Soil Use and Management

WILEY | BRITISH SOCIETY OF SOIL SCIENCE

RESEARCH ARTICLE OPEN ACCESS

Limited Protective Effect of Paddock Grids on Horse Trails Compared to Unprotected Trails in a Swiss Field Experiment

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Received: 16 October 2025 | **Revised:** 19 February 2026 | **Accepted:** 21 April 2026

Keywords: equine | soil stabilization | soil structure | soil water content

ABSTRACT

Paddock grids on horse trails are used to protect animals from injuries, but the impact of paddock grids on soil quality is not well documented. In a 15 months experimental field study, we investigated possible protective effects of two types of paddock grids used on paddock trails (referred to as 'basic' and 'reinforced') on key soil quality indicators in comparison to unprotected trails also used by the horses. These installations of paddock grids were analysed with and without wood chip buffering layers. Horse-induced soil degradation was measured in all treatments, leading to a significant increase in soil bulk density, decreases in microbial biomass and soil organic carbon content, and smaller changes in water content in response to precipitation and dry phases. The soil of the unprotected trail was particularly affected by the horses, and no recovery in vegetation cover within 7 weeks after removal of the horses was observed. Comparing the two types of paddock grids showed that the soil under the reinforced paddock grid was marginally less compacted compared to the soil under the basic paddock grid. An additional wood chips buffering layer was found to have no additional protective effect. In conclusion, we found no significant difference in the negative impact induced by horses on physical and microbiological parameters of soil quality between trails with and without paddock grids (independent of the type and installation of the paddock grids) during the timespan of this study. However, we found that paddock grids allowed a faster recovery of vegetation cover than unprotected trails after the horses were removed from the trails.

1 | Introduction

Paddock trails are one of many modern forms of equine husbandry. By keeping horses in this type of housing system, they should be able to express a full range of natural and rewarding behaviours, including social interactions among conspecifics, the continuous intake of small amounts of feed and enhanced free movement through the separation of vital areas (sleeping, drinking and feeding) (Yarnell et al. 2015; Jackson 2016). Paddock trails require a certain space, typically on agricultural land and the increased movement on spatially limited trails inevitably leads to sward and possibly soil degradation, and frequently used trails rapidly become bare and muddy under wet conditions due to insufficient plant cover (Hiltbrunner et al. 2012). This increases the risk of infections, for example, equine pastern dermatitis (mud fever) (Colles et al. 2010), and potentially injuries from slipping. To prevent unfavourable soil conditions, paddock grids are increasingly installed on highly frequented trails. These installations typically require the removal of surface soil to create an even surface for the subsequent placement of paddock grids. Often, an additional buffering material, such as gravel, sand, wood chips, etc. is applied as a thin layer between the soil and the paddock grids to create a stabilizing effect (Sharpe and Kenny 2025). Commercially available paddock grids are typically made from recycled plastic, but they can vary in size, weight and form, depending on the manufacturer. They are permeable, allowing water and gas exchange between soil and atmosphere, as well as plant roots to perforate through the grids into the soil. Despite their widespread use, data on whether and how paddock grids protect soil compared to barren, uncovered trails, and if buffering layers further mitigate negative impacts on soil quality are lacking. Hiltebrand et al. (2025) evaluated soil quality changes on horse paddock trails in an on-farm study, finding topsoil degradation under both grid and non-grid trails. Expanding on the results from Hiltebrand et al. (2025), this study examines soil quality changes on paddock trails at an experimental site with controlled horse numbers per trail, enabling improved quantification of horse-induced soil pressure through monitoring of their movement. Additionally, this study not only distinguishes between grid and non-grid trails, but the influence of different types of paddock grids and installations on soil quality responses and further analyses impacts on soil processes (water dynamics) and vegetation.

While the impact of cattle grazing has received some attention, the effect of horses on soil properties is less well documented (Steinfeld et al. 2006). The higher weight-to-hoofprint ratio in horses suggests a potential for localized soil compaction which exceeds that of cattle (Cox and Amador 2018). This damage to the soil is particularly harmful under wet conditions (Cox and Amador 2018; Roesch et al. 2019). Furthermore, overgrazing and trampling of soil may negatively affect soil quality by impairing soil structure, soil organic carbon (SOC) cycling and microbial activity (Lai and Kumar 2020). These changes result in a cascade of detrimental effects on the topsoil, including the reduction of plant cover, disturbed SOC dynamics, decreased soil stability and diminished water infiltration (Roesch et al. 2019; Taddese et al. 2002).

The objectives of this study were to (1) quantify the impact of horse-induced soil degradation and (2) determine the influence of differing paddock grid types with and without a wood chip buffering layer on physico-chemical and microbial soil properties in a field experimental setup. We hypothesized that:

i. We find horse-induced soil degradation after a 15-months period, evidenced by increased soil bulk density, and reduced microbial biomass and SOC.
ii. Unprotected trails (without paddock grids) show stronger negative impacts, characterized by higher soil bulk density, lower SOC, reduced microbial biomass and a slower vegetation recovery compared to trails with paddock grids.
iii. A wood chip buffering layer can further mitigate soil compaction and better sustain microbial growth and activity due to a more efficient pressure distribution of the grids.

Besides measuring direct impacts on soil quality and vegetation cover, we performed numerical simulations of stress transmission to better understand if and how paddock grids reduce mechanical impacts from horse trampling.

2 | Materials and Methods

2.1 | Paddock Trail Field Study: Site Description and Experimental Set-Up

A field experiment was established in 2022 in St. Aubin, western Switzerland (46°52′59.0″N 6°59′50.5″E) on an arable field (ploughing depth approximately 0.25 m depth) with a mean sand content of 32%, mean silt content of 32% and mean clay content of 37% in topsoil (0–20 cm). On this field, four identical paddock trail systems (i.e., four experimental blocks; Figure 1) were built between October 2022 and December 2022. Each paddock trail was 0.5 ha (30 m × 166 m) and included a sleeping and drinking area (15 m × 30 m; orange area in Figure 1), a feeding area (20 m × 30 m; blue area in Figure 1), a pasture (15 m × 31 m; green area in Figure 1) and a prepared trail used as a connecting path between the sleeping and drinking area (5 m × 131 m; purple area in Figure 1) with six treatments (each 5 m × 16.5 m; coloured boxes in Figure 1).

The construction and periodic sampling of the present experiment was approved by the Cantonal Veterinary Commission under licence No. 36983.

