereby this maximum cover was already obtained after 30 days with spraying and after 60 days with broadcasting. For this, it was beneficial for moss growth to apply a nutrient solution, maintain the soil water content at 15 to 25%, and provide moderate shade in summer. In comparison, Doherty et al. (2020b) developed a moss-colonized burlap fabric, which was placed in the field for restoration, and was able to establish itself when applied face-down despite drought during the observation period.

In addition, there have also been some encouraging experiments on the application of moss restoration strategies in practice, for example in agriculture (Doherty et al., 2020a), or for post-fire recovery of forests (Grover et al., 2019; Grover et al., 2022), although the moss cover remained small after restoration in all cases. This shows that there are still major challenges in the development of sustainable technologies for moss restoration, which should be the focus of restoration research so that application in practice over large areas becomes possible in the future.

~~Furthermore~~So far, some areas of application, such as viticulture, have not yet been considered for moss restoration, although the approach could be particularly promising for erosion control in vineyards. For example, unlike cover crops, mosses do not require mowing, thereby reducing maintenance efforts and costs. Furthermore, mosses may thrive in conditions where vascular plants struggle, such as low pH soils, steep slopes, or managed soils (Gall et al., 2022b; Corbin and Thiet, 2020). However, the sunny, warm and often dry conditions of vineyards provide an unusual and difficult environment for the establishment of mosses, which is also known from moss restorations studies in drylands (Antoninka et al., 2020). Therefore, it is unclear whether moss restoration will be successful in vineyards. This research gap emphasizes the need for studies focusing on the establishment of moss restoration and the effectiveness of mosses in reducing soil erosion in vineyards.~~This gap in research highlights the necessity for studies focused on the efficacy of mosses in reducing soil erosion, particularly in vineyard environments.~~

This study aims to address this research gap by investigating the restoration of mosses in a temperate vineyard and evaluating their impact on surface runoff, and sediment discharge~~, and soil water content of the topsoil~~. The following two~~hree~~ hypotheses are formulated: (1)

Mosses will begin to establish in the vineyard after being introduced to the field. (2)

Moss restoration reduces surface runoff and sediment discharge compared to cover crops and bare soil.

~~**(1) Moss restoration increases soil water content in the upper 5 mm of the topsoil during rainfall simulations.**~~

With this research we want to contribute to the understanding of mosses as a practicable erosion control measure and provide practical knowledge for the management of vineyards to ~~maintain soil fertility and~~ prevent erosion.

2 Methodology

2.1 Study site

The study took place in a vineyard south of Fellbach, ~~which is situated in s~~Southwest~~ern~~ Germany, approximately 10 km northeast of Stuttgart (Figure 1). The vineyard ~~cultivates~~ produces the Lemberger vine variety ~~Lemberger~~, and the soil between the vines is continuously ~~overgrown~~covered with cover crops such as *Lolium perenne*, *Trifolium repens*, *Trisetum flavescens*, and *Achillea millefolium*. It is located at an altitude of 324 m above sea level at the foot of the Kappelberg (469 m above sea level) with flat slopes of 5° and is part of the Keuperbergland, which consists of Triassic hills stratified by sandstones, marlstones, and claystones (Geyer et al., 2023). ~~According to the geological map (LGRB, 2022), the study site belongs to the Grabfeld Formation, an alternating sequence of sulphate rocks (gypsum and anhydrite) and claystones in the upper Triassic series. A Rigosol as soil type was identified using a drill stick (Pürckhauer),~~A Mollic Anthrosol (Relocatic) was identified as a soil type (IUSS Working Group WRB, 2022), which is typically formed in vineyards by deep ploughing~~, regular digging~~. Mixed samples of the topsoil (0-5 cm) and subsoil (approx. 40 cm) were taken to describe ~~main~~ general soil characteristics (Table 1).~~:~~ ~~Soil texture was medium clayey loam (Sand: 23.17%, Silt: 38.93%, Clay: 37.8%), the pH ($CaCl_2$) was 7.2, soil bulk density was 0.96 g m^{-3}, and SOC was 2.32%.~~ An ~~climate~~ agrometeorological station in the immediate vicinity of the study site (48.80158° N 9.28113° E) revealed~~s~~ an average annual temperature of 11.5 °C between 2007 and 2023, while the average annual precipitation over the same period was 668.3 mm (Agrarmeteorologie Baden-Württemberg, 2024b).

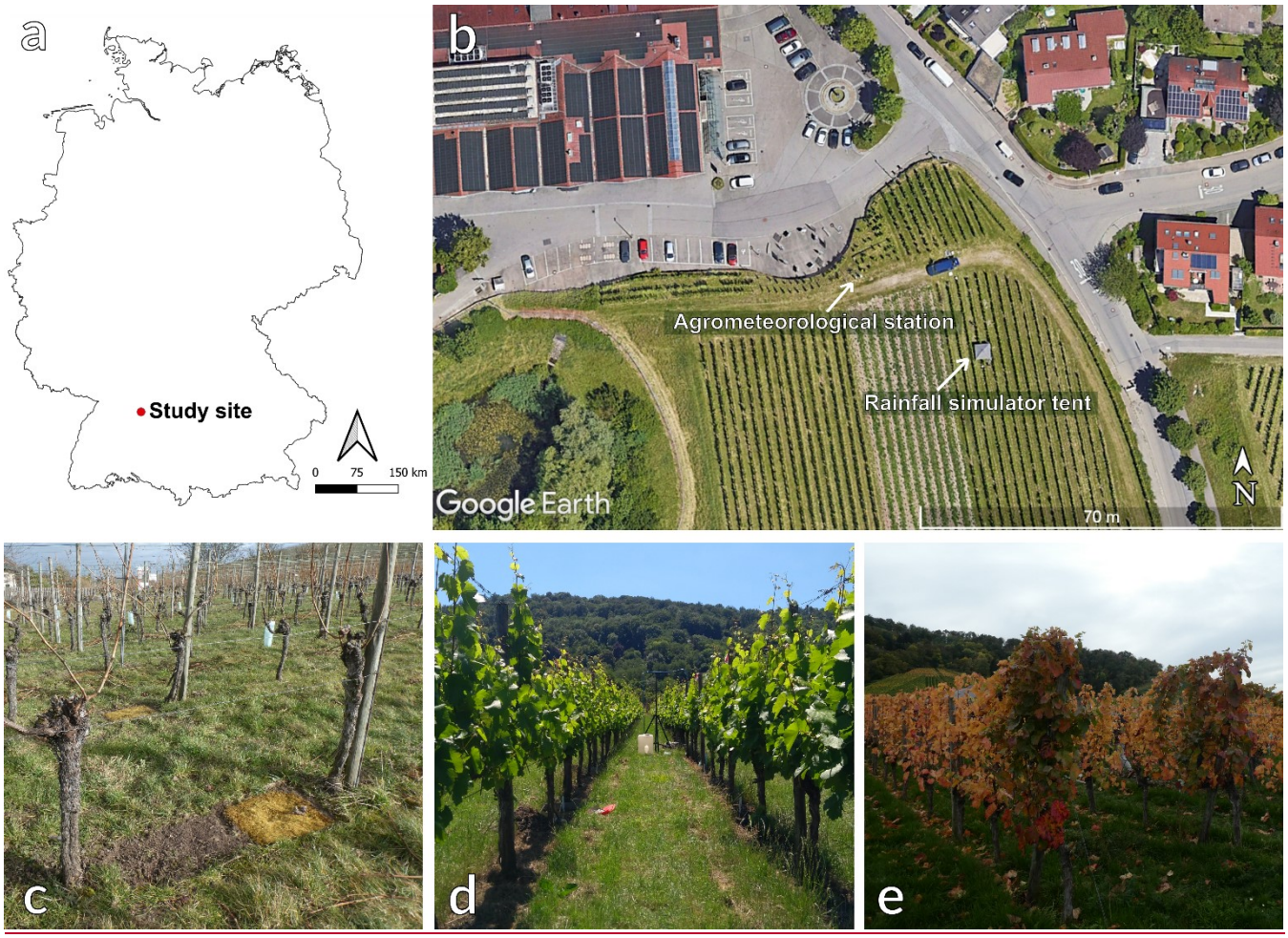


Figure 1: Location map and overview of the study site at different seasons. (a) Location of the study site in southwestern Germany (© GeoBasis-DE / BKG 2024, data modified). (b) Google Earth aerial photo of the vineyard with locations of the rainfall simulator tent and the agrometeorological station (© Google Earth 2022 Image Landsat / Copernicus). (c) Installation of the moss mats on February 17, 2022. (d) The vineyard during the 2nd rainfall simulator experiment on June 15, 2022. (e) The vineyard during the 3rd rainfall simulator experiment on October 24, 2022.

Table 1: General soil characteristics at the study site.

Soil horizon	Sand (%)	Silt (%)	Clay (%)	Texture	pH ($CaCl_2$)	Total nitrogen (%)	Total carbon (%)	Soil organic carbon (%)	Soil bulk density (g m^{-3})
0-25 cm	23.2	38.9	37.8	Clay loam	7.2	0.22	4.68	2.33	0.96
25-90 cm	23.8	42.3	34.0	Clay loam	-	0.09	3.76	0.81	-

2.2 Field methods

Treatment preparation

The treatments were established on February 17, 2022, ~~directly~~ within the study site's vine rows~~ at the study site~~. In total, there are three treatments: moss restoration (moss), bare soil (bare), and cover crop~~s~~ (grass), each with four replicates.

The bare treatment was set up by completely weeding the soil. Due to vegetation growth, this procedure had to be repeated before each rainfall simulation experiment, although the soil surface was kept intact to avoid influencing soil erosion processes. This regular weeding maintained a minimal vegetation cover (2-20%), leaving only cut grass tufts and mosses.

The grass treatment utilizes the existing planted cover crops without additional preparation, which include mainly grasses but also other vascular plants and a few moss species underneath. Common species were, for example, *Lolium perenne*, *Trifolium repens*, *Trisetum flavescens*, and *Achillea millefolium* (identified using Jäger and Werner (2005)).

The moss treatment uses artificially grown moss mats with a mixture of mosses (*Amblystegium serpens* (Hedw.) Schimp., *Brachythecium rutabulum* (Hedw.) Schimp., *Funaria hygrometrica* Hedw., *Homalothecium lutescens* (Hedw.) Robins, *Oxyrrhynchium hians* (Hedw.) Loeske), produced by Hummel InVitro GmbH Stuttgart, Germany. Cultures of these moss species were propagated in hydraulic fluid in an in vitro environment and grown on jute fleece so that these moss mats can be easily rolled, transported and spread in a similar way to rolled turf. The moss treatment was installed by weeding the area, cutting the moss mats to 40 × 40 cm, laying them on the bare soil, and securing them with a nail in each corner. Each moss mat was initially watered with 0.5 litres and periodically during dry, hot weather to ensure establishment.

~~For continuous temperature and soil moisture measurement, TMS-4 dataloggers (TOMST, Czech Republic) were installed on April 14, 2022 in all treatments. Each TMS-4 has three temperature sensors located 6 cm below the soil surface, 2 cm, and 15 cm above the soil surface, while the moisture sensor measures to a soil depth of approximately 14 cm (Wild et al., 2019). The data was collected for 21 months for analysis.~~

Rainfall simulation experiments

To analyse the effect of moss restoration on initial soil erosion and ~~soil water content~~surface runoff, three rainfall simulation~~s~~ experiments were conducted within one year, ~~at three measurement times:~~on April 13-14, June 14-15, and October 24-25, 2022 (referred to as measurement times). Each rainfall simulation experiment comprises 12 individual rainfall simulations, resulting in a total of 36 rainfall simulations in one year. The~~se~~ given dates were chosen to study initial soil erosion across seasons and to monitor the development of the moss mats. The first and second rainfall simulation~~s~~ experiments also assessed the impact of vine foliage on soil erosion: vines were leafless in April but nearly fully leafed by June. Surface runoff and sediment discharge were measured using micro-scale runoff plots (ROPs, 40 ×~~x~~ 40 cm; cf. (Seitz, 2015)) for each treatment. The portable Tübingen rainfall simulator, modified with a pavilion for wind protection and an adjusted rainfall height of 2

meters, was used (Figure 2). It featured a Lechler 490.808.30.CE nozzle set to a rainfall intensity of 45 mm h^{-1} for 30 minutes. Runoff and sediment were collected in 1 liter sample bottles. Soil water content was measured with biocrust wetness probes (BWP) from UP GmbH, Cottbus, Germany for each rainfall simulation experiment. Therefore, BWPs were placed in the upper 5 mm of the soil surface underneath the respective vegetation. To determine vegetation cover with a photogrammetric survey, perpendicular photos of all ROPs were taken with a digital compact camera (Panasonic DC-TZ91, Osaka, Japan) during each rainfall simulation experiment. Afterwards, the photos were analysed with the grid square method using a digital grid overly with 100 subdivisions (Belnap et al., 2001). For each subdivision bare soil and vegetation covers were separated by hue distinction.

Figure 2: Installation of the portable Tübingen rainfall simulator in the vineyard with the runoff plots directly within the vine rows. (a) Tübingen rainfall simulator during rainfall simulation experiment in April in the vineyard without foliage. (b) Tübingen rainfall simulator during rainfall simulation experiment in June in the vineyard with foliage.

