Effects of moss restoration on surface runoff and initial soil erosion 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. Therefore, the search for alternative management practices becomes vital, and vegetation covers, including mosses, have the potential to reduce soil erosion. However, research on moss restoration 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 experiments (45 mm h^{-1} for 30 minutes) with small-scale runoff plots at three measurement times during one year (April, June, and October).

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 reduced surface runoff slightly more, and sediment discharge slightly less 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. 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.

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 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 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 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 soil fertility by increasing the 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.

An argument against organic management practices in vineyards is that the soil-covering vegetation might compete with the vines for water and nutrients (Celette et al., 2009; Dittrich et al., 2021). For example, Celette et al. (2005) found that vine vigour was reduced in a vineyard intercropped with tall fescue grass compared to a conventional vineyard using chemical weed control, attributing this not only to the competition for water, but also other soil resources, such as nutrients, or allelopathy effects. 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. 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.

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), and also effectively mitigate soil erosion (Gall et al., 2022a; Gall et al., 2024a; Juan et al., 2023). Additionally, some studies have demonstrated that mosses can 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., 2022), especially with low rainfall intensities (Tu et al., 2022), and have increased soil evaporation (Li et al., 2022). Due to their potential beneficial effects on the soil, 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.

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 in low-pH soils, on steep slopes, or in 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 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. The following two 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. 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 prevent erosion.

2 Methodology

2.1 Study site

The study took place in a vineyard south of Fellbach, Southwest Germany, approximately 10 km northeast of Stuttgart (Figure 1). The vineyard produces the Lemberger vine variety and the soil between the vines is continuously 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). A Mollic Anthrosol (Relocatic) was identified as a soil type (IUSS Working Group WRB, 2022), which is typically formed in vineyards by deep ploughing. Mixed samples of the topsoil (0-5 cm) and subsoil (approx. 40 cm) were taken to describe general soil characteristics (Table 1). An agrometeorological station in the immediate vicinity of the study site (48.80158° N 9.28113° E) revealed 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).