2.2 | Trail Treatments

Each trail consisted of six treatments (coloured rectangles in Figure 1), which were randomly distributed within a trail. Five out of six treatments included paddock grids, and one treatment was unprotected (Figure 2). A basic paddock grid ('HIT Weidegitter Green Trail' HIT, Hinrichs Innovation & Technik GmbH, Weddingstedt, Germany; dimension 400 mm × 600 mm × 45 mm) and a reinforced paddock grid ('TTE MultiDrain Plus', HÜBNER-LEE GmbH & Co. KG, Holzgünz, Germany; dimension 800 mm × 400 mm × 60 mm) were used to compare two types of paddock grids (hereafter referred to as 'basic' and 'reinforced'). Both grid types are widely used in practice. The *basic* paddock grid is lighter, softer and cheaper compared to the *reinforced* paddock grid. In each trail, both types of paddock grids were installed directly on the soil (Figure 2 $\text{BASIC}_{\text{Grass}}$; $\text{REINFORCED}_{\text{Grass}}$; $\text{REINFORCED}_{\text{Grass\_Stones}}$) and on an additional wood chip buffering layer (Figure 2 $\text{BASIC}_{\text{Wood}}$; $\text{REINFORCED}_{\text{Wood\_Stones}}$). The *reinforced* paddock grid additionally has the option to add cobblestones for further stabilization, so this paddock grid was tested three times: (i) without cobblestones on soil (Figure 2 $\text{REINFORCED}_{\text{Grass}}$) with 100% of the embayment surface available for the plants to grow, (ii) with cobblestones on the soil (Figure 2 $\text{REINFORCED}_{\text{Grass\_Stones}}$) with 50% of the embayment surface available for the plants to grow (and 50% filled with cobblestones), and (iii) with cobblestones installed on a wood chip buffering layer (Figure 2 $\text{REINFORCED}_{\text{Wood\_Stones}}$) and 50% of the embayment surface available for plant growth. The *basic* paddock grid was tested twice per paddock trail: directly installed on the soil (Figure 2 $\text{BASIC}_{\text{Grass}}$) and on a wood chip buffering layer (Figure 2 $\text{BASIC}_{\text{Wood}}$). Both basic

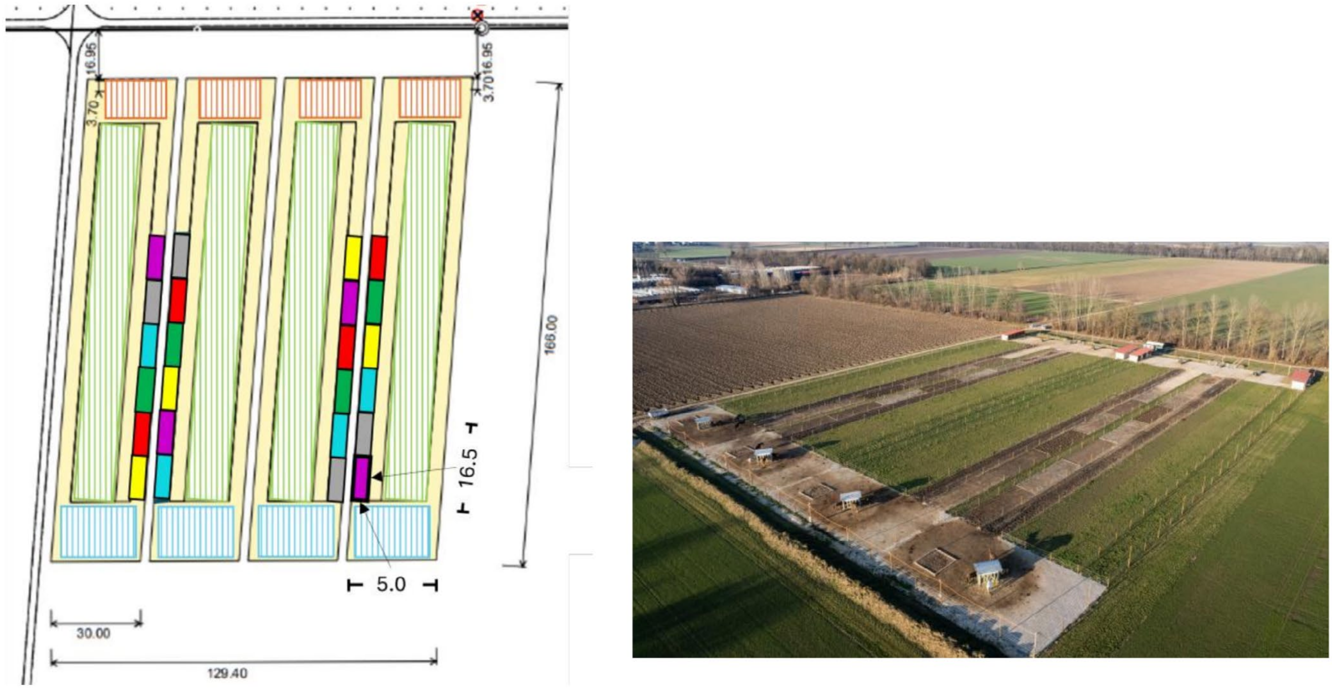

FIGURE 1 | Left: Illustration of the study site including four paddock trails, each with six treatments (coloured rectangles). Functional areas are visualized by coloured frames with pattern filling (sleeping and drinking in orange; feeding in blue; pasture in green). Right: Photo of the experimental study site housing 20 horses (5 per trail) taken in January 2024.