2.3 ~~Climatic~~ Weather conditions after treatment preparation ~~and before rainfall simulations~~

To evaluate the progress of moss restoration, the ~~climatic~~ weather conditions from the preparation of the treatments to the first rainfall simulation experiment must be taken into account, as shown in Figure 3~~1~~, which was created based on the data of the ~~climate~~ agrometeorological station ~~of~~ in Fellbach (Agrarmeteorologie Baden-Württemberg, 2024b, a). A total of 51.1 mm of precipitation was recorded and the average air temperature was 6.65 ± 0.15 °C for the period 48 days from the start of the moss restoration until one week before the first rainfall simulation experiment (February 17th 2022 – April 5th 2022). In February and March 2022, precipitation sums were especially low compared to the respective monthly long-term averages of the region (1961 to 1990 climate station in Waiblingen; February 2022: 34.3 mm, long-term average for February: 48.8 mm; March 2022:

20.3 mm, long-term average for March: 48.8 mm), while average air temperature was especially high (February 2022: 6.4 °C, long-term average for February: 1.5°C; March 2022: 7.2 °C, long-term average for March: 5.1°C). Figure 3~~1~~ also shows that high daily sums of global radiation were achieved at some days, which is also reflected in increased hours of sunshine compared to the long-term average (February 2022: 85 hours, long-term average for February: 80 hours; March 2022: 199 hours, long-term average for March: 124 hours). For this reason, the average values for relative humidity were below 50% on some days.

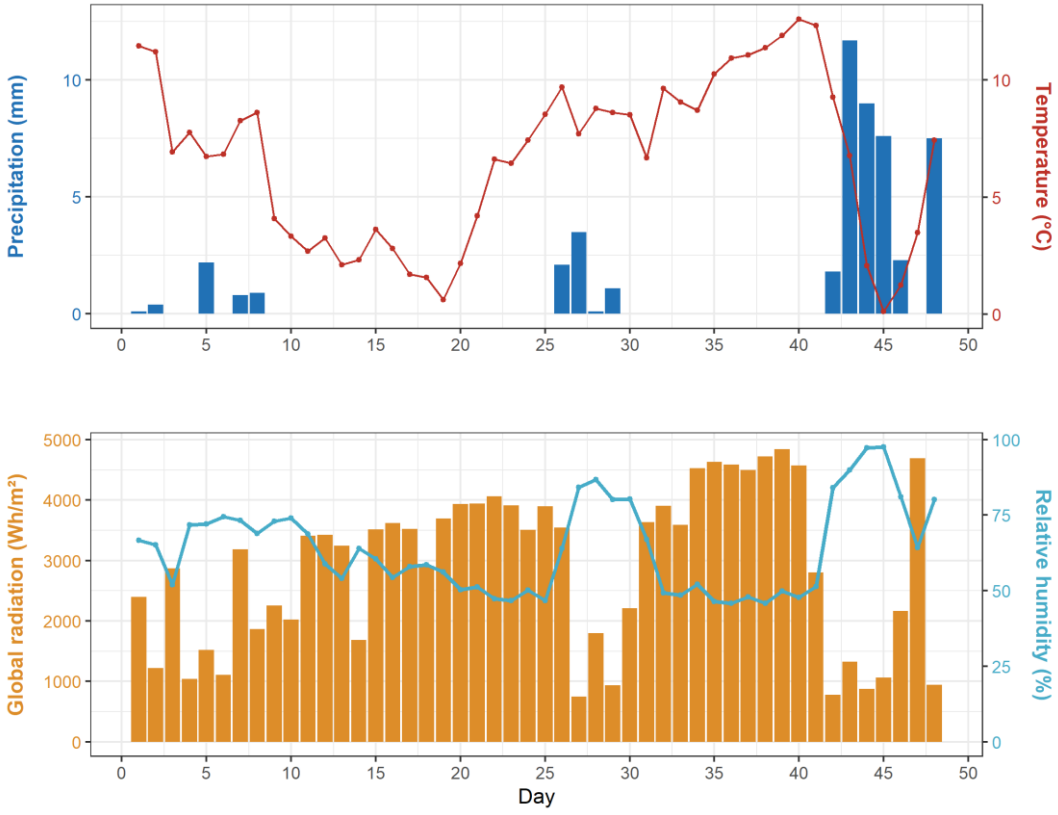
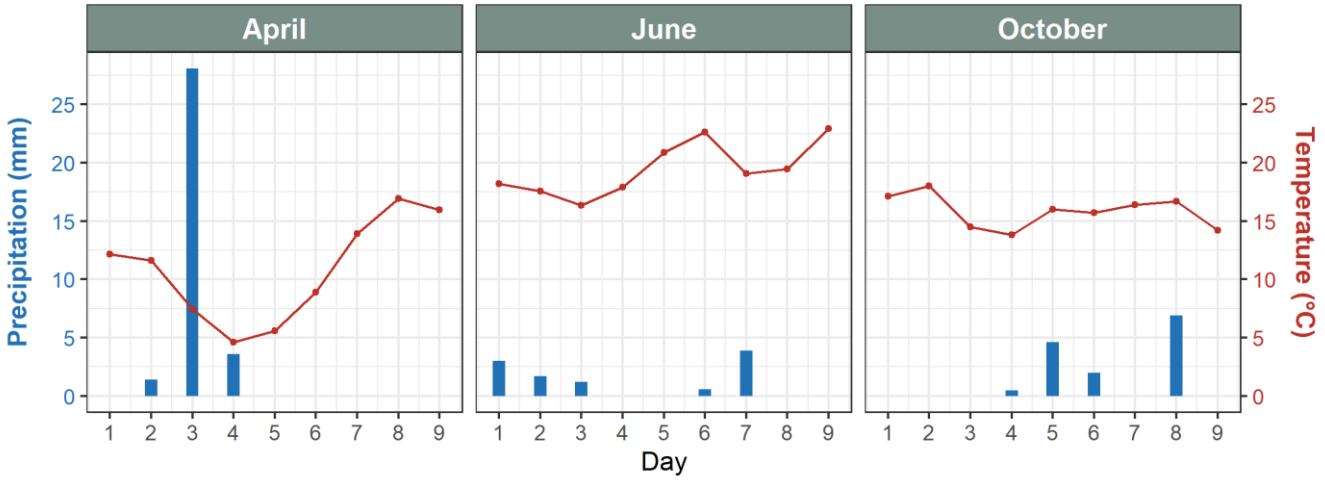


Figure 3~~1~~: ~~Climate~~ Weather diagram for Fellbach with daily sum of precipitation (mm), average air temperature (°C), daily sum of global radiation (Wh m^{-2}) and average relative humidity (%). Displayed are the 48 days from the start of the moss restoration until one week before the 1. rainfall simulation experiment from February 17th 2022 to April 5th 2022 (Agrarmeteorologie Baden-Württemberg, 2024b, a)

In addition, the ~~climatic~~ weather conditions~~-~~ for the entire observation period from the beginning of February to the end of October 2022 are presented in Figure S1 of the supplement~~prior to the rainfall simulations can be useful for assessing the time course of soil moisture~~. This information is intended to provide a better understanding of the development of moss restoration over the course of the year. ~~Figure 2 therefore shows the week before each rainfall simulation with the two days on which the simulations were carried out, i.e. a total of 9 days. In April, the sum of precipitation amounted to 33.1 mm during this time period, with 25 mm occurring on one day alone. The average temperature was 10.80 ± 0.38 °C, dropping to a minimum of 4.64 °C on day 4 and rising steadily thereafter. In contrast, the total sum of precipitation in the week before the second rainfall~~

~~simulation in June was much lower at 10.4 mm and distributed over five days. The average temperature was considerably higher at 19.44 ± 0.33 °C, whereby the changes in the daily average temperature were smaller compared to April. In June, the total sum of precipitation in the week before the third rainfall simulation was 14 mm, which was distributed over four days. Between the first and second day of the rainfall simulation, a rainfall event of 6.9 mm occurred in the evening. The average temperature was 15.84 ± 0.21 °C, with only slight fluctuations in the daily average.~~



~~**Figure 2: Climate diagrams for Fellbach with daily sum of precipitation (mm) and average air temperature (°C). The seven days before and the two days of rainfall simulation (day 8 and 9) are shown (April 6th – April 14th 2022; June 7th – June 15th 2022, October 17th – October 25th 2022,** **Agrarmeteorologie Baden-Württemberg (2024b, 2024a)~~

2.4 Laboratory analysis ~~and BWP calibration~~

After the rainfall simulation~~s~~ experiments, the amount of surface runoff was determined using the sample bottle scales. Surface runoff samples were then evaporated at 40 °C in a compartment drier to weigh the eroded sediment. The following basic soil properties were determined using the mixed soil sample collected prior to the first rainfall simulation experiment: grain size distribution with an x-ray particle size analyser (Sedigraph III, Micromeritics, Norcross, GA, USA); soil pH in a 0.01 M $CaCl_2$ solution with a pH meter with Sentix 81 electrodes (WTW, Weilheim, Germany); soil organic carbon ~~(SOC)~~ with an elemental analyser (Vario EL II, Elementar Analysensysteme GmbH, Hanau, Germany); soil bulk density in 100 cm^3 core samples using the mass-per-volume method (Blake and Hartge, 1986).

~~Since the electrical conductivity recorded by the BWP is temperature-dependent, a correction was applied to adjust all measurements to 25 °C, following Weber et al. (2016). Furthermore, a simplified calibration procedure, as suggested by Weber et al. (2016), was used to calibrate the BWP values from electrical conductivity (mV) to a gravimetric water content (g g^{-1}). Therefore, soil samples were weighed in 100 cm^3 core cutters in both water saturated and dry (40 °C) conditions to establish linear calibration functions for the minimum and maximum water content of each soil substrate.~~

2.5 Data analysis

Data analysis was conducted using R software version 4.0.4 (R Core Team, 2021). Normality was tested with the Shapiro-Wilk test prior to all statistical tests, while homoscedasticity was verified with Levene's test. As our data were not normally distributed and not homoescedastic, the Kruskal-Wallis test was used to screen for significant differences. Dunn's test was applied as a posthoc test, as it allows for a check of significant differences with a small sample size. ~~The 10-second time series of the water content were analysed using minute mean values, with the Wilcoxon rank sum test applied for differences between treatments and the Dunn's test for differences between measurement times within treatments.~~ Significant differences were postulated in all cases at $p < 0.05$. For all mean values described, the standard error was also given (mean ± standard error). ~~Spearman pairwise correlation analysis was performed to describe relationships between different parameters.~~ The colours selected for all figures are from the R package "wesanderson" (Karthik et al., 2018).

3 Results

3.1 Development of moss restoration

The percentage vegetation cover per ROP (Figure 4~~3~~) was determined for each measurement time and is summarized in Table 2~~1~~. The bare treatment had~~s~~ the lowest vegetation cover for all measurement times, whereby in April and June the remaining vegetation ~~is~~ was characterized by cut grass tufts, and in October some mosses could not be removed without damaging the soil surface. In the grass treatment, the vegetation cover was 100% for all measurement times, although a noticeably lower growth height of the grasses can be seen in April compared to June and October. The moss treatments dried out considerably in April and June and in both measurement times the jute fleece under the mosses ~~is~~ was still clearly visible. Additionally, the moss cover had~~s~~ noticeably decreased from April to June. Only in October the jute fleece under the mosses ~~is~~ was completely decomposed, the moss cover had~~s~~ increased again and the mosses appeared green and vital.

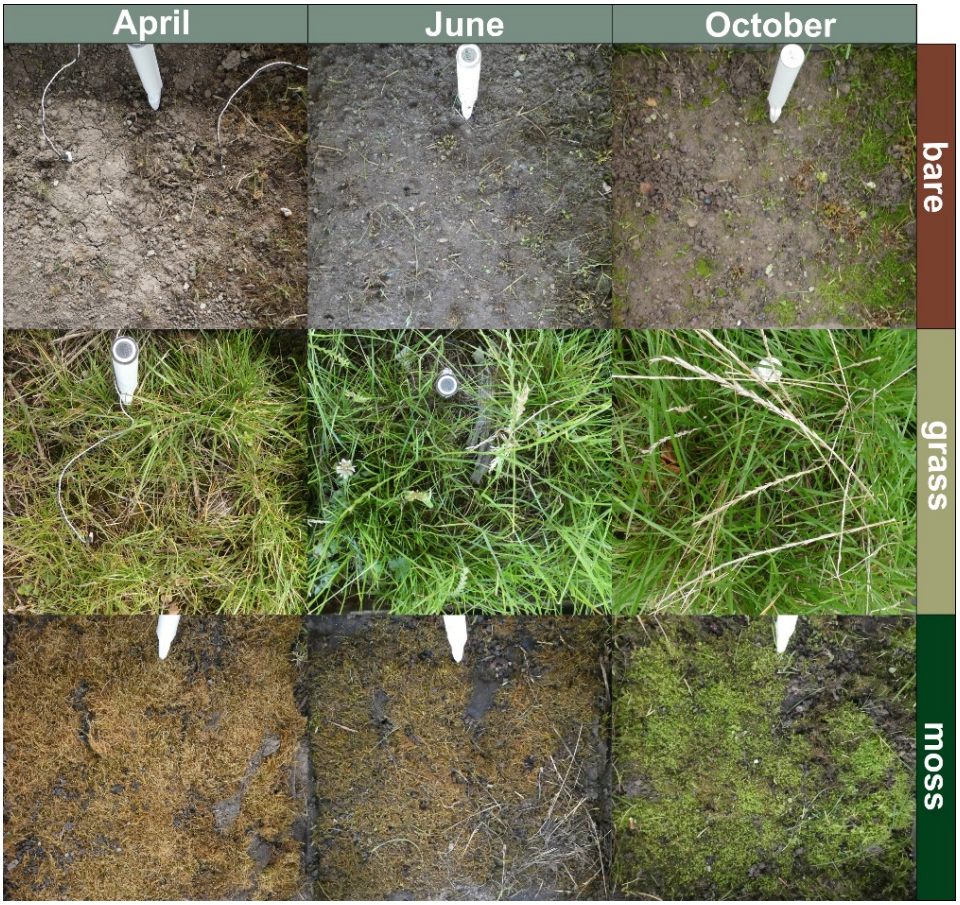


Figure 43: Exemplary development of vegetation cover over time in one runoff plot for all three treatments, respectively.