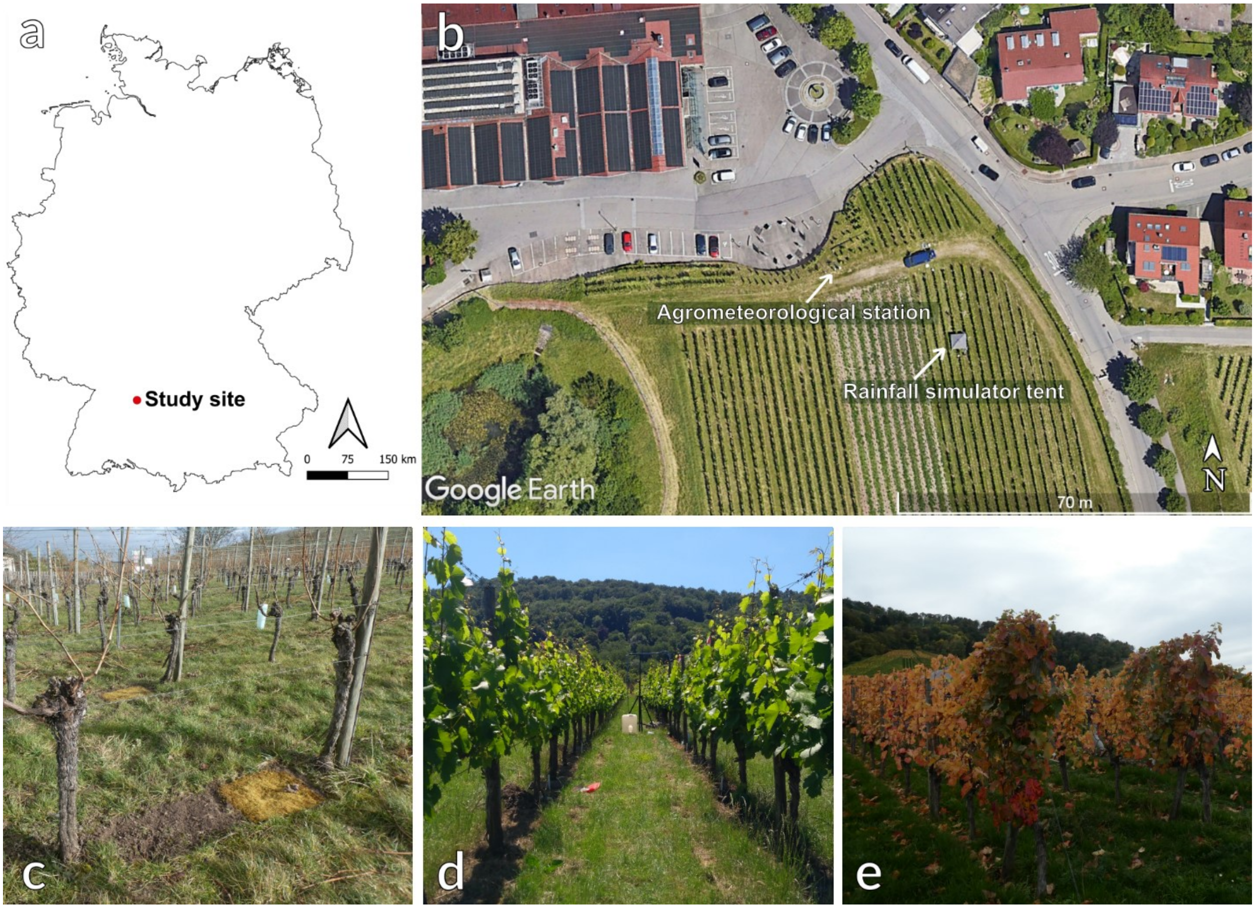

Figure 1: Location map and overview of the study site at different seasons. (a) Location of the study site in southwestern Germany (© GeoBasis-DE / BKG 2024, data modified). (b) Google Earth aerial photo of the vineyard with locations of the rainfall simulator tent and the agrometeorological station (© 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, within the study site's vine rows. In total, there are three treatments: moss restoration (moss), bare soil (bare), and cover crop (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.

Rainfall simulation experiments

To analyse the effect of moss restoration on initial soil erosion and surface runoff, three rainfall simulation experiments were conducted within one year, 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 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 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 × 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-litre 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 Weather conditions after treatment preparation

To evaluate the progress of moss restoration, the weather conditions from the preparation of the treatments to the first rainfall simulation experiment must be taken into account, as shown in Figure 3, which was created based on the data of the agrometeorological station 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 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.