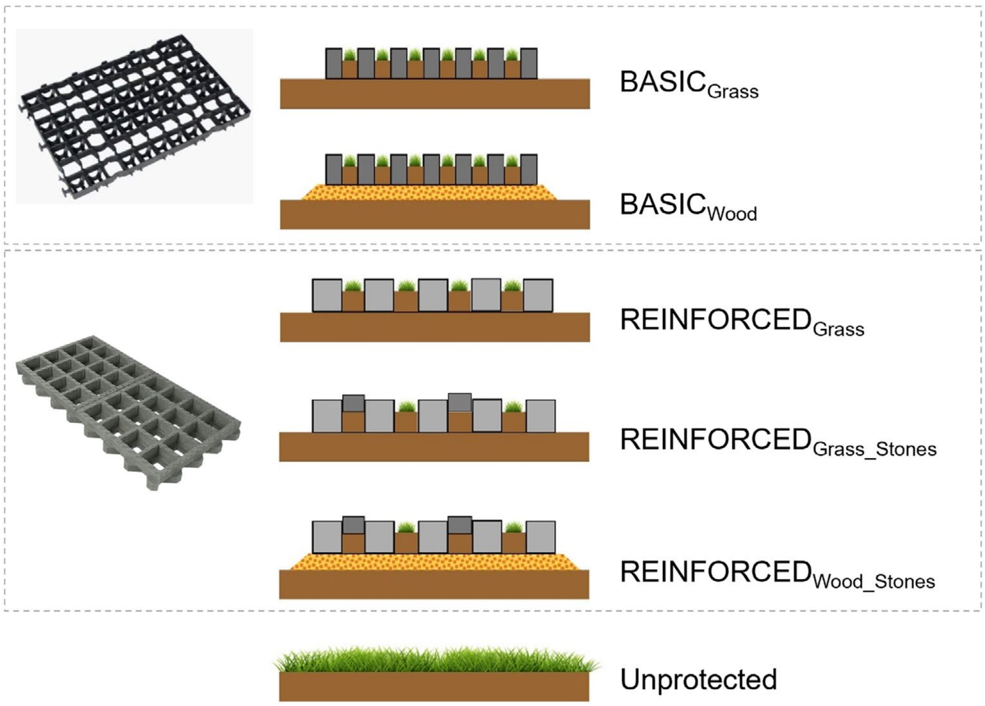

FIGURE 2 | Schematic representation of the six treatments used in this study with two types of paddock grids (BASIC and REINFORCED) and the unprotected trail. BASIC$_{Grass}$ is installed directly on the soil and BASIC$_{Wood}$ on a wood chip buffering layer. REINFORCED$_{Grass}$ is installed directly on the soil, REINFORCED$_{Grass_Stones}$ installed directly on the soil with integrated cobblestones, and REINFORCED$_{Wood_Stones}$ on a wood chips buffering layer and cobblestones. Unprotected represents the unprotected treatment consisting of grassland.

paddock grid treatments had 100% of the embayment surface available for plant growth. Finally, each trail also contained an unprotected treatment consisting of grassland (Figure 2 Unprotected).

The installation of the treatments occurred between October 2022 and November 2022. For this, approximately 5 cm of topsoil were removed with an excavator shovel, to ensure a plain surface before installing the paddock grids. During this procedure, the excavator shovel was operated without the machinery being positioned on the treatment area, thereby preventing any soil compaction resulting from the excavator. This soil removal was not done for the unprotected treatment (Unprotected in Figure 2), where the grassland remained untreated. If the treatments with paddock grids included a wood chip buffering layer ($Basic_{Wood}$ and $REINFORCED_{Wood\_Stones}$ in Figure 2), a single layer of wood chips (approximately 5 cm thickness) was evenly spread before the paddock grids were applied according to the specifications of the manufacturers. If the treatments with paddock grids did not require a wood chip buffering layer, the paddock grids were directly installed on the soil ($Basic_{Grass}$, $REINFORCED_{Grass}$ and $REINFORCED_{Grass\_Stones}$ in Figure 2). After installation, the previously removed surface soil layer was filled in the remaining free space between the plastic frames of the paddock grids. In spring 2023, each treatment was reseeded (UFA AG, Herzogenbuchsee, Switzerland) mixture Nr. 485 with *Festuca arundinacea* (tall fescue), *Lolium perenne* (English plantain), *Poa pratensis* (bluegrass), *Phleum pratense* (timothy grass), *Agrostis stolonifera* (creeping bentgrass) and *Cynosurus cristatus* (crested dog's-tail) seeds and the vegetation in the unprotected grassland trails was cut back with a grass trimmer and removed from the trails in June 2023 to allow a similar level of development of the vegetation and height across all treatments before the start of the experiment. In July 2023, the horses had access to the treatments for the first time and had permanent access until October 2024. Hence, the study reported here was conducted between July 2023 and October 2024, incorporating a total duration of 15 months of applied pressure through horse exposure.

2.3 | Horses

Twenty warmblood mares were housed on the four paddock trails in groups of five horses, to achieve a similar impact on the treatments in all four paddock trails. Horses were either shoed with steel horseshoes or barefoot, depending on their needs and their pre-experimental situation. The horses had access to a time-regulated feeding station and during summers (May to September), they additionally had restricted access to the pasture within the paddock trail for a limited number of hours per day. If horses were injured during the experiment, they were brought to a nearby clinic and returned to the paddock trails after the condition was fully cured. If a horse was injured to a significant degree, the horse was removed from the study, and a new mare was integrated into the group to ensure a similar pressure through horse exposure on each trail and ensure 20 horses (five per group) were housed in the system simultaneously.

2.4 | Continuous Measurements

2.4.1 | Estimation of Trail Use by Horses Using GPS Data

To get an estimation of how similar the four paddock trails were used by the horses, we collected Global Positioning System (GPS) data of coordinate position and corresponding time of each horse from June 2023, when the horses were put on the paddock trails, until July 2024. Data were collected each 4–5 weeks for seven consecutive days, at a frequency of 0.1 Hz using a GPS-data logger (Qstarz BT-Q1000XT from QSTARZ International Co. Ltd., Taiwan) with a modified battery pack allowing for long term data collection. The GPS-tracking device was put into a waterproof container, sufficiently padded and fixed to a modified cattle collar. We used the QSTARZ Data viewer software (version 3.00.000, Qstarz International Co. Ltd., Taiwan.) to read and view the tracked data from each device and to record it as a gpx file, which was then transcribed into a csv file using R 4.1.1 software (R Core Team 2021). Collective data from 2023 to 2024 including all horses were split into the four paddock trails in this study (with five horses per group) to obtain the mean distance walked per day of each group. This was calculated and graphically illustrated in R 4.1.1 software.

2.4.2 | Soil Water Content

Temperature-Moisture sensors (TMS) were used in this study to estimate the volumetric water content [m^3/m^3] at 20 cm depth (TMS-4 data logger, TOMST Inc., Chicago; length 0.29 m). One sensor per treatment per paddock trail and one sensor per trail in a horse-excluded control area next to the trails was buried into the soil. The TMS probes measure soil water content every 15 min using the time-domain transmission (TDT) method and store the data and the corresponding time using a 32.768-kHz crystal with an accuracy of ±2 min per month (Wild et al. 2019). Data were downloaded using the Lolly Software (version 1.57), a software provided by TOMST Inc. For treatments protected with paddock grids, the sensors were buried underneath the paddock grids (Figure 3). For the unprotected treatments and the horse-excluded control areas next to the trails, the sensors were buried directly into the soil at the same soil depth as the sensors of the trails with paddock grids (Figure 3). Daily precipitation data was obtained from a weather station in Praz (approximately 10 km away from the experimental site) provided by Agrometeo (Agrometeo 2025). During the experiment, the annual precipitation was 1068.5 mm in 2023 and 1177.5 mm in 2024.