Table 21: Vegetation cover in % for all runoff plots (ROPs) and treatments in April, June, and October

	bare			grass			moss		
ROP number	**April**	**June**	**Oct.**	**April**	**June**	**Oct.**	**April**	**June**	**Oct.**
1	4	6	10	100	100	100	91	81	82
2	3	2	8	100	100	100	83	67	82
3	10	6	20	100	100	100	91	87	94
4	6	4	7	100	100	100	96	60	65
Mean	**5.75**	**4.50**	**11.25**	**100**	**100**	**100**	**90.25**	**73.75**	**80.75**

3.2 Effect of moss restoration on surface runoff ~~and sediment discharge~~

Taking the mean for all measurement times, it can be observed that both the moss and the grass treatment significantly reduce surface runoff (moss: 6.27 ± 1.92 L m^{-2}, $p < 0.01$; grass: 6.99 ± 2.27 L m^{-2}, $p < 0.01$) compared to the bare treatment (21.92 ±

2.52 L m^{-2}), which corresponds to a decrease in surface runoff of 71.4% and 68.1%, respectively. Even though the moss treatment has a slightly lower mean surface runoff than the grass treatment, no significant difference is detected between the two treatments. A separate consideration of the measurement times shows that the surface runoff is influenced by seasonality (Figure 54). Especially for the moss treatment, there is a significant increase in surface runoff between April (0.91 ± 0.20 L m^{-2}) and October (10.39 ± 4.12 L m^{-2}, $p < 0.05$). Additionally, surface runoff for the moss treatment is significantly lower than for the bare treatment in April, while the reduction in surface runoff is only significant for the grass treatment in June. In October, no significant difference in surface runoff is observed between the three treatments.

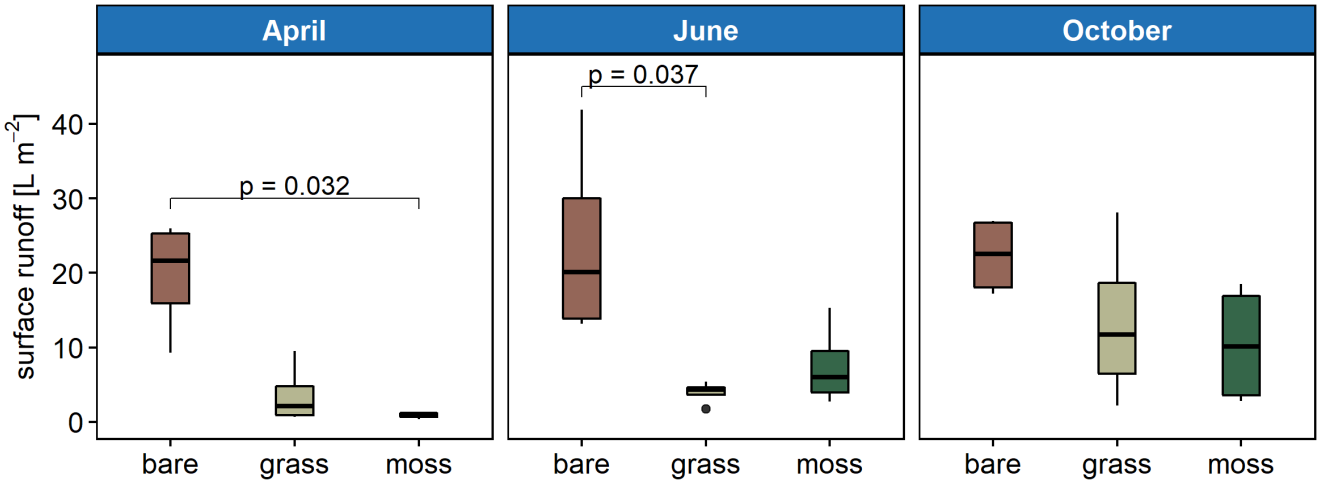


Figure 54: Surface runoff [L m^{-2}] for three treatments and three measurement times ($n = 4$). Lines within boxplots represent median values, while bottom and top of the boxplot show the first and third quartiles. Whiskers extend up to 1.5 times the interquartile range (IQR) of the data. Outliers are defined as more than 1.5 times the IQR and are displayed as points. The p values presented indicate significant differences between treatments and are based on the Dunn`s test.

3.3 Effect of moss restoration on sediment discharge

On average for all measurement times, sediment discharge is highest for bare treatments (139.49 ± 34.57 g m^{-2}) with a significant reduction in the grass treatment (17.21 ± 3.91 g m^{-2}, $p < 0.001$) and the moss treatment (33.74 ± 13.08 g m^{-2}, $p < 0.01$), corresponding to a reduction in sediment discharge of 87.7% and 75.8%, respectively. However, there is no significant difference in sediment discharge between grass and moss treatment. As with surface runoff, the influence of seasonality is also visible in sediment discharge separated by measurement time (Figure 65). In all treatments, there is an increase in sediment discharge between April and June, followed by a reduction in October., ~~whereby~~ The significant increase in sediment discharge in the moss treatment between April (1.31 ± 0.73 g m^{-2}) and June (83.25 ± 24.12 g m^{-2}, $p < 0.01$) is particularly noteworthy. In April, the moss treatment leads to a significant reduction in sediment discharge compared to the bare treatment, while in June and October, the grass treatment produces significantly lower sediment discharge than the bare treatment and not the moss treatment.

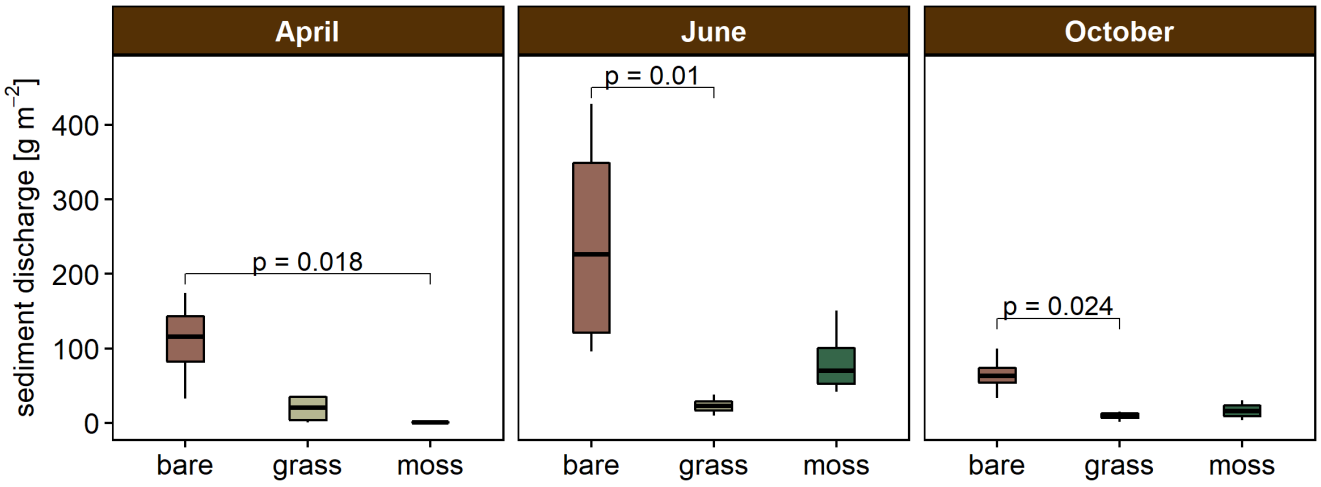


Figure 6~~5~~: Sediment discharge [g m^{-2}] for three treatments and three measurement times (n = 4). Lines within boxplots represent median values, while bottom and top of the boxplot show the first and third quartiles. Whiskers extend up to 1.5 times the interquartile range (IQR) of the data. Outliers are defined as more than 1.5 times the IQR and are displayed as points. The p values presented indicate significant differences between treatments and are based on the Dunn`s test.

~~**3.3 Effect of moss restoration on soil water content**~~

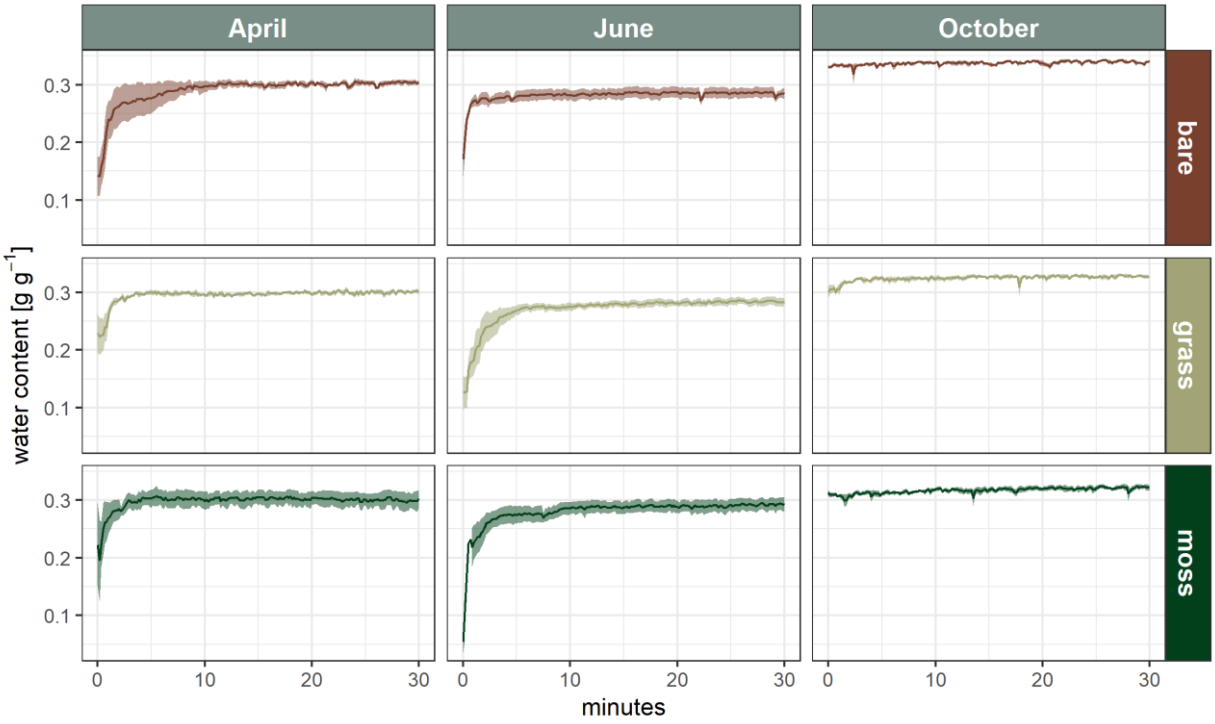
~~The results of the water content measurements in the first 5 mm of the topsoil are shown in Figure 6 for all rainfall simulations and treatments. Depending on the season in which the rainfall simulation was carried out, differences in the course of the water content between the three treatments can be recognized.~~

~~In the first rainfall simulation in April, water content in bare soil (0.181 ± 0.014 g g^{-1}) is significantly lower than in both grass (0.235 ± 0.009 g g^{-1}, $p < 0.05$) and moss treatments (0.240 ± 0.018 g g^{-1}, $p < 0.05$) within the first minute. There is no significant difference between grass and moss treatments. During the fifth and sixth minutes, water content remains lower in bare compared to moss treatments (both $p < 0.05$). After this period, no significant differences are observed between the three treatments for the rest of the rainfall simulation.~~

~~In contrast, the second rainfall simulation in June shows higher water content in bare soil (0.238 ± 0.009 g g^{-1}) than in moss (0.172 ± 0.019 g g^{-1}, $p < 0.05$) and grass treatments (0.155 ± 0.010 g g^{-1}, $p < 0.001$) within the first minute. Similarly, bare soil maintains higher water content compared to grass treatments in the second and third minutes. After these initial minutes, no significant differences are detected among the treatments.~~

~~The third rainfall simulation in October presents a different scenario: During the first minute, water content in bare soil (0.333 ± 0.001 g g^{-1}) is higher than in moss (0.309 ± 0.001 g g^{-1}, $p < 0.001$) and grass treatments (0.305 ± 0.003 g g^{-1}, $p < 0.001$), with no significant difference between moss and grass. However, from the second minute onwards, significant differences are consistently observed among all treatments for the duration of the simulation. Bare soil exhibits the highest water content, followed by grass, and the lowest water content is found in moss treatments.~~