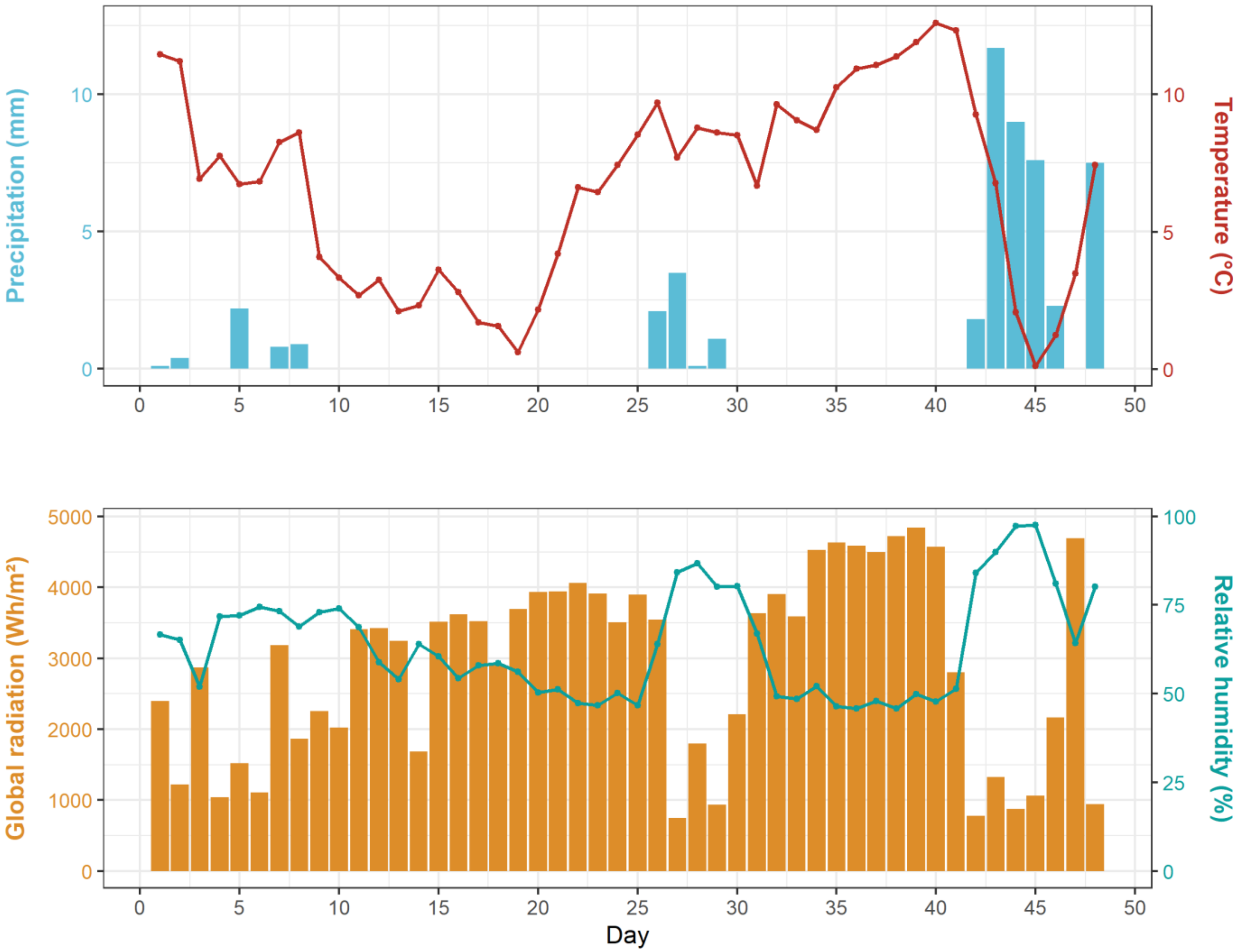

Figure 3: Weather diagram for Fellbach with daily sum of precipitation (mm), average air temperature (°C), daily sum of global radiation (Wh m^{-2}) and average relative humidity (%). Displayed are the 48 days from the start of the moss restoration until one week before the 1st rainfall simulation experiment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

In addition, the 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. This information is intended to provide a better understanding of the development of moss restoration over the course of the year.

2.4 Laboratory analysis

After the rainfall simulation 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 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).

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 post hoc test, as it allows for a check of significant differences with a small sample size. 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). 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) was determined for each measurement time and is summarized in Table 2. The bare treatment had the lowest vegetation cover for all measurement times, whereby in April and June the remaining vegetation 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 was still clearly visible. Additionally, the moss cover had noticeably decreased from April to June. Only in October the jute fleece under the mosses was completely decomposed, the moss cover had increased again and the mosses appeared green and vital.