2.5 | Occasional Soil Sampling and Analysis

Sampling of the top 5–35 cm (soil bulk density, air permeability and gas diffusion in 10–15 cm and 30–35 cm; microbial biomass and physico-chemical soil parameters in 5–20 cm) (Figure 3) of soil took place on four occasions. The first collection date was in October 2022, before the installation of the paddock trails, and the final samples were taken in October 2024 from all treatments, including all soil analysis. Additional samples were taken in October 2023 and March 2024 to monitor changes in soil compactness after 3 months and 8 months after the horses were put on the paddock trails, but included only the treatments $BASIC_{Grass}$, $REINFORCED_{Wood\_Stones}$ and the unprotected trails (Table S1) and only soil bulk density was analysed from these samples. This limited sampling design was done to monitor changes in the soil across the three treatments that differed the most and included both types of paddock grids, the installation on a wood chips buffering layer, as well as the unprotected soil.

At the beginning and at the end of this study, samples were taken on each of the six treatments on the four trails (24 plots in

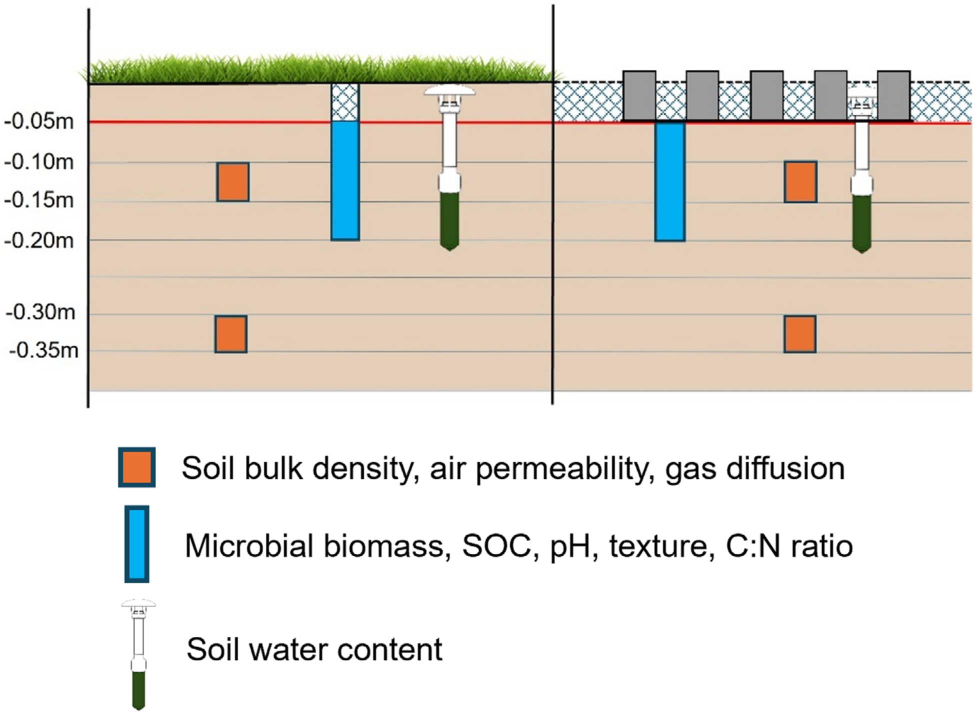

FIGURE 3 | Illustration of the sampling depths for soil bulk density, air permeability and gas diffusion (orange), microbial biomass and chemical parameters (SOC, C:N ratio, pH) (blue), and the sensors for soil water content of unprotected trails (left panel) and trails with paddock grids (right panel).

total) on three locations per plot according to the following criteria: (i) the sampling area was at least 1 m away from treatment borders, (ii) the three sampling locations per treatment were at least 4 m away from each other and (iii) the sampling locations were distributed across the whole treatment. For all treatments with paddock grids, a small opening had to be cut into the plastic frame of the paddock grid (using an Oszillierer MultiMaster AMM 300 PLUS, Fein GmbH, Germany) and the soil between the paddock grid was removed to sample the soil from underneath the paddock grids. For all unprotected treatments, the top 5 cm of the topsoil was removed before the samples were taken (Figure 3). This ensured that all samples from the trails with paddock grids and unprotected treatments were taken from the same depths and could be compared with each other (Figure 3). From each sampling location, samples for the analysis of SOC content, total carbon and nitrogen content, pH, soil bulk density, air permeability, gas diffusion and microbial biomass (carbon and nitrogen) were collected.

2.5.1 | Air Permeability and Gas Diffusion

Undisturbed soil core samples (diameter: 50 mm; height: 50 mm) were taken in two sampling depths (10–15 cm, and 30–35 cm) using a cylindrical closed tube soil sampler (Figure 3). A total of 144 samples were collected at each sampling date, including three soil samples in two soil depths per treatment and experimental block. All samples were individually packed in plastic containers and stored in a cool storage room (4°C) until further processing. Before the measurements, each sample was carefully prepared in the laboratory by cutting away any excess soil from the soil core and carefully pressing the soil close to the cylinder wall to minimize leakage of airflow and then equilibrated at a matric potential of −100 hPa.

For the measurement of air permeability, each cylinder sample was connected to an air permeameter (Martínez et al. 2016) and analysed using a steady-state method similar to Iversen et al. (2001). Airflow was recorded when the volumetric flow rate was stabilized at 2 hPa.

After measuring air permeability, all samples were used to analyse gas diffusion. For this, each cylinder sample was fixed into to a one-chamber apparatus (Martínez et al. 2016), similar to the one described by Schjønning et al. (2013), using O_2 as the diffusing gas. Rubber O-rings were applied to ensure no leaking of gas during the measurement. Before the start of the measurement, the head space above each sample cylinder was flushed with nitrogen, until oxygen concentration in the chamber went down from 21% to 0%. Then, each chamber was hermetically closed, and the measurement was started and finished after 45 min. The diffusion constant was determined from the relationship between time and the logarithm of the O_2 concentration difference (between the chamber and the ambient air) described by Schjønning et al. (2013). Reference samples made of Ytong (a mixture of limestone, cement, sand and air; Hug Baustoff AG, Switzerland) were analysed in between measurements of soil samples to guarantee a consistent quality of data.