~~In addition, there are notable seasonal differences in water content across the treatments. Figure 6 illustrates that water content is highest in October for all treatments, followed by April, and is lowest in June, and these visible differences are statistically significant in most cases. The only exceptions are that no significant differences are found in the bare treatment between April and June in the period of 2 to 10 minutes, in the moss treatment between April and October in the period of 4 to 9 minutes (and some individual minutes thereafter), and in the moss treatment between April and June in the period of 10 to 30 minutes.~~



~~**Figure 6: Temporal dynamics of soil water content [g g^{-1}] of each treatment and measurement time. The mean values of the 10-second measurements are shown as a line and the standard errors as a ribbon (n = 4). Soil water content was measured with biocrust wetness probes (BWP) in the first 5 mm of the topsoil.**~~

4 Discussion

4.1 Development of moss restoration

The moss mats have established themselves in the vineyard more slowly than we originally expected. This can be attributed primarily to the atypical ~~climatic~~ weather conditions observed during the restoration period (Figure 3~~1~~). The composition of the moss mats includes species that thrive in a variety of habitats from shaded forest floor to open grassland (Nebel et al., 2000; Atherton et al., 2010). Moss species growing in these environments can generally tolerate at least occasionally dry periods, but they are not known to be particularly desiccation-tolerant (Proctor et al., 2007). Especially~~,~~ for the initial growing and acclimatisation of the mosses in the vineyard, a high water requirement was expected and based on historical ~~climate~~ weather

data, we assumed that March would provide sufficient rainfall for moss establishment (Agrarmeteorologie Baden-Württemberg, 2024b). Instead, the mosses experienced substantial stress due to the unusually dry and warm weather, which led to desiccation and a subsequent decline in moss cover during the summer months. Similar findings from other studies emphasize that water availability is a critical factor for the success of moss restoration efforts (Grover et al., 2022; Doherty et al., 2020b). Although there were extended dry periods in July and August after the second rainfall simulation experiment (Figure S1) Nevertheless, the great resistance of the moss species involved led to a final establishment success. Even though soil protection was less effective in the summer months, a vital and healthy moss cover was re-established from October onwards and fulfilled the expected ecosystem functions. This can be seen as an advantage of moss mats in changing extreme climatic weather situations.

There have already been promising approaches to moss restoration that employ adaptive management strategies to account for climatic weather variability. Bu et al. (2018) have shown, for example, that the rapid restoration of moss worked well with sufficient irrigation (70 litre per plot of 1 ×x 1 m in 75 days, in addition to natural rainfall) and shading. Applying this strategy in vineyards would require an adaptation of irrigation practices to ensure adequate water supply during the establishment phase, especially in regions with limited rainfall. While shading is beneficial for moss establishment, it poses a challenge in vineyards as the vines require sunlight. A simple transfer of these approaches of moss restoration is therefore not possible without additional adaptations to the conditions and requirements in vineyards. However

Additionally, besides sufficient water supply and temperature, many more factors such as soil pH, nutrients, calcium carbonate content, or soil texture play an essential role for moss growth (Glime, 2021). This suggests that it may be necessary to develop species-specific solutions for moss restoration in vineyards, taking into account the major constraints of the species involved (Adessi et al., 2021). One promising species is the extremotolerant moss *Syntrichia caninervis* (Mitt.) Broth., which is known to survive and adapt to extreme conditions, such as severe desiccation and high radiation, including conditions simulated for Mars (Li et al., 2024). *S. caninervis* is also suitable for moss restoration, as Liu et al. (2021) showed that an efficient regeneration is possible for various fragments of gametophytes (leaves, stems, and rhizoids) using peat pellets as substrates. In summary, future research should focus on the development of moss restoration approaches adapted to vineyard conditions, taking into account alternative restoration techniques and the selection of moss species adapted to the particular challenges of these environments.

4.2 Effect of moss restoration on surface runoff and sediment discharge

Overall, surface runoff was strongly reduced by moss restoration and cover crops compared to bare soil, although the reduction in runoff was slightly higher for moss restoration, albeit not significantly. Several studies, also using rainfall simulation experiments, have already shown that organic management practices in vineyards, such as planting grasses as cover crops, can reduce surface runoff compared to bare soils in conventional vineyards (Rodrigo Comino et al., 2016; Seeger et al., 2019). In some cases, however, grass covers had no significant influence on the amount surface runoff, but was in the same range as for tilled vineyard soils (Telak et al., 2021; Dugan et al., 2023). Morvan et al. (2014) also reported a high variability of surface

runoff in vineyard soils covered with grass, which could not be explained by soil type, soil moisture, slope, or agricultural practices, but by the density of the grass cover. This emphasizes the importance of maintaining a dense and consistent grass cover to effectively reduce runoff.

However, according to Dugan et al. (2023), the season also had a significant effect on the hydrological response of vineyard soils, which has been confirmed across all treatments studied, including tilled soils, grass cover, and straw mulch. Similarly, our study found that the reduction in runoff varied seasonally. This phenomenon was also demonstrated in vineyards in Croatia using rainfall simulator experiments, where surface runoff in the wet season in May was significantly higher in both tilled and grass-covered treatments compared to the dry season in September (Telak et al., 2021). Biddoccu et al. (2017) also observed this seasonal effect during a two-year monitoring experiment with natural rainfall in an Italian vineyard. They concluded that runoff primarily occurred in the grass cover treatment due to topsoil saturation, while total annual runoff reduction reached approximately 63%. Our measurements of topsoil water content during rainfall simulation experiments also show seasonal differences in water content, which partly explains the seasonal variation in surface runoff (Figure S3).

The seasonal variation in surface runoff are particularly noticeable with regard to the restoration of mosses~~particularly with regard to the restoration of moss~~, which in~~de~~creased steadily from April to October. This can be ~~ascribed~~attributed to the decline in moss cover on the one hand, ~~but~~and ~~also~~ to the delayed decomposition of the jute ~~mats~~fleece on the other. We had originally assumed that the surface runoff would decrease ~~as soon as~~once the mosses had established themselves at the site.~~,~~ ~~but~~However, on average the highest surface runoff was measured in October. One possible explanation is that, despite the full establishment of mosses in October, soil coverage was still lower compared to April.~~One reason for this could be that in October, despite the complete establishment of the mosses, the soil coverage was lower than in April.~~ In addition, it ~~could be~~is possible that the jute material itself has contributed substantially to runoff reduction, as jute nets are also often used as a geotextile for soil protection and their runoff and erosion-reducing effect has been demonstrated in several studies (Bhattacharyya et al., 2010; Mitchell et al., 2003).~~,~~ However, Kertész et al. (2007) testing the use of jute mats for erosion control in vineyards found that surface runoff increased when jute mats were applied. In summary, it is challenging to disentangle the surface runoff effects of the moss and the underlying jute fleece. Therefore, it would be important for future research to specifically investigate the effects of jute fleece alone.~~ Here the measurement was influenced by the low decomposition rates caused by the summer drought.~~

The runoff-reducing effect of mosses has already been confirmed in several studies (Xiao et al., 2015; Tu et al., 2022).~~,~~ However, to the best of our knowledge, no comparable data are available for vineyards, as mosses have not yet been applied in this context for erosion control. The ~~with the~~ extent of the surface runoff reduction by mosses ~~varying~~ varies widely from 28.8% in Juan et al. (2023) to 91% reduction compared to bare soil in Gall et al. (2024a). However, Gall et al. (2024a) could show that runoff reduction was also strongly influenced by desiccation cracks. In contrast to our results, Bu et al. (2015) measured a runoff reduction of 37.3% by moss-dominated biocrusts compared to bare soils, while two different grass species alone (*Stipa bungeana* Trin. and *Caragana korshinskii* Kom.) reduced surface runoff even more (58.5% and 90.1%,

respectively). A combination of mosses and the two grasses increased the runoff reduction by just 7.4% and 5.7%, respectively. This wide range of runoff reduction also shows that, in addition to moss cover, many other factors influence surface runoff such as antecedent soil moisture, aggregate structure, soil texture, and many more (Le Bissonnais and Singer, 1993; Le Bissonnais et al., 1995; Knapen et al., 2007).

~~In addition, the reduction in runoff varied seasonally,(Dugan et al., 2023; Telak et al., 2021; Biddoccu et al., 2017) particularly with regard to the restoration of moss, which decreased steadily from April to October. This can be ascribed to the decline in moss cover on the one hand, but also to the delayed decomposition of the jute mats on the other. We had originally assumed that the surface runoff would decrease as soon as the mosses had established themselves at the site, but on average the highest surface runoff was measured in October. One reason for this could be that in October, despite the complete establishment of the mosses, the soil coverage was lower than in April. In addition, it could be that the jute material itself has contributed substantially to runoff reduction, as jute nets are also often used as a geotextile for soil protection and their runoff and erosion-reducing effect has been demonstrated in several studies. Here the measurement was influenced by the low decomposition rates caused by the summer drought.~~

4.3 Effect of moss restoration on sediment discharge

Moss restoration markedly reduced sediment discharge in the vineyard, but cover crops appeared to reduce sediment discharge to an even greater extent, although the difference was not significant.~~Moss restoration strongly reduced sediment discharge in the vineyard, but erosion was more strongly reduced by cover crops, although the difference was not significant.~~ Similarly, the study by Bu et al. (2015) showed that two different grass species reduced ~~soil erosion~~sediment discharge more compared to bare soils (*Stipa bungeana* Trin. by 95.9% and *Caragana korshinskii* Kom. by 99.5%) than moss-dominated biocrusts (erosion reduction by 81.0%). In contrast, Gall et al. (2022a) found that moss-dominated runoff plots reduced sediment discharge by 77%, while runoff plots dominated by vascular vegetation just mitigated sediment discharge by 59%, albeit the difference was not significant. However, it is important to distinguish between moss-dominated biocrusts and moss-covered soils (Weber et al., 2022), as these two types of mosses can likely have different effects on runoff and erosion control due to their very different structure. While biocrusts form in the upper millimetres of the soil and create an encrusted surface, with only a small part of their biomass protruding above the soil surface, mature moss covers grow mainly on top of the soil surface, and depending on the species, they are not even attached to the soil and create thick mats or lawns (Weber et al., 2022). For instance, Juan et al. (2023) have shown in a soil flume experiment combined with rainfall simulations that mature moss covers, produced by cultivation, can reduce sediment discharge by 64.87% compared to bare soils. Due to the diverse life forms of mosses (Bates, 1998), it is also possible that the impact on runoff formation and sediment discharge varies from species to species (Tu et al., 2022; Gall et al., 2024a; Thielen et al., 2021).

Our findings, along with other studies using rainfall simulator experiments, consistently demonstrate that vegetation covers, such as grasses, reduce sediment discharge in vineyards (Rodrigo Comino et al., 2016; Dugan et al., 2023; Seeger et al., 2019;

Kirchhoff et al., 2017). While seasonal differences in sediment discharge were observed, grass covers consistently reduced sediment discharge across dry and wet seasons (Telak et al., 2021). ~~Biddoccu et al. (2017)~~A critical consideration for these organic management strategies is that grasses can compete with vines for water and nutrients, which can negatively impact vineyard productivity (Celette et al., 2005; Ruiz-Colmenero et al., 2011). In comparison, mosses can also absorb a very high amount of water (Thielen et al., 2021; Wang and Bader, 2018), but most species are not able to extract water from the soil because they do not have roots but rhizoids that are not designed for water absorption or nutrient uptake (Glime, 2021). This could lead to less competition with the vines. Future research should focus on evaluating the water consumption of mosses in vineyard environments to assess their feasibility as an erosion control strategy.

The seasonal fluctuations in sediment discharge~~, especially~~ between April and June in the moss restoration, can be attributed to the fact that the moss cover decreased significantly during this period and that the vines were foliated in June, which was not the case in April. So far, only a few studies have examined the impact of leaves and species-specific plant traits on soil erosion. For example, Seitz et al. (2016) found that in a young subtropical forest in China, trees influence soil erosion based on species and their respective functional traits, whereby particularly high crown cover and leaf area index significantly controlled soil erosion. Investigating species' functional traits is crucial, as they greatly affect throughfall kinetic energy, consequently affecting splash erosion (Seitz et al., 2016; Goebes et al., 2016; Goebes et al., 2015).

However, the effect of individual trees or tall plants, such as vines, on soil erosion is still unclear, as to our knowledge no study deals with the effect of vine leaves on soil erosion. This is presumably due to the fact that a large part of the studies using rainfall simulator experiments in vineyards are carried out between vine rows instead of within the vine rows (Telak et al., 2021; Rodrigo Comino et al., 2016), where the effect of the leaves is probably smaller. For instance, Neumann et al. (2022) observed that the presence of vines and their canopy interception influenced results in a rainfall simulation experiment in vineyards in the Czech Republic. Using two different-sized rainfall simulators, they measured 1.5 times higher soil loss with the larger simulator, despite 30–50% less runoff, highlighting the complex interplay of factors, including the vines. In our study, ~~T~~the leaf blades of the ~~investigated~~ vines are pointed at the front, which may lead to the formation of particularly large droplets that result in a higher splash effect. For instance, Nanko et al. (2013) showed that leaf geometry is, among other things, decisive for leaf drip drop size distribution. Additionally, a further splash effect became visible on bare soils, as we found drop impact holes on the soil surface after the rainfall simulation~~s~~ experiment. We suspect that large drops have repeatedly formed at structurally-mediated woody surface drip points, leading to this severe form of erosion, which was recently reported by Katayama et al. (2023), who described these concentrated points as hotspots of soil erosion in forests.