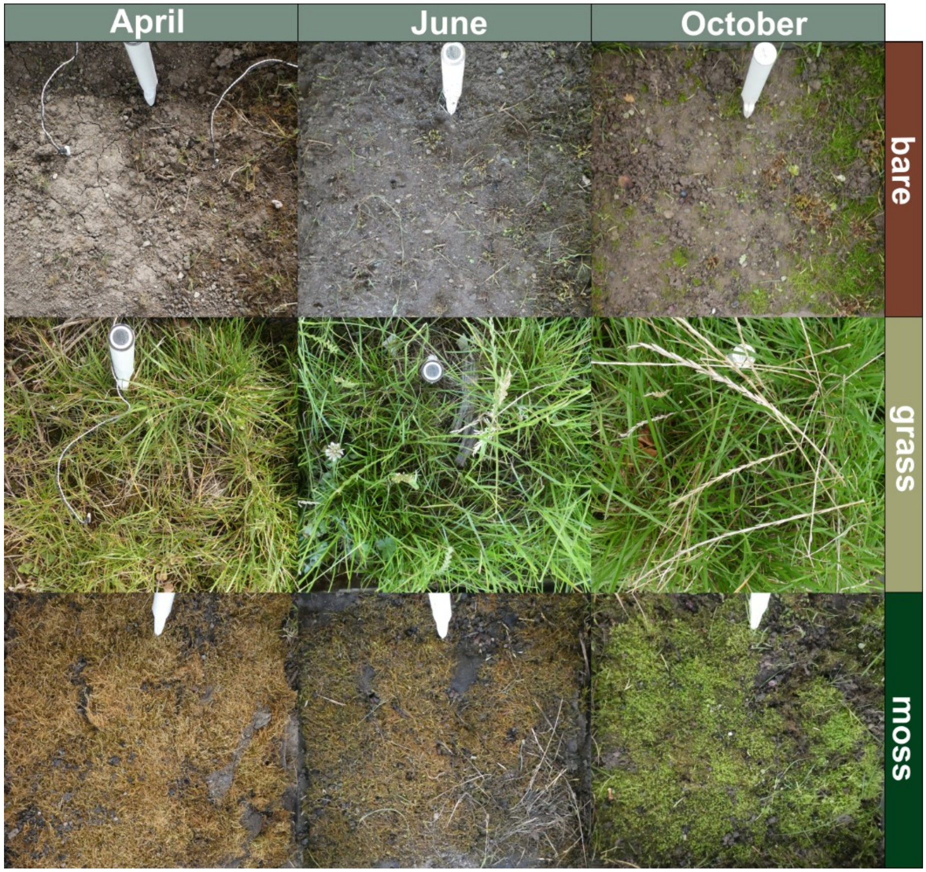

Figure 4: Exemplary development of vegetation cover over time in one runoff plot for all three treatments, respectively.

Table 2: 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

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 5). 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.

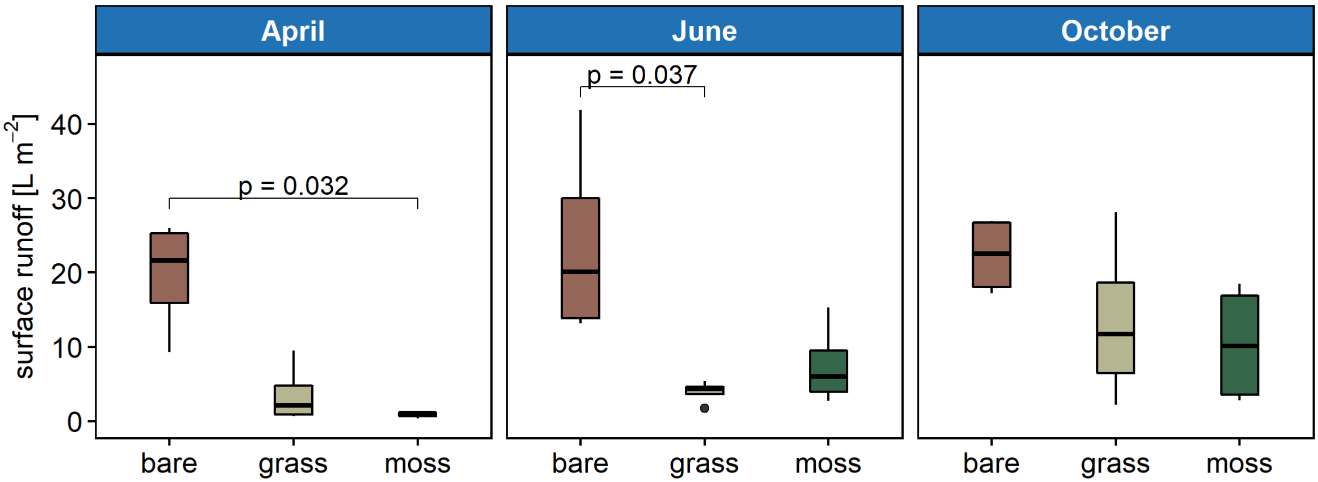

Figure 5: Surface runoff [L m^{-2}] for three treatments and three measurement times (*n = 4*). Lines within boxplots represent median values, while bottom and top of the boxplot show the first and third quartiles. Whiskers extend up to 1.5 times the interquartile range (IQR) of the data. Outliers are 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 6). In all treatments, there is an increase in sediment discharge between April and June, followed by a reduction in October. 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.