2.5.2 | Soil Bulk Density

The undisturbed soil core samples used for air permeability and gas diffusion were oven dried (105°C) for at least 48 h and cooled down in a hermetically closed vacuum desiccator to prevent any water absorption during the cooling process. When cooled off, each cylinder sample was weighed and the soil bulk density [g/cm^3] (BD) was calculated. As the stone content within each cylinder sample was negligible, total bulk density measured equalled fine soil bulk density.

2.5.3 | Microbial Biomass

For assessing microbial biomass, approximately 1.5 kg of soil was collected from the topsoil (5–20 cm; Figure 3) as a composite using a Pürckhauer drill (UKB System Technology GmbH Geotechnik, Germany; diameter: 3 cm). Three locations (as basis for the composite sample) per treatment resulted in a total of 72 samples at each sampling date. Each sample was collected in a labelled plastic bag and stored in a cool storage room (4°C) until further processing. The preparation of each sample included the removal of stones and visible living or unprocessed organic matter (earthworms, plant material), and the sieving of the field-fresh sample to 2 mm. Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) was quantified using the fumigation extraction method according to Vance et al. (1987). For this, each sample was split into two parts, where one part was fumigated with chloroform for 24 h and the other part remained unprocessed. The microbial biomass (carbon and nitrogen) was then calculated by comparing the fumigated and non-fumigated soil of each sample. The results are given as microbial biomass carbon [mg C(FE)/kg soil dry matter] and microbial biomass nitrogen [mg N(FE)/kg soil dry matter], with an accuracy of 1 mg (Agroscope 2020). The C:N ratio of microbial biomass (CN_{mic}) was calculated by dividing MBC by MBN of each sample.

2.5.4 | Physico-Chemical Soil Parameters

The remaining sieved (< 2 mm) soil material of the samples used for the microbial biomass (5–20 cm) was further used to analyse pH, SOC, total carbon (C) and nitrogen (N) and soil texture. For this, the sieved samples were oven dried (40°C) for 24 h. Soil pH was determined with a water suspension test and a soil: water ratio of 1:2.5. SOC was measured by wet combustion, using potassium dichromate and sulphuric acid (ISO 10694) according to Walkley and Black (1934). Soil texture was determined with the pipette method and classified according to USDA classification (USDA 1993). Total C and N in the soil were evaluated using the Dumas combustion method with an elementary analyser (ISO 13878). The soil carbon to nitrogen ratio (C:N ratio) was evaluated by dividing the total C by the total N of each sample.

2.6 | Vegetation Cover Estimation

We documented the condition of each treatment's vegetation cover by creating an orthomosaic drone image (DJI Mavic II, DJI, China) on four occasions (June 2023, June 2024, October 2024 and May 2025). The images were created by flying over the paddock trail system on a preset route at an altitude of 40 m above soil surface using the Pix4D application (Pix4D S.A., Switzerland). During each flight, we collected 338 single images, which were subsequently stitched to a single orthomosaic image. We then created a polygon detailing each treatment based on the orthomosaic drone image in QGIS Desktop version 3.34.4 (QGIS, Switzerland). To mitigate any fence effects, the total polygon of each treatment (2400 pixels) was reduced in size (350 × 1400 pixels (width × height)) to cover only the central part of each treatment. The treatments of each trail were separated and saved as tiff images, resulting in a total of 24 processed images per flight. In a next step, the polygon and the drone image were processed in R version 4.3.3. R Core Team (2021) using the R package *terra* to create raster data for each polygon containing pixels with stored values about the specific vegetation cover.

Our approach uses only one index and a single clustering step to distinguish green cover from background. For each valid pixel (i.e., non-transparent or non-black), we calculated the Excess Green (ExG) index (Killian et al. 2025): ExG = 2 × G—R—B, where R, G and B are red, green and blue channel values respectively. In a second step, we pooled the ExG values of all pixels from each image into a single vector containing all ExG pixel values due to a formatting issue, on which the clustering was then performed. Then, we ran *k*-means with $k = 2$ to divide the data into two clusters. The cluster with the higher average ExG was labelled 'Vegetation' and the other 'No Vegetation'. In a last step, we computed the silhouette coefficient (> 0.5), allowing to determine the quality of clustering.

2.7 | Simulations of Soil Stress Reduction by Paddock Grids

To simulate how paddock grids modulate soil stress and to assess differences in horse-induced soil stress across treatments, we used the finite element modelling (FEM) framework of COMSOL Multiphysics Version 6.3 (COMSOL Inc., Burlington, Mass., USA). The model allowed us to investigate how material properties and design of the protective material (i.e., Young's modulus [E], Poisson's ratio [ν] and grid height [h]) affect the vertical stress (σ_v) propagation in soil. The geometry consisted of a 2D axisymmetric problem with a soil domain (3 m radius and 3 m depth) and a circular plate with 0.6 m radius on the soil surface representing the paddock grid as protective material. As boundary conditions, we restricted the displacements in radial (horizontal) direction, u and the displacement in axial (vertical) direction at the lower boundary, w, (Figure S1). A free triangular mesh with approximately 2192–2261 elements (depending on the simulation scenario) was applied to the model.

We used a linear-elastic model as a constitutive relationship, which was applied to both the soil and protective material domains. Young's modulus (E), Poisson's ratio (ν) and bulk density (ρ) of the soil domain were considered as $E_{soil} = 3000$ kPa, $\nu = 0.33$ and $\rho = 1.0\ \mathrm{Mg\,m^{-3}}$, respectively, which are typical properties of arable soils (Keller et al. 2014). For paddock grids, we varied E by 1, 10, 100, 1000, 10,000 or 100,000 times the E_{soil}, whereas ν were assigned values of either 0.25, 0.30, 0.35 or 0.40. Simulations were performed for paddock grid heights of 1, 5, 10 and 20 cm. Bulk density of the simulated protective material was $0.91\ \mathrm{Mg\,m^{-3}}$, corresponding to Polypropylene polymer, obtained from the COMSOL Multiphysics material properties library. The load from a horse leg was simulated by applying a surface pressure of 200, 400 or 800 kPa on top of the paddock grid, over a circular area with a 14 cm diameter (similar to the diameter of a horse's hoof) (Figure S1). The three different stress levels correspond to the stress applied by a walking, trotting and galloping horse (Witte et al. 2004, 2006; Bobbert et al. 2007). To compare the vertical stress reaching the soil with and without paddock grids, we also simulated a scenario without a protection plate, that is, with the stress applied directly on the unprotected soil.