~~**4.3 Effect of moss restoration on soil water content**~~

~~During the rainfall simulations in April and June, there were no differences in soil water content in the upper 5 millimetres between bare soil, cover crops, and moss restoration, but the initial soil water content in bare soil was lower in April and higher~~

in June than in both vegetation covered soils. This can probably be explained by the climate conditions before the rainfall simulations (Figure 2).

In April, there was no natural precipitation and air temperature steadily increased three days before the rainfall simulation, so that the bare soil desiccated on the upper soil surface, while cover crops and moss restoration prevented desiccation of the soil surface. Similar results were obtained by Thielen et al. (2021), who found that mosses prevent the desiccation of the soil and mitigate soil evaporation. However, other studies suggest that moss-dominated biocrusts increase evaporation (Li et al., 2022a; Li et al., 2022b), although this may be due to the encrustation, which does not occur in our moss restoration. Interestingly, Chen et al. (2019) discovered that mosses actively regulate evaporation to keep their temperature below a threshold of 30°, although they are theoretically unable to do so due to their poikilohydric nature (Glime, 2021). Despite some initial studies, the influence of mosses on soil evaporation remains enigmatic, highlighting the need for further research on this topic.

In June, there was a small natural rainfall event of less than 5 mm one day before the rainfall simulation, which may have resulted in the bare soil being wetter than the two vegetation covered soils due to rainfall interception. Interception plays a decisive role, especially in the case of small rainfall events, as water may not reach the soil (Dunkerley, 2000). As mosses can absorb a lot of water (Wang and Bader, 2018; Thielen et al., 2021), it can be assumed that the interception effect of mosses is very high. For example, Price et al. (1997) found that moss covers were able to retain 16.8 mm of precipitation, corresponding to approximately 21% of the precipitation input in a boreal forest. However, the initial difference in the soil water content already disappeared after one minute of rainfall simulation in our experiment, so no difference between bare soil, cover crops, and moss restoration could be found.

In contrast, there was a clear difference in soil water content between the treatments in October, with bare soil exhibiting the highest and moss restoration the lowest water contents. This indicates that the type of soil cover has a greater influence on the soil water content in October than in other seasons. Such seasonality of soil water content was also observed in a study by Marques et al. (2020), comparing cover crops with conventional tillage management in a Spanish vineyard. However, the cover crops here led to an increase in soil water content at a depth of 10 cm in autumn on wetter soils, while in spring and summer soil water content under cover crops was considerably lower compared to conventional tillage management. This is an opposite trend compared to our results, which can probably be attributed to different climatic conditions and soil characteristics of the research sites.

In addition, the water content in all treatments is highest in October, followed by April and lowest in June. Such seasonal differences in soil water content were also measured by Siwach et al. (2021) at three different sites in the temperate forest zone of the Garhwal Himalayas, whereby the water content in winter was higher under moss than in the soil without moss and in the monsoon season exactly the other way round. These different responses in various seasons highlight the need to consider seasonal variations in soil and vegetation management practices.

5 ~~5~~ Conclusion

This study investigated moss restoration in a temperate vineyard, evaluating its impact on surface runoff, and sediment discharge~~, and soil water content at the soil surface~~. The moss mats were able to establish in a temperate vineyard despite challenging environmental conditions. ~~The conclusions regarding our hypotheses are as follows:~~

Due to unexpected dry weather ~~and insufficient watering~~, the mosses initially dried out after restoration in February and recovered in October, albeit with less cover. Therefore, future moss restoration projects should incorporate flexible planning to address ~~climatic~~ weather fluctuations such as selecting more desiccation-tolerant species or providing additional irrigation during critical periods. Developing species-specific solutions considering major constraints may be also necessary.

The strongest reduction in surface runoff was achieved by moss restoration (71.4%), and was slightly higher than the reduction by cover crops (68.1%). ~~Runoff reduction varied seasonally, decreasing steadily from April to October due to declining moss cover and delayed jute mat decomposition.~~ Moss restoration also significantly reduced sediment discharge by 75.8% compared to bare soil, but cover crops reduced ~~erosion~~ sediment discharge more (by 87.7%). ~~The seasonal fluctuations in sediment discharge, especially from April to June, are due to the decline in moss cover and the foliage of the vines in June, as concentrated canopy drip points have formed on the leaves and woody surfaces of the vines, which considerably increase erosion.~~

~~1. During the rainfall simulations in April and June, soil water content in the top 5 millimetres was similar across bare soil, cover crops, and moss restoration. However, bare soil had lower initial soil water content in April and higher in June and October compared to vegetation-covered soils. In October, bare soil had the highest and moss restoration the lowest water content.~~

This study demonstrated that moss restoration can reduce ~~soil erosion~~sediment discharge and surface runoff ~~without decreasing near-surface soil water content during the dry summer months in temperate vineyards~~. With improved application methods, mosses could effectively limit soil erosion under vine rows, particularly in steep vineyards or those with challenging parent material that are difficult for vascular plants to colonize. Additionally, mosses require minimal maintenance once established, as they do not need mowing. This characteristic makes them particularly suitable as ground cover under vines, where mowing is impractical and herbicides are commonly used. Consequently, successful moss restoration in viticulture has the potential to reduce the environmentally harmful application of herbicides, though further research is necessary to realize this potential.

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Data availability

The dataset compiled and analysed in this study is available on figshare (Gall et al., 2024b).

Code availability

The codes used in this study are available upon request.

Author contribution

CG, StS and MN designed the experiment. SO, CG, and StS carried out field measurements. SO was responsible for laboratory analyses, while SO and CG conducted data analyses. CG prepared the manuscript with contributions from all other co-authors.

Competing interests

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

References

Adessi, A., De Philippis, R., and Rossi, F.: Drought-tolerant cyanobacteria and mosses as biotechnological tools to attain land degradation neutrality, Web Ecol., 21, 65-78, https://doi.org/10.5194/we-21-65-2021, 2021.

Agrarmeteorologie Baden-Württemberg: Stundenwerte der Globalstrahlung und der relativen Luftfeuchtigkeit an der Wetterstation in Fellbach [dataset], https://www.wetter-bw.de/Internet/AM/NotesBwAM.nsf/bwweb/353153acec539eb8c1257ca7003c1860?OpenDocument, (last access: 03.12.2024), 2024a.

Agrarmeteorologie Baden-Württemberg: Stundenwerte für Lufttemperatur (2 m) und Niederschlag an der Wetterstation in Fellbach [dataset], https://www.wetter-

bw.de/Internet/AM/NotesBwAM.nsf/bwweb/353153acec539eb8c1257ca7003c1860?OpenDocument, (last access: 03.12.2024), 2024b.

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., and Sparks, D. L.: Soil and human security in the 21st century, Science, 348, 1261071, https://doi.org/10.1126/science.1261071, 2015.

Antoninka, A., Faist, A., Rodriguez-Caballero, E., Young, K. E., Chaudhary, V. B., Condon, L. A., and Pyke, D. A.: Biological soil crusts in ecological restoration: emerging research and perspectives, Restoration Ecology, 28, 150-159, https://doi.org/10.1111/rec.13201, 2020.

Atherton, I., Bosanquet, S., and Lawley, M.: Mosses and Liverworts of Britain and Ireland - A field guide, 1, British Bryological Society, Plymouth ISBN 978-0-9561310-1-0, 2010.

Bagagiolo, G., Biddoccu, M., Rabino, D., and Cavallo, E.: Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards, Environmental Research, 166, 690-704, https://doi.org/10.1016/j.envres.2018.06.048, 2018.

Bates, J. W.: Is 'Life-Form' a Useful Concept in Bryophyte Ecology?, Oikos, 82, 223-237, https://www.jstor.org/stable/3546962 (last access: 03.12.2024), 1998.

Belnap, J., Kaltenecker, J. H., Rosentreter, R., Williams, J., Leonard, S., and Eldridge, D.: Biological soil crusts: ecology and management, US Department of the Interior, Bureau of Land Management, Denver, Colorado, https://www.ars.usda.gov/ARSUserFiles/6112/biologicalSoilCrusts2.pdf (last access: 08.08.2024), 2001.

Bhattacharyya, R., Smets, T., Fullen, M. A., Poesen, J., and Booth, C. A.: Effectiveness of geotextiles in reducing runoff and soil loss: A synthesis, Catena, 81, 184-195, https://doi.org/10.1016/j.catena.2010.03.003, 2010.

Biddoccu, M., Ferraris, S., Opsi, F., and Cavallo, E.: Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy), Soil and Tillage Research, 155, 176-189, https://doi.org/10.1016/j.still.2015.07.005, 2016.

Biddoccu, M., Ferraris, S., Pitacco, A., and Cavallo, E.: Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy, Soil and Tillage Research, 165, 46-58, https://doi.org/10.1016/j.still.2016.07.017, 2017.

Blake, G. R. and Hartge, K. H.: Bulk density, in: Methods of soil analysis, Part 1: physical and mineralogical methods, 2. ed., edited by: Arnold, K., American Society of Agronomy, Inc. and Soil Science Society of America, Inc., Madison, 363-375, https://doi.org/10.2136/sssabookser5.1.2ed.c13, 1986.

Bonifacio, E., Said-Pullicino, D., Stanchi, S., Potenza, M., Belmonte, S. A., and Celi, L.: Soil and management effects on aggregation and organic matter dynamics in vineyards, Soil and Tillage Research, 240, 106077, https://doi.org/10.1016/j.still.2024.106077, 2024.

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., and Ballabio, C.: Land use and climate change impacts on global soil erosion by water (2015-2070), Proceedings of the National Academy of Sciences, 117, 21994-22001, https://doi.org/10.1073/pnas.2001403117, 2020.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. V., Montanarella, L., and Panagos, P.: An assessment of the global impact of 21st century land use change on soil erosion, Nature Communications, 8, 2013, https://doi.org/10.1038/s41467-017-02142-7, 2017.

Bu, C., Li, R., Wang, C., and Bowker, M. A.: Successful field cultivation of moss biocrusts on disturbed soil surfaces in the short term, Plant and Soil, 429, 227-240, https://doi.org/10.1007/s11104-017-3453-0, 2018.

Bu, C., Wu, S., Han, F., Yang, Y., and Meng, J.: The combined effects of moss-dominated biocrusts and vegetation on erosion and soil moisture and implications for disturbance on the Loess Plateau, China, PLOS ONE, 10, e0127394, https://doi.org/10.1371/journal.pone.0127394, 2015.

Celette, F., Findeling, A., and Gary, C.: Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate, European Journal of Agronomy, 30, 41-51, https://doi.org/10.1016/j.eja.2008.07.003, 2009.

Celette, F., Wery, J., Chantelot, E., Celette, J., and Gary, C.: Belowground interactions in a vine (Vitis vinifera L.)-tall fescue (Festuca arundinacea Shreb.) intercropping system: water relations and growth, Plant and Soil, 276, 205-217, https://doi.org/10.1007/s11104-005-4415-5, 2005.

Chen, S., Yang, Z., Liu, X., Sun, J., Xu, C., Xiong, D., Lin, W., Li, Y., Guo, J., and Yang, Y.: Moss regulates soil evaporation leading to decoupling of soil and near-surface air temperatures, Journal of Soils and Sediments, 19, 2903-2912, https://doi.org/10.1007/s11368-019-02297-4, 2019.

Corbin, J. D. and Thiet, R. K.: Temperate biocrusts: mesic counterparts to their better-known dryland cousins, Frontiers in Ecology and the Environment, 18, 456-464, https://doi.org/10.1002/fee.2234, 2020.

Costantini, E. A. C., Castaldini, M., Diago, M. P., Giffard, B., Lagomarsino, A., Schroers, H.-J., Priori, S., Valboa, G., Agnelli, A. E., Akça, E., D'Avino, L., Fulchin, E., Gagnarli, E., Kiraz, M. E., Knapič, M., Pelengić, R., Pellegrini, S., Perria, R., Puccioni, S., Simoni, S., Tangolar, S., Tardaguila, J., Vignozzi, N., and Zombardo, A.: Effects of soil erosion on agro-ecosystem services and soil functions: A multidisciplinary study in nineteen organically farmed European and Turkish vineyards, Journal of Environmental Management, 223, 614-624, https://doi.org/10.1016/j.jenvman.2018.06.065, 2018.

Dittrich, F., Iserloh, T., Treseler, C.-H., Hüppi, R., Ogan, S., Seeger, M., and Thiele-Bruhn, S.: Crop diversification in viticulture with aromatic plants: effects of intercropping on grapevine productivity in a steep-slope vineyard in the Mosel area, Germany, Agriculture, 11, 95, https://doi.org/10.3390/agriculture11020095, 2021.

Doherty, K., Bowker, M. A., Durham, R. A., Antoninka, A., Ramsey, P., and Mummey, D.: Adapting mechanized vascular plant seed dispersal technologies to biocrust moss restoration, Restoration Ecology, 28, 25-31, https://doi.org/10.1111/rec.12998, 2020a.

Doherty, K. D., Grover, H. S., Bowker, M. A., Durham, R. A., Antoninka, A. J., and Ramsey, P. W.: Producing moss-colonized burlap fabric in a fog chamber for restoration of biocrust, Ecological Engineering, 158, 106019, https://doi.org/10.1016/j.ecoleng.2020.106019, 2020b.