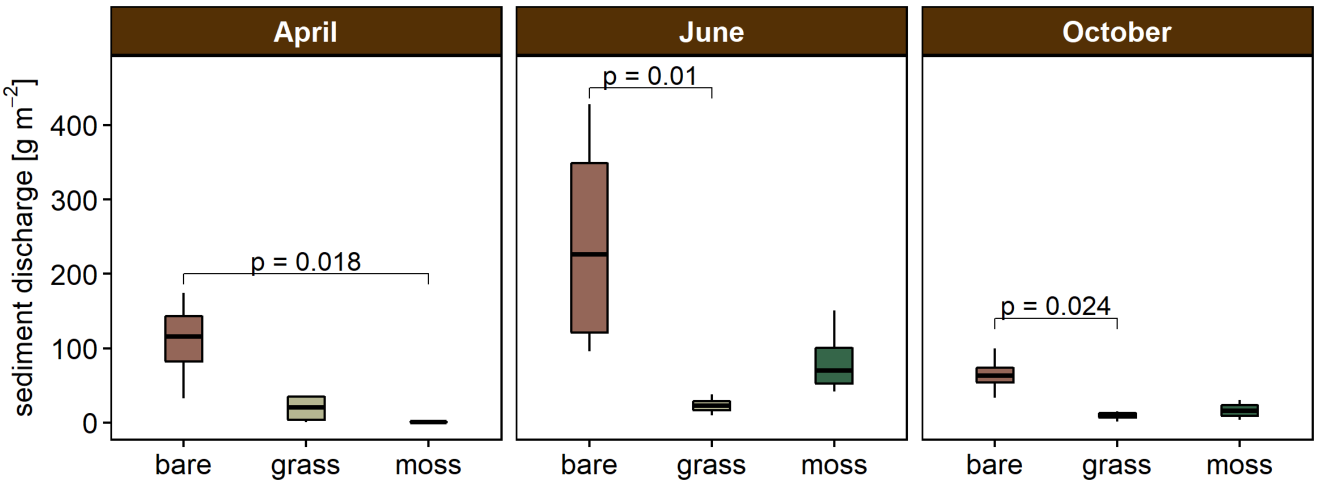

Figure 6: Sediment discharge [g m^{-2}] for three treatments and three measurement times (*n* = *4*). Lines within boxplots represent median values, while bottom and top of the boxplot show the first and third quartiles. Whiskers extend up to 1.5 times the interquartile range (IQR) of the data. Outliers 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.

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 weather conditions observed during the restoration period (Figure 3). 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 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), 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 weather situations.

There have already been promising approaches to moss restoration that employ adaptive management strategies to account for 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 × 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.

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

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 (Figure S3), which partly explains the seasonal variation in surface runoff.

The seasonal variation in surface runoff are particularly noticeable with regard to the restoration of moss, which increased steadily from April to October. This can be attributed to the decline in moss cover on the one hand, and to the delayed decomposition of the jute fleece on the other. We had originally assumed that the surface runoff would decrease once the mosses had established themselves at the site. 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. In addition, it 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.

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 extent of the surface runoff reduction by mosses 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).

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. Similarly, the study by Bu et al. (2015) showed that two different grass species reduced 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). 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 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, the leaf blades of the 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 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.

5 Conclusion

This study investigated moss restoration in a temperate vineyard, evaluating its impact on surface runoff and sediment discharge. The moss mats were able to establish in a temperate vineyard despite challenging environmental conditions. Due to unexpected dry weather, 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 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%). Moss restoration also significantly reduced sediment discharge by 75.8% compared to bare soil, but cover crops reduced sediment discharge more (by 87.7%).

This study demonstrated that moss restoration can reduce sediment discharge and surface runoff. 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.

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