2.8 | Statistical Analysis

All statistical analysis were performed using the R 4.1.1 software (R Core Team 2021). Visual inspections of the distribution (histogram and Q-Q plot) and a Shapiro–Wilk tests were performed to ascertain normal distribution of the data. An ANOVA Linear-Mixed Effects Model was used to compare soil properties between the treatments with y ~fixed effect + (1|random effect). Depending on the analysis, y was either the soil bulk density, microbial biomass (MBC and MBN), pH, soil C:N ratio, SOC or gas transport properties (gas diffusion and air permeability). The fixed effects considered the different treatments, the time of sampling and, only for bulk density, different sampling depths. The random effects included the four different paddock trails, containing an interaction between the four paddock trails and the different treatments, as well as the difference in sampling depths. A post hoc paired-sample *t*-test was conducted using the t.test() function in R to find statistical differences in soil quality parameters (soil bulk density, microbial biomass, pH, soil C:N and SOC) between treatments and across the different sampling dates. Statistical significance was defined at $p = 0.05$. Symbols used to indicate significance were used according to APA style 7th edition with ns = $p > 0.05$, *$p \leq 0.05$, **$p \leq 0.01$ and ***$p \leq 0.001$.

3 | Results

3.1 | Changes in Physico-Chemical Soil Properties Under Various Paddock Trail Treatments

The GPS-data we collected over 1 year showed similar mean daily distance walked by the horses in the four groups in this study (Figure S2). This indicates that the pressure of the horses on the soil was comparable across the four paddock trails. Seasonal patterns revealed a lower pressure during winter (October until March) due to a lower mean daily distance walked during those months.

From 2022 to 2024 and across all treatments with and without paddock grids, we measured a significant increase in soil bulk density in the topsoil (10–15 cm depth), subsoil (30–35 cm depth) or both, for most treatments. Bulk densities in the topsoil (10–15 cm) were always lower than in the subsoil (30–35 cm) across all sampling dates and treatments (Table 1, Table S1). The highest increase in bulk density in the topsoil (+15.9%) and the subsoil (+14.6%) was measured for BASIC$_{Grass}$. The second largest increase in bulk density was found for the unprotected trail with a significant increase both in the topsoil (+11.0%) and the subsoil (+18.2%). No significant increase in bulk density was found in the topsoil of REINFORCED$_{Wood_Stones}$ with a percentage increase of +2.6% in the topsoil and +8.4% in the subsoil. In addition to the increase in bulk density, we measured a significant decrease in air permeability (Lperm) (Table 1) and gas diffusion (Table S2) across all treatments from 2022 to 2024, suggesting a decrease in the continuity and connectivity of soil pores.

Compared to the conditions before the start of the trial, no statistically significant change in SOC could be found across all treatments except for both types of paddock grids installed on wood chip buffering layer (BASIC$_{Wood}$; REINFORCED$_{Wood_Stones}$), where we found an increase in SOC in the soil (Table 1). A significant increase in the soil C:N ratio was observed across all treatments, except for the REINFORCED$_{Wood_Stones}$ treatment and the unprotected trail, which revealed the lowest increases in soil C:N ratio. We also found a minor increase in pH in all treatments except the unprotected trail.

3.2 | Impact of Paddock Trail Treatments on Soil Microbial Biomass

Mean values of MBC decreased from 2022 to 2024 in all treatments (Figure 4A), but due to large variation in the data, changes were not significantly different between treatments or timepoints. The highest, and only significant decreases in MBC were found for the unprotected trail (−21.3%) and REINFORCED$_{Grass}$ (− 16.3%). In contrast, MBN increased in most treatments, though again not significant in most cases due to high variation. The only significant increase in MBN was found for BASIC$_{Wood}$ with a positive percentage change of 37.4% from 2022 to 2024. The only decrease in MBN was measured in the unprotected trail, with a non-significant decrease of −5.1% from 2022 to 2024 (Figure 4B).

Due to the overall reduction in MBC and the increase in MBN, the C:N$_{mic}$ reduced significantly for all treatments from 2022 to 2024 (Figure 4C). The smallest change in C:N$_{mic}$ was found for the unprotected trail (−16.7%), while the largest change was in REINFORCED$_{Wood_Stones}$ (−34.9%).

3.3 | Impact of Paddock Trail Treatments on Vegetation Cover and Vegetation Recovery Within 7 Weeks After Horses Were Removed From the Trails

Notable differences in the vegetation cover were observed between trails with and without paddock grids. Before the experiment started and the horses were put on the trails in June 2023, we already observed differences in growth and coverage ratio of the freshly reseeded vegetation across the treatments (Figure 5A). At the start of the experiment, the highest vegetation cover was found for the unprotected trails with a near perfect coverage ratio (99.7 (0.2)%). Comparing the different treatments with paddock grids showed high vegetation coverage for both types of paddock grids when installed directly on the soil (BASIC$_{Grass}$ 87.2 (1.9)%; REINFORCED$_{Grass}$ 75.5 (6.8)%). The reinforced paddock grid with cobblestones (REINFORCED$_{Grass_Stones}$) had a lower vegetation coverage of 37.5 (16.5)% (with only 50% of the embayment surface available for the plants to grow). Both types of paddock grids with wood chips buffering layers (BASIC$_{Wood}$;

TABLE 1 | Mean values and standard deviations (in brackets) of soil organic carbon content (SOC), soil C:N-ratio, pH, soil bulk density and air permeability (Lperm) of the installation of the treatments with the basic paddock grid (BASIC) directly installed on the soil ($BASIC_{Grass}$) or on a wood chip buffering layer ($Basic_{Wood}$), the reinforced paddock grid (REINFORCED) directly installed on the soil ($REINFORCED_{Grass}$), with integrated cobblestones installed directly on the soil ($REINFORCED_{Grass\_Stones}$) or with integrated cobblestones on a wood chip buffering layer ($REINFORCED_{Wood\_Stones}$), and the unprotected trail (Unprotected).