Dugan, I., Bogunovic, I., and Pereira, P.: Soil management and seasonality impact on soil properties and soil erosion in steep vineyards of north-western Croatia, Journal of Hydrology and Hydromechanics, 71, 91-99, https://doi.org/10.2478/johh-2022-0038, 2023.

Dunkerley, D.: Measuring interception loss and canopy storage in dryland vegetation: a brief review and evaluation of available research strategies, Hydrological Processes, 14, 669-678, https://doi.org/10.1002/(SICI)1099-1085(200003)14:4<669::AID-HYP965>3.0.CO;2-I, 2000.

FAO and ITPS: Status of the World's Soil Resources (SWSR) – Main Report, Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy, https://www.fao.org/3/i5199e/i5199e.pdf (last access: 08.08.2024), 2015.

Fleishman, S. M., Bock, H. W., Eissenstat, D. M., and Centinari, M.: Undervine groundcover substantially increases shallow but not deep soil carbon in a temperate vineyard, Agriculture, Ecosystems & Environment, 313, 107362, https://doi.org/10.1016/j.agee.2021.107362, 2021.

Gall, C., Nebel, M., Quandt, D., Scholten, T., and Seitz, S.: Pioneer biocrust communities prevent soil erosion in temperate forests after disturbances, Biogeosciences, 19, 3225–3245, https://doi.org/10.5194/bg-19-3225-2022, 2022a.

Gall, C., Nebel, M., Scholten, T., Thielen, S. M., and Seitz, S.: Water's path from moss to soil Vol. 2: how soil-moss combinations affect soil water fluxes and soil loss in a temperate forest, Biologia, https://doi.org/10.1007/s11756-024-01666-w, 2024a.

Gall, C., Oldenburg, S., Nebel, M., Scholten, T., and Seitz, S.: Effects of moss restoration on soil erosion and soil water content in a temperate vineyard [dataset], https://doi.org/10.6084/m9.figshare.26510614.v1, 2024b.

Gall, C., Ohan, J., Glaser, K., Karsten, U., Schloter, M., Scholten, T., Schulz, S., Seitz, S., and Kurth, J. K.: Biocrusts: Overlooked hotspots of managed soils in mesic environments, Journal of Plant Nutrition and Soil Science, 185, 745-751, https://doi.org/10.1002/jpln.202200252, 2022b.

Geyer, M., Nitsch, E., and Simon, T.: Geologie von Baden-Württemberg, E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart, Germany, ISBN 978-3-510-65526-7, 2023.

Glime, J. M.: Volume 1: Physiological Ecology, edited by: Glime, J. M., Michigan Technological University, Michigan, https://digitalcommons.mtu.edu/oabooks/4 (last access: 03.12.2024), 2021.

Goebes, P., Schmidt, K., Härdtle, W., Seitz, S., Stumpf, F., Oheimb, G. v., and Scholten, T.: Rule-based analysis of throughfall kinetic energy to evaluate biotic and abiotic factor thresholds to mitigate erosive power, Progress in Physical Geography: Earth and Environment, 40, 431-449, https://doi.org/10.1177/0309133315624642, 2016.

Goebes, P., Bruelheide, H., Härdtle, W., Kröber, W., Kühn, P., Li, Y., Seitz, S., Oheimb, G. v., and Scholten, T.: Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture, PLoS ONE, 10, https://doi.org/10.1371/journal.pone.0128084, 2015.

Green, T. G. A. and Lange, O. L.: Photosynthesis in poikilohydric plants: A comparison of lichens and bryophytes, in: Ecophysiology of photosynthesis, edited by: Schulze, E.-D., and Caldwell, M. M., Springer, New York, 319-341, https://doi.org/10.1007/978-3-642-79354-7_16, 1994.

Grover, H. S., Bowker, M. A., and Fulé, P. Z.: Improved, scalable techniques to cultivate fire mosses for rehabilitation, Restoration Ecology, 28, 1-7, https://doi.org/10.1111/rec.12982, 2019.

Grover, H. S., Bowker, M. A., Fulé, P. Z., Sieg, C. H., and Antoninka, A. J.: Pelletized inoculation of fire mosses in severely burned conifer forests overcomes initial barriers to Bryum argenteum establishment but does not increase cover, Ecological Engineering, 176, 106513, https://doi.org/10.1016/j.ecoleng.2021.106513, 2022.

IUSS Working Group WRB (Ed.) World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps, International Union of Soil Sciences, Vienna, Austria, https://wrb.isric.org/files/WRB_fourth_edition_2022-12-18_errata_correction_2024-09-24.pdf (last access: 19.11.2024), 2022.

Jäger, J. E. and Werner, K.: Rothmaler - Exkursionsflora von Deutschland, Band 4: Kritischer Band, Spektrum Akademischer Verlag, München, ISBN 978-3-8274-1496-0, 2005.

Juan, J., Dongdong, L., YuanHang, F., and Pu, L.: Combined effects of moss colonization and rock fragment coverage on sediment losses, flow hydraulics and surface microtopography of carbonate-derived laterite from karst mountainous lands, Catena, 229, 107202, https://doi.org/10.1016/j.catena.2023.107202, 2023.

Karthik, R., Wickham, H., Richards, C., and Bagget, A.: wesanderson: A Wes Anderson palette generator (R package version 0.3.7), CRAN [code], https://cran.r-project.org/web/packages/wesanderson/index.html (last access: 08.08.2024), 2018.

Katayama, A., Nanko, K., Jeong, S., Kume, T., Shinohara, Y., and Seitz, S.: Short communication: Concentrated impacts by tree canopy drips – hotspots of soil erosion in forests, Earth Surface Dynamics, 11, 1275-1282, https://doi.org/10.5194/esurf-11-1275-2023, 2023.

Kertész, Á., Tóth, A., Szalai, Z., Jakab, G., Kozma, K., Booth, C. A., Fullen, M. A., and Davies, K.: Geotextile as a tool against soil erosion in vineyards and orchards, Sustainable Development and Planning III, https://doi.org/10.2495/sdp070592, 2007.

Kirchhoff, M., Rodrigo-Comino, J., Seeger, M., and Ries, J. B.: Soil erosion in sloping vineyards under conventional and organic land use managements (Saar-Mosel Valley, Germany), Cuadernos de Investigación Geográfica, 43, 119-140, https://doi.org/10.18172/cig.3161, 2017.

Knapen, A., Poesen, J., Govers, G., Gyssels, G., and Nachtergaele, J.: Resistance of soils to concentrated flow erosion: A review, Earth-Science Reviews, 80, 75-109, https://doi.org/10.1016/j.earscirev.2006.08.001, 2007.

Le Bissonnais, Y. and Singer, M. J.: Seal formation, runoff, and interrill erosion from seventeen California soils, Soil Science Society of America Journal, 57, 224-229, https://doi.org/10.2136/sssaj1993.03615995005700010039x, 1993.

Le Bissonnais, Y., Renaux, B., and Delouche, H.: Interactions between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils, Catena, 25, 33-46, https://doi.org/10.1016/0341-8162(94)00040-L, 1995.

LGRB: Geologische Karte von Baden-Württemberg (GK-BW), Regierungspräsidium Freiburg - Landesamt für Geologie, Rohstoffe und Bergbau (LGRB), Freiburg, https://maps.lgrb-bw.de/, (last access: 08.08.2024), 2022.

Li, S., Bowker, M. A., and Xiao, B.: Impacts of moss-dominated biocrusts on rainwater infiltration, vertical water flow, and surface soil evaporation in drylands, Journal of Hydrology, 612, 128176, https://doi.org/10.1016/j.jhydrol.2022.128176, 2022a.

Li, S., Bowker, M. A., and Xiao, B.: Biocrust impacts on dryland soil water balance: A path toward the whole picture, Global change biology, 28, 6462-6481, https://doi.org/10.1111/gcb.16416, 2022b.

Li, X., Bai, W., Yang, Q., Yin, B., Zhang, Z., Zhao, B., Kuang, T., Zhang, Y., and Zhang, D.: The extremotolerant desert moss Syntrichia caninervis is a promising pioneer plant for colonizing extraterrestrial environments, The Innovation, 5, 100657, https://doi.org/10.1016/j.xinn.2024.100657, 2024.

Liu, X., Zhou, P., Li, X., and Zhang, D.: Propagation of desert moss Syntrichia caninervis in peat pellet: a method for rapidly obtaining large numbers of cloned gametophytes, Plant Methods, 17, 42, 10.1186/s13007-021-00740-7, 2021.

Liu, Z., Chen, R., Qi, J., Dang, Z., Han, C., and Yang, Y.: Control of mosses on water flux in an alpine shrub site on the Qilian Mountains, Northwest China, Plants, 11, 3111, https://doi.org/10.3390/plants11223111, 2022.

López-Vicente, M., Calvo-Seas, E., Álvarez, S., and Cerdà, A.: Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard, Land, 9, 230, https://doi.org/10.3390/land9070230 2020.

Marks, J. N. J., Lines, T. E. P., Penfold, C., and Cavagnaro, T. R.: Cover crops and carbon stocks: how under-vine management influences SOC inputs and turnover in two vineyards, Science of The Total Environment, 831, 154800, https://doi.org/10.1016/j.scitotenv.2022.154800, 2022.

Marques, M., Ruiz-Colmenero, M., Bienes, R., García-Díaz, A., and Sastre, B.: Effects of a permanent soil cover on water dynamics and wine characteristics in a steep vineyard in the Central Spain, Air, Soil and Water Research, 13, 1-10, https://doi.org/10.1177/1178622120948069, 2020.

Mitchell, D. J., Barton, A. P., Fullen, M. A., Hocking, T. J., Zhi, W. B., and Yi, Z.: Field studies of the effects of jute geotextiles on runoff and erosion in Shropshire, UK, Soil Use and Management, 19, 182-184, https://doi.org/10.1111/j.1475-2743.2003.tb00301.x, 2003.

Morgan, R. P. C.: Soil Erosion and Conservation, 3, Blackwell Publishing, Oxford, ISBN 140514467X, 2005.

Morvan, X., Naisse, C., Malam Issa, O., Desprats, J. F., Combaud, A., and Cerdan, O.: Effect of ground-cover type on surface runoff and subsequent soil erosion in Champagne vineyards in France, Soil Use and Management, 30, 372-381, https://doi.org/10.1111/sum.12129, 2014.

Nanko, K., Watanabe, A., Hotta, N., and Suzuki, M.: Physical interpretation of the difference in drop size distributions of leaf drips among tree species, Agricultural and Forest Meteorology, 169, 74-84, https://doi.org/10.1016/j.agrformet.2012.09.018, 2013.

Nebel, M., Philippi, G., Ahrens, M., Holz, I., Sauer, M., and Schoepe, G.: Die Moose Baden-Württembergs, Band 1: Bryophytina I, Andreaeales bis Funariales, Eugen Ulmer Verlag, Stuttgart, ISBN 9783800135271, 2000.

Neumann, M., Kavka, P., Devátý, J., Stašek, J., Strouhal, L., Tejkl, A., Kubínová, R., and Rodrigo-Comino, J.: Effect of plot size and precipitation magnitudes on the activation of soil erosion processes using simulated rainfall experiments in vineyards, Frontiers in Environmental Science, 10, https://doi.org/10.3389/fenvs.2022.949774, 2022.

Novara, A., Cerda, A., Barone, E., and Gristina, L.: Cover crop management and water conservation in vineyard and olive orchards, Soil and Tillage Research, 208, 104896, https://doi.org/10.1016/j.still.2020.104896, 2021.

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, D. J., and Stringer, L.: Land degradation, in: Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, edited by: Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissik, K., Belkameci, M., and Malley, J., Intergovernmental Panel on Climate Change (IPCC), https://doi.org/10.1017/9781009157988.006, 2019.

Price, A. G., Dunham, K., Carleton, T., and Band, L.: Variability of water fluxes through the black spruce (*Picea mariana*) canopy and feather moss (*Pleurozium schreberi*) carpet in the boreal forest of Northern Manitoba, Journal of Hydrology, 196, 310-323, https://doi.org/10.1016/S0022-1694(96)03233-7, 1997.

Proctor, M. C. F., Nagy, Z., Csintalan, Z., and Takács, Z.: Water-content components in bryophytes: Analysis of pressure-volume relationships, Journal of experimental botany, 49, 1845-1854, https://doi.org/10.1093/jxb/49.328.1845, 1998.

Proctor, M. C. F., Oliver, M., Wood, A., Alpert, P., Stark, L., Cleavitt, N., and Mishler, B.: Desiccation-tolerance in bryophytes: A review, The Bryologist, 110, 595-621, https://doi.org/10.1639/0007-2745(2007)110[595:DIBAR]2.0.CO;2, 2007.

Prosdocimi, M., Cerdà, A., and Tarolli, P.: Soil water erosion on Mediterranean vineyards: A review, Catena, 141, 1-21, https://doi.org/10.1016/j.catena.2016.02.010, 2016a.

Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., and Cerdà, A.: The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards, Science of The Total Environment, 547, 323-330, https://doi.org/10.1016/j.scitotenv.2015.12.076, 2016b.

R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing [code], https://www.R-project.org/ (last access: 08.08.2024), 2021.

Rodrigo-Comino, J.: Five decades of soil erosion research in "terroir". The State-of-the-Art, Earth-Science Reviews, 179, 436-447, https://doi.org/10.1016/j.earscirev.2018.02.014, 2018.