Installation	Sampling date	SOC [g/kg]	Soil C:N ratio	pH [in H_2O]	Bulk density [g/cm^3]		Lperm [µm^2]	
Sampling depth [cm]			5–20		10–15	30–35	10–15	30–35
$BASIC_{Grass}$	Autumn 2022	22.1 (3.19)	8.7 (0.10)	7.1 (0.44)	1.3 (0.1)	1.4 (0.2)	62.2 (45.9)	14.8 (16.2)
	Autumn 2024	20.3 (4.27)	10.1 (0.91)	7.3 (0.15)	1.5 (0.1)	1.6 (0.1)	0.4 (0.7)	0.2 (0.3)
	% change [%]	−10.0	+15.7***	+2.8	+15.9***	+14.6**	−99.4***	−98.8***
$BASIC_{Wood}$	Autumn 2022	22.1 (3.19)	8.7 (0.10)	7.1 (0.44)	1.3 (0.1)	1.3 (0.1)	48.9 (29.0)	13.2 (9.2)
	Autumn 2024	25.4 (6.10)	10.4 (1.01)	7.3 (0.19)	1.4 (0.1)	1.4 (0.1)	0.2 (0.3)	1.4 (2.8)
	% change [%]	+12.1	+19.9***	+2.9	+8.8**	+9.7*	−99.7***	−89.1***
$REINFORCED_{Grass}$	Autumn 2022	22.1 (3.19)	8.7 (0.1)	7.1 (0.44)	1.3 (0.1)	1.3 (0.1)	15.1 (16.7)	20.4 (27.1)
	Autumn 2024	20.3 (2.37)	9.9 (0.91)	7.2 (0.19)	1.4 (0.1)	1.5 (0.1)	0.4 (0.5)	0.4 (0.5)
	% change [%]	−9.0	+13.8***	+2.4	+5.3*	+14.3***	−97.6***	−98.3***
$REINFORCED_{Grass\_Stones}$	Autumn 2022	22.1 (3.19)	8.7 (0.10)	7.1 (0.44)	1.2 (0.1)	1.3 (0.1)	50.4 (56.2)	17.0 (18.6)
	Autumn 2024	22.2 (3.25)	9.2 (0.92)	7.4 (0.27)	1.4 (0.1)	1.5 (0.1)	0.6 (0.8)	0.3 (0.3)
	% change [%]	−1.2	+6.4	+5.4*	+9.5**	+10.7**	−98.8***	−98.4***
$REINFORCED_{Wood\_Stones}$	Autumn 2022	22.1 (3.19)	8.7 (0.10)	7.1 (0.44)	1.3 (0.1)	1.3 (0.1)	41.9 (64.5)	9.9 (17.4)
	Autumn 2024	25.0 (3.48)	10.6 (1.64)	7.4 (0.17)	1.3 (0.1)	1.4 (0.1)	1.5 (4.2)	0.6 (1.0)
	% change [%]	+11.0*	+22.3**	+4.8*	+2.6	+8.4*	−96.4***	−94.1***
Unprotected	Autumn 2022	22.1 (3.19)	8.7 (0.10)	7.1 (0.44)	1.3 (0.1)	1.3 (0.1)	37.8 (47.3)	23.0 (27.8)
	Autumn 2024	20.3 (3.57)	8.9 (0.91)	6.8 (0.32)	1.4 (0.1)	1.6 (0.1)	0.25 (0.4)	8.58 (14.7)
	% change [%]	−9.9	+2.1	−3.5	+11.0**	+18.2***	−99.3***	−2.7***

Note: The percentage change [%] represents an increase (+) or decline (−) of the soil property values from autumn 2022 (before the paddock trails were built) to autumn 2024. The asterisks indicate a statistical significance (ns = $p > 0.05$, *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$) of the difference between 2022 and 2024.