Rodrigo-Comino, J., Novara, A., Gyasi-Agyei, Y., Terol, E., and Cerdà, A.: Effects of parent material on soil erosion within Mediterranean new vineyard plantations, Engineering Geology, 246, 255-261, https://doi.org/10.1016/j.enggeo.2018.10.006, 2018.

Rodrigo Comino, J., Brings, C., Lassu, T., Iserloh, T., Senciales, J. M., Martínez Murillo, J. F., Ruiz Sinoga, J. D., Seeger, M., and Ries, J. B.: Rainfall and human activity impacts on soil losses and rill erosion in vineyards (Ruwer Valley, Germany), Solid Earth, 6, 823-837, https://doi.org/10.5194/se-6-823-2015, 2015.

Rodrigo Comino, J., Iserloh, T., Lassu, T., Cerdà, A., Keestra, S. D., Prosdocimi, M., Brings, C., Marzen, M., Ramos, M. C., Senciales, J. M., Ruiz Sinoga, J. D., Seeger, M., and Ries, J. B.: Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards, Science of The Total Environment, 565, 1165-1174, https://doi.org/10.1016/j.scitotenv.2016.05.163, 2016.

Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Afana, A., and Solé-Benet, A.: Effects of biological soil crusts on surface roughness and implications for runoff and erosion, Geomorphology, 145, 81-89, https://doi.org/10.1016/j.geomorph.2011.12.042, 2012.

Ruiz-Colmenero, M., Bienes, R., and Marques, M. J.: Soil and water conservation dilemmas associated with the use of green cover in steep vineyards, Soil and Tillage Research, 117, 211-223, https://doi.org/10.1016/j.still.2011.10.004, 2011.

Seeger, M., Rodrigo-Comino, J., Iserloh, T., Brings, C., and Ries, J. B.: Dynamics of runoff and soil erosion on abandoned steep vineyards in the Mosel Area, Germany, Water, 11, 2596, https://doi.org/10.3390/w11122596, 2019.

Seitz, S.: Mechanisms of soil erosion in subtropical chinese forests - Effects of species diversity, species identity, functional traits and soil fauna on sediment discharge, Dissertation, Universitätsbibliothek Tübingen, http://dx.doi.org/10.15496/publikation-8010, 2015.

Seitz, S., Goebes, P., Song, Z., Bruelheide, H., Härdtle, W., Kühn, P., Li, Y., and Scholten, T.: Tree species and functional traits but not species richness affect interrill erosion processes in young subtropical forests, SOIL, 2, 49-61, https://doi.org/10.5194/soil-2-49-2016, 2016.

Siwach, A., Kaushal, S., and Baishya, R.: Effect of Mosses on physical and chemical properties of soil in temperate forests of Garhwal Himalayas, Journal of Tropical Ecology, 37, 126-135, https://doi.org/10.1017/S0266467421000249, 2021.

Telak, L. J., Pereira, P., and Bogunovic, I.: Management and seasonal impacts on vineyard soil properties and the hydrological response in continental Croatia, Catena, 202, 105267, https://doi.org/10.1016/j.catena.2021.105267, 2021.

Thielen, S. M., Gall, C., Ebner, M., Nebel, M., Scholten, T., and Seitz, S.: Water's path from moss to soil: A multi-methodological study on water absorption and evaporation of soil-moss combinations, Journal of Hydrology and Hydromechanics, 69, 421-435, https://doi.org/10.2478/johh-2021-0021, 2021.

Trigo-Córdoba, E., Bouzas-Cid, Y., Orriols-Fernández, I., Díaz-Losada, E., and Mirás-Avalos, J. M.: Influence of cover crop treatments on the performance of a vineyard in a humid region, Spanish Journal of Agricultural Research, 13, e0907, https://doi.org/10.5424/sjar/2015134-8265 2015.

Tu, N., Dai, Q., Yan, Y., Peng, X., Meng, W., and Cen, L.: Effects of moss overlay on soil patch infiltration and runoff in karst rocky desertification slope land, Water, 14, 3429, https://doi.org/10.3390/w14213429, 2022.

Vogel, H.-J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., Wiesmeier, M., and Wollschläger, U.: Quantitative evaluation of soil functions: Potential and state, Frontiers in Environmental Science, 7, 164, https://doi.org/10.3389/fenvs.2019.00164, 2019.

Wang, Z. and Bader, M. Y.: Associations between shoot-level water relations and photosynthetic responses to water and light in 12 moss species, AoB Plants, 10, ply034, https://doi.org/10.1093/aobpla/ply034, 2018.

Weber, B., Berkemeier, T., Ruckteschler, N., Caesar, J., Heintz, H., Ritter, H., Braß, H., and Freckleton, R.: Development and calibration of a novel sensor to quantify the water content of surface soils and biological soil crusts, Methods in Ecology and Evolution, 7, 14-22, https://doi.org/10.1111/2041-210x.12459, 2016.

Weber, B., Belnap, J., Büdel, B., Antoninka, A. J., Barger, N. N., Chaudhary, V. B., Darrouzet-Nardi, A., Eldridge, D. J., Faist, A. M., Ferrenberg, S., Havrilla, C. A., Huber-Sannwald, E., Malam Issa, O., Maestre, F. T., Reed, S. C., Rodriguez-Caballero, E., Tucker, C., Young, K. E., Zhang, Y., Zhao, Y., Zhou, X., and Bowker, M. A.: What is a biocrust? A refined, contemporary definition for a broadening research community, Biological Reviews, 97, 1768-1785, https://doi.org/10.1111/brv.12862, 2022.

Wild, J., Kopecký, M., Macek, M., Šanda, M., Jankovec, J., and Haase, T.: Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement, Agricultural and Forest Meteorology, 268, 40-47, https://doi.org/10.1016/j.agrformet.2018.12.018, 2019.

Xiao, B., Zhao, Y., Wang, Q., and Li, C.: Development of artificial moss-dominated biological soil crusts and their effects on runoff and soil water content in a semi-arid environment, Journal of Arid Environments, 117, 75-83, https://doi.org/10.1016/j.jaridenv.2015.02.017, 2015.

Supplement of

Effects of moss restoration on surface runoff and initial soil erosion ~~and soil water content~~ in a temperate vineyard

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- Figure S2: Development of each moss restoration replicate from February to October 2022.
- Results and discussion on the effect of moss restoration on near-surface soil water content, including Figure S3: Temporal dynamics of soil water content [g g^{-1}] of each treatment and measurement time.

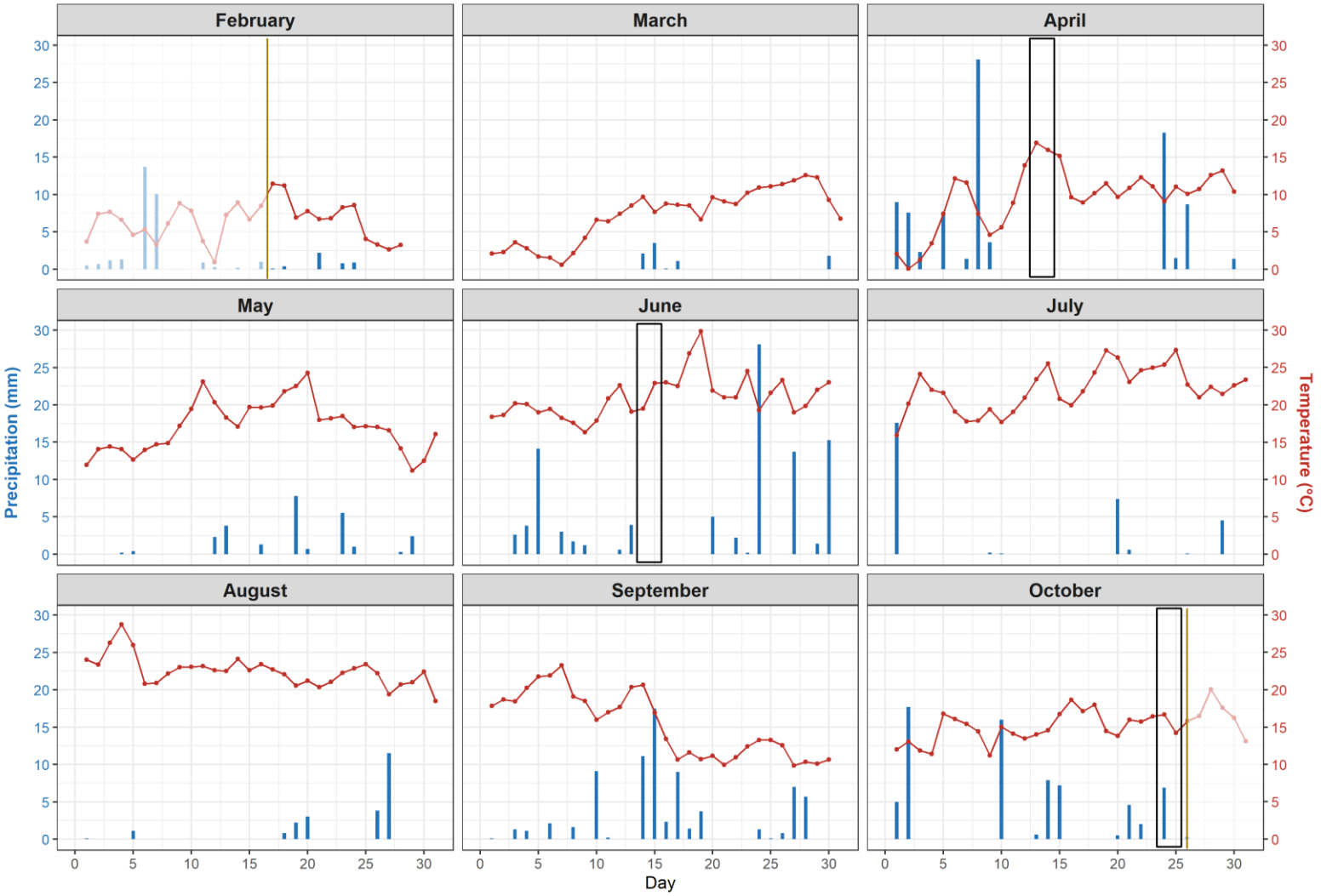

Figure S1: Weather diagrams for Fellbach with daily sum of precipitation (mm), and average air temperature (°C). The yellow lines mark the observation period from the beginning of the moss restoration on February 17, 2022, to the end of the third rainfall simulation experiment on October 25, 2022. The times of the three rainfall simulation experiments are marked with a black rectangle.

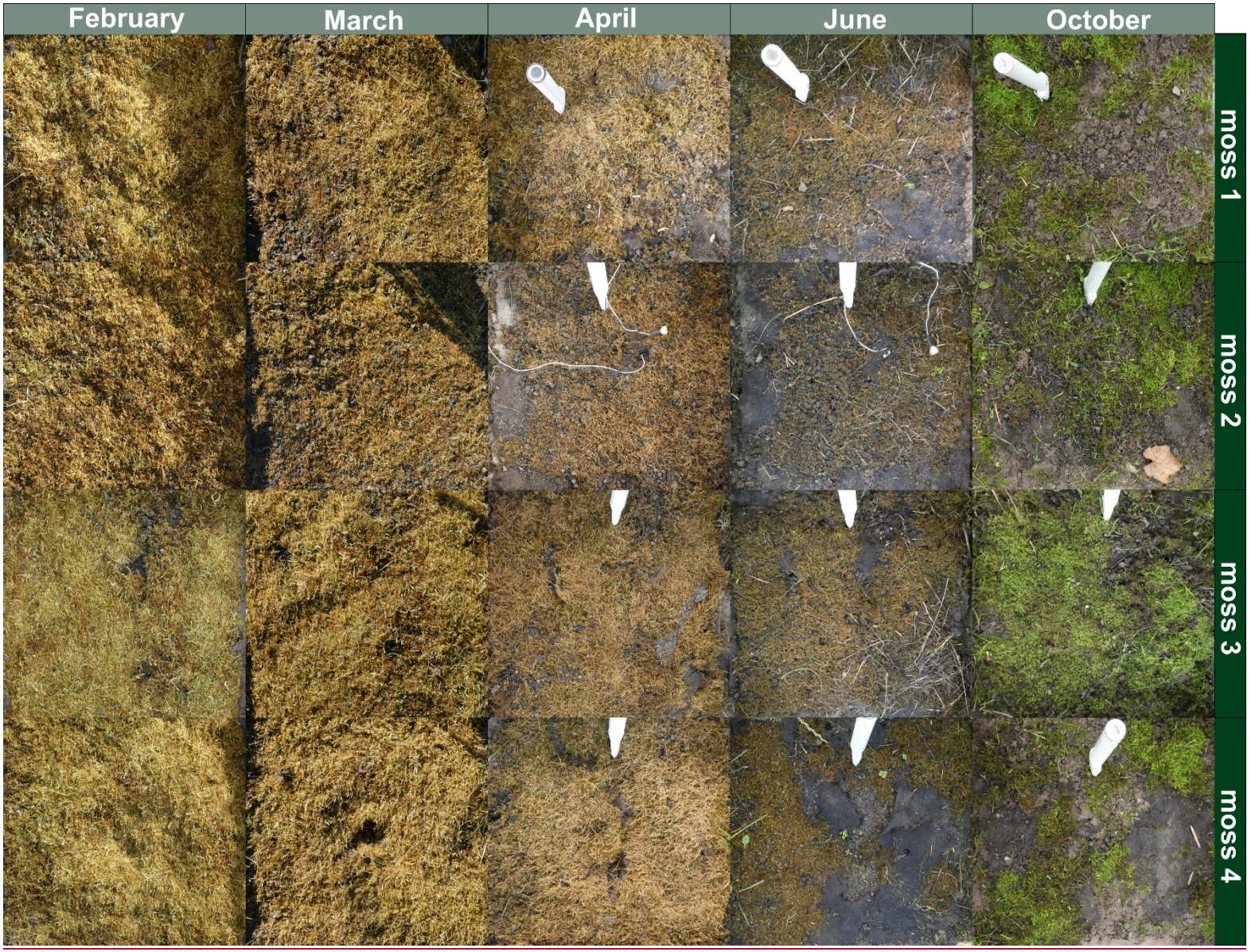

Figure S2: Development of each moss restoration replicate from February to October 2022.

Effect of moss restoration on near-surface soil water content

During rainfall simulation experiments, electrical conductivity was measured every 10 seconds in the first 5 mm of the topsoil of each treatment using biocrust wetness probes (BWP) from UP GmbH, Cottbus, Germany, connected to a GP2 Data Logger (Delta-T Devices, Cambridge, UK). Since the electrical conductivity recorded by the BWP is temperature-dependent, a correction was applied to adjust all measurements to 25 °C, following Weber et al. (2016). Furthermore, a simplified calibration procedure, as suggested by Weber et al. (2016), was used to calibrate the BWP values from electrical conductivity (mV) to a gravimetric water content (g g^{-1}). Therefore, soil samples were weighed in 100 cm^3 core cutters in both water-saturated and dry (40 °C) conditions to establish linear calibration functions for the minimum and maximum water content of each soil substrate. The 10-second time series of the water content were analysed using minute mean values, with the Wilcoxon rank sum test applied for differences between treatments and the Dunn's test for differences between measurement times within treatments.

~~3 Results: Effect of moss restoration on soil water content~~

The results of the water content measurements in the first 5 mm of the topsoil are shown in Figure ~~6~~S3 for all rainfall ~~simulations~~simulation experiments and treatments. Depending on the season in which the rainfall simulation experiment was carried out, differences in the course of the water content between the three treatments can be recognized.

In the first rainfall simulation experiment in April, water content in bare soil (0.181 ± 0.014 g g^{-1}) is significantly lower than in both grass (0.235 ± 0.009 g g^{-1}, $p < 0.05$) and moss treatments (0.240 ± 0.018 g g^{-1}, $p < 0.05$) within the first minute. There is no significant difference between grass and moss treatments. During the fifth and sixth minutes, water content remains lower in bare compared to moss treatments (both $p < 0.05$). After this period, no significant differences are observed between the three treatments for the rest of the rainfall simulation experiment.

In contrast, the second rainfall simulation experiment in June shows higher water content in bare soil (0.238 ± 0.009 g g^{-1}) than in moss (0.172 ± 0.019 g g^{-1}, $p < 0.05$) and grass treatments (0.155 ± 0.010 g g^{-1}, $p < 0.001$) within the first minute. Similarly, bare soil maintains higher water content compared to grass treatments in the second and third minutes. After these initial minutes, no significant differences are detected among the treatments.

The third rainfall simulation experiment in October presents a different scenario: During the first minute, water content in bare soil (0.333 ± 0.001 g g^{-1}) is higher than in moss (0.309 ± 0.001 g g^{-1}, $p < 0.001$) and grass treatments (0.305 ± 0.003 g g^{-1}, $p < 0.001$), with no significant difference between moss and grass. However, from the second minute onwards, significant

differences are consistently observed among all treatments for the duration of the rainfall simulation experiment. Bare soil exhibits the highest water content, followed by grass, and the lowest water content is found in moss treatments.

In addition, there are notable seasonal differences in water content across the treatments. Figure ~~6~~S3 illustrates that water content is highest in October for all treatments, followed by April, and is lowest in June, and these visible differences are statistically significant in most cases. The only exceptions are that no significant differences are found in the bare treatment between April and June in the period of 2 to 10 minutes, in the moss treatment between April and October in the period of 4 to 9 minutes (and some individual minutes thereafter), and in the moss treatment between April and June in the period of 10 to 30 minutes.

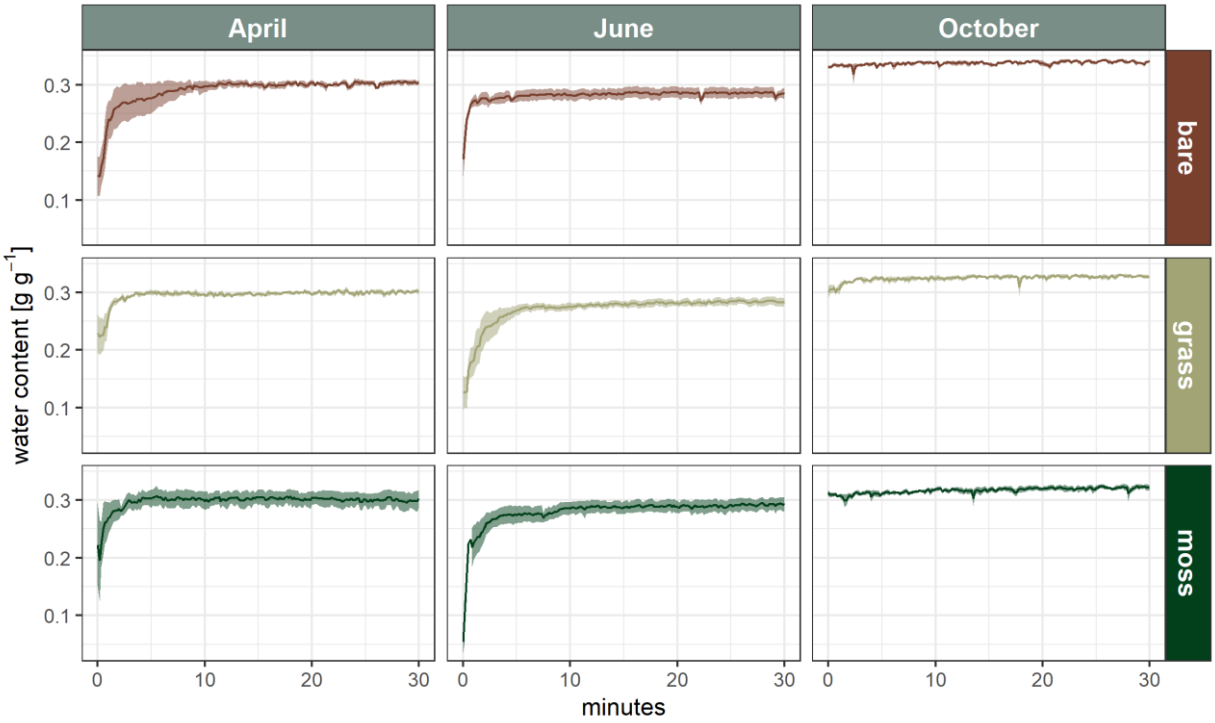

Figure ~~6~~S3: Temporal dynamics of soil water content [g g^{-1}] of each treatment and measurement time. The mean values of the 10-second measurements are shown as a line and the standard errors as a ribbon ($n = 4$). Soil water content was measured with biocrust wetness probes (BWP) in the first 5 mm of the topsoil.

~~**4 Discussion: 4.3 Effect of moss restoration on soil water content**~~

During the rainfall ~~simulations~~simulation experiments in April and June, there were no differences in soil water content in the upper 5 millimetres between bare soil, cover crops, and moss restoration, but the initial soil water content in bare soil was

lower in April and higher in June than in both vegetation-covered soils. This can probably be explained by the ~~climate~~weather conditions before the rainfall ~~simulations~~simulation experiments (Figure ~~2~~S1).

In April, there was no natural precipitation and air temperature steadily increased three days before the rainfall simulation experiment, so that the bare soil desiccated on the upper soil surface, while cover crops and moss restoration prevented desiccation of the soil surface. Similar results were obtained by Thielen et al. (2021), who found that mosses prevent the desiccation of the soil and mitigate soil evaporation. However, other studies suggest that moss-dominated biocrusts increase evaporation (Li et al., 2022a; Li et al., 2022b), although this may be due to the encrustation, which does not occur in our moss restoration. Interestingly, Chen et al. (2019) discovered that mosses actively regulate evaporation to keep their temperature below a threshold of 30°, although they are theoretically unable to do so due to their poikilohydric nature (Glime, 2021). Despite some initial studies, the influence of mosses on soil evaporation remains enigmatic, highlighting the need for further research on this topic.

In June, there was a small natural rainfall event of less than 5 mm one day before the rainfall simulation experiment, which may have resulted in the bare soil being wetter than the two vegetation-covered soils due to rainfall interception. Interception plays a decisive role, especially in the case of small rainfall events, as water may not reach the soil (Dunkerley, 2000). As mosses can absorb a ~~lot~~very high amount of water (Wang and Bader, 2018; Thielen et al., 2021), it can be assumed that the interception effect of mosses is also very high. For example, Price et al. (1997) found that moss covers were able to retain 16.8 mm of precipitation, corresponding to approximately 21% of the precipitation input in a boreal forest. However, the initial difference in the soil water content already disappeared after one minute of our rainfall simulation ~~in our~~ experiment, so no difference between bare soil, cover crops, and moss restoration could be found.

In contrast, there was a clear difference in soil water content between the treatments in October, with bare soil exhibiting the highest and moss restoration the lowest water contents. This indicates that the type of soil cover has a greater influence on the soil water content in October than in other seasons. Such seasonality of soil water content was also observed in a study by Marques et al. (2020), comparing cover crops with conventional tillage management in a Spanish vineyard. However, the cover crops here led to an increase in soil water content at a depth of 10 cm in autumn on wetter soils, while in spring and summer soil water content under cover crops was considerably lower compared to conventional tillage management. This is an opposite trend compared to our results, which can probably be attributed to different ~~climatic~~weather conditions and soil characteristics of the research sites.

In addition, the water content in all treatments is highest in October, followed by April and lowest in June. Such seasonal differences in soil water content were also measured by Siwach et al. (2021) at three different sites in the temperate forest zone of the Garhwal Himalayas, whereby the water content in winter was higher under moss than in the soil without moss and in the monsoon season exactly the other way round. These different responses in various seasons highlight the need to consider seasonal variations in soil and vegetation management practices.

References

Chen, S., Yang, Z., Liu, X., Sun, J., Xu, C., Xiong, D., Lin, W., Li, Y., Guo, J., and Yang, Y.: Moss regulates soil evaporation leading to decoupling of soil and near-surface air temperatures, Journal of Soils and Sediments, 19, 2903-2912, https://doi.org/10.1007/s11368-019-02297-4, 2019.

Dunkerley, D.: Measuring interception loss and canopy storage in dryland vegetation: a brief review and evaluation of available research strategies, Hydrological Processes, 14, 669-678, https://doi.org/10.1002/(SICI)1099-1085(200003)14:4<669::AID-HYP965>3.0.CO;2-I, 2000.

Glime, J. M.: Volume 1: Physiological Ecology, edited by: Glime, J. M., Michigan Technological University, Michigan, https://digitalcommons.mtu.edu/oabooks/4 (last access: 03.12.2024), 2021.

Li, S., Bowker, M. A., and Xiao, B.: Impacts of moss-dominated biocrusts on rainwater infiltration, vertical water flow, and surface soil evaporation in drylands, Journal of Hydrology, 612, 128176, https://doi.org/10.1016/j.jhydrol.2022.128176, 2022a.

Li, S., Bowker, M. A., and Xiao, B.: Biocrust impacts on dryland soil water balance: A path toward the whole picture, Global change biology, 28, 6462-6481, https://doi.org/10.1111/gcb.16416, 2022b.

Marques, M., Ruiz-Colmenero, M., Bienes, R., García-Díaz, A., and Sastre, B.: Effects of a Permanent Soil Cover on Water Dynamics and Wine Characteristics in a Steep Vineyard in the Central Spain, Air, Soil and Water Research, 13, 1-10, https://doi.org/10.1177/1178622120948069, 2020.

Price, A. G., Dunham, K., Carleton, T., and Band, L.: Variability of water fluxes through the black spruce (*Picea mariana*) canopy and feather moss (*Pleurozium schreberi*) carpet in the boreal forest of Northern Manitoba, Journal of Hydrology, 196, 310-323, https://doi.org/10.1016/S0022-1694(96)03233-7, 1997.

Siwach, A., Kaushal, S., and Baishya, R.: Effect of Mosses on physical and chemical properties of soil in temperate forests of Garhwal Himalayas, Journal of Tropical Ecology, 37, 126-135, https://doi.org/10.1017/S0266467421000249, 2021.

Thielen, S. M., Gall, C., Ebner, M., Nebel, M., Scholten, T., and Seitz, S.: Water's path from moss to soil: A multi-methodological study on water absorption and evaporation of soil-moss combinations, Journal of Hydrology and Hydromechanics, 69, 421-435, https://doi.org/10.2478/johh-2021-0021, 2021.

Wang, Z. and Bader, M. Y.: Associations between shoot-level water relations and photosynthetic responses to water and light in 12 moss species, AoB Plants, 10, ply034, https://doi.org/10.1093/aobpla/ply034, 2018.