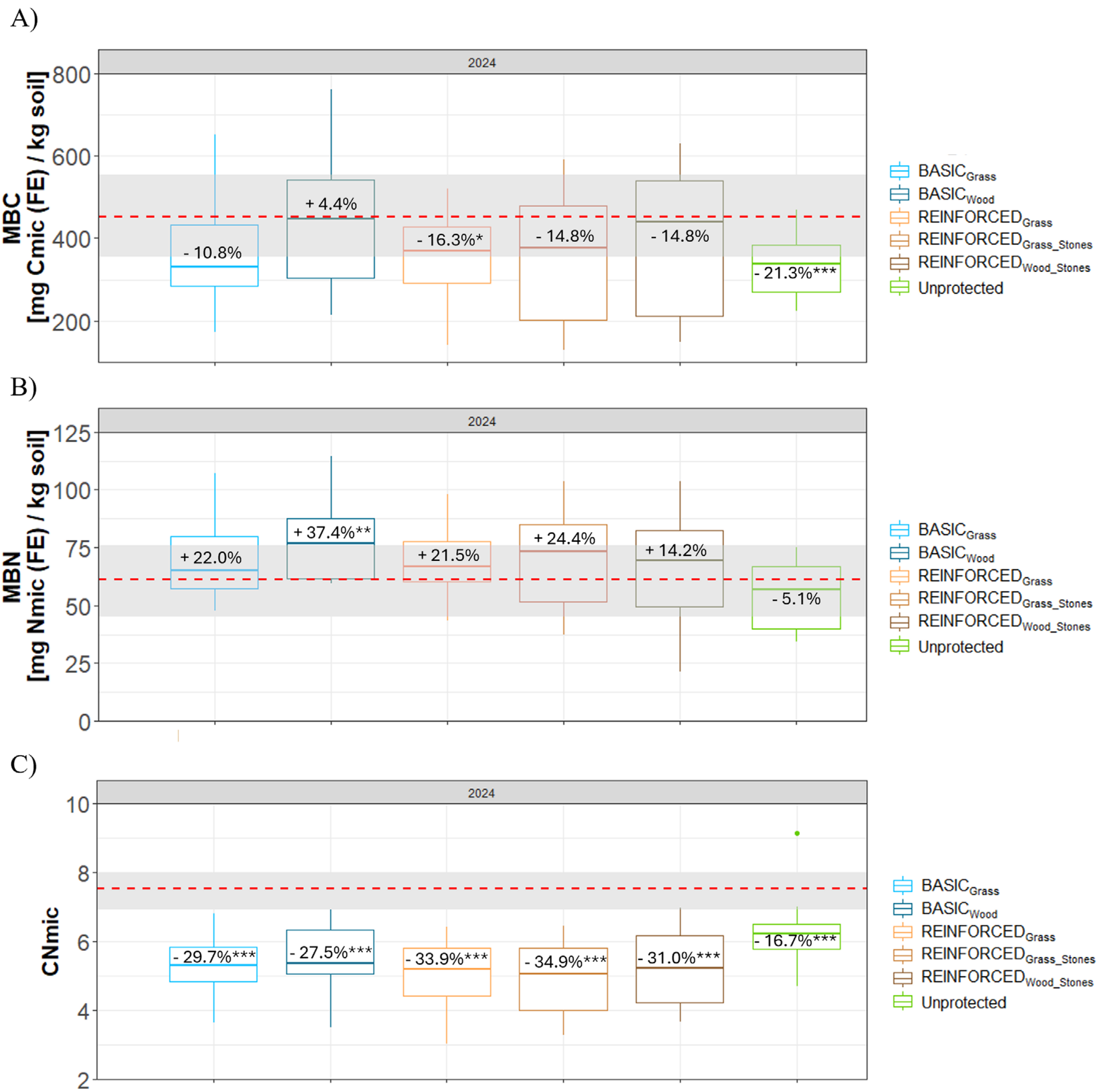

FIGURE 4 | Boxplots of microbial biomass (A) carbon, (B) nitrogen and (C) microbial C:N ratio of all treatments in 2024. The red dotted line represents the median value of the whole study field in 2022 (before the installation of the paddock trails) and the grey area represents the range (min–max values) of these values. The percentages represent the deviation of the median from each treatment from the values recorded in 2022.

REINFORCED$_{WOOD_Stones}$) had notably lower vegetation coverage with a coverage percentage of 0%–1%. In June 2024, after 1 year of the horses being on the trails, we found a complete loss of vegetation in all treatments with and without paddock grids despite variation at the start of the trial (Figure 5B). This loss of vegetation was still noticeable in October 2024 for all treatments (Figure 5C), after 15 months of permanent horse pressure. A recovery of the vegetation was detected in May 2025 after the horses had not been on the trails for 7 weeks (Figure 5D). Vegetative cover was 88.6 (7.6)% for REINFORCED$_{Grass}$, followed by REINFOCED$_{Grass_Stones}$ (57.9 (31.1)%; with only 50% of the embayment surface available for the plants to grow), and lower recovery for BASIC$_{Grass}$ (23.7 (30.4)%). Nearly no vegetation recovery was found for the unprotected trails, where we still observed largely bare and uneven soil.

3.4 | The Influence of Paddock Grids on Soil Moisture Dynamics

We measured no significant differences in mean volumetric water contents of the different treatments when considering all data from July 2023 to October 2024. However, the mean volumetric water content in the horse-excluded control areas next to

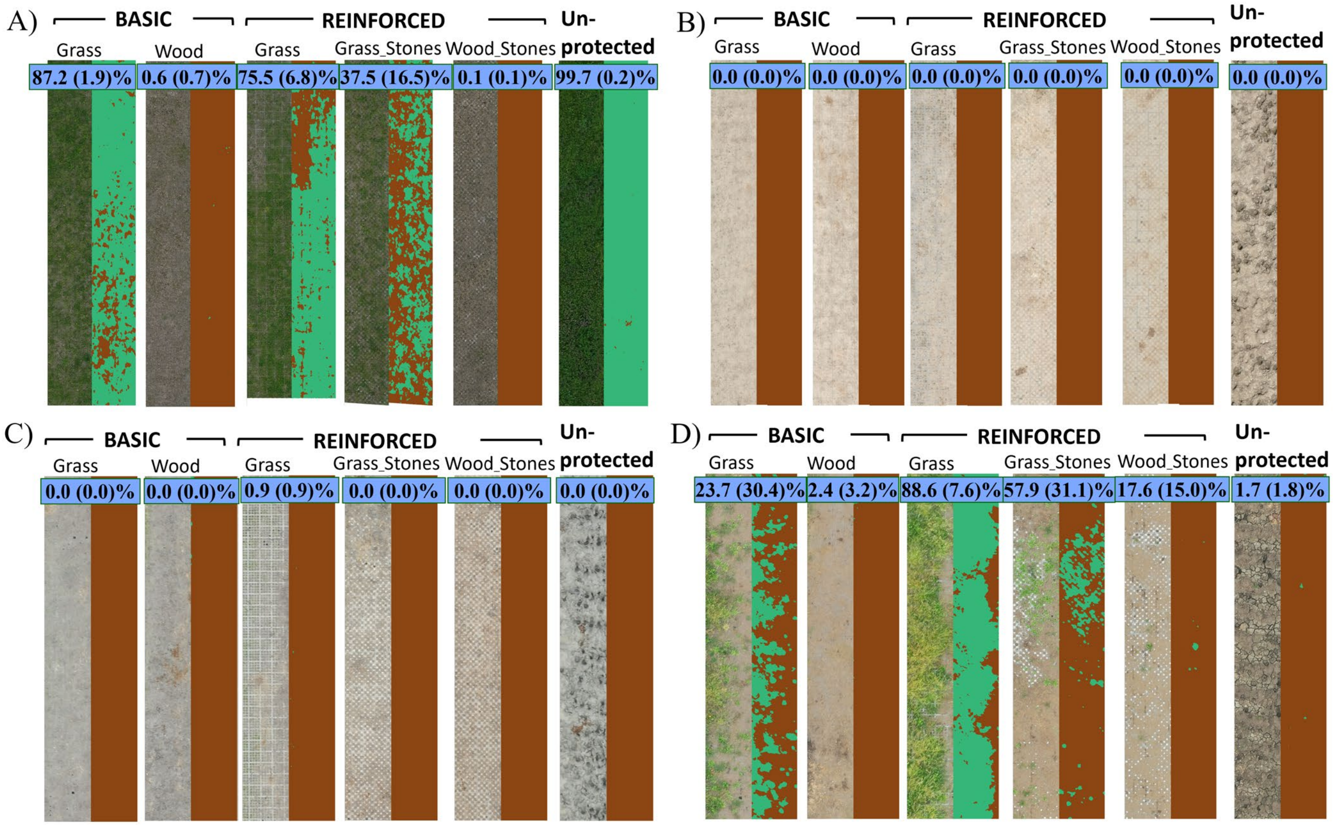

FIGURE 5 | Vegetation cover monitoring of all six treatments, where vegetation is marked in green and bare soil (= no vegetation) is marked in brown. (A) before the horses were kept on the paddock trails (June 2023), (B) after 1 year of the experiment (June 2024), (C) at the end of the experiment (October 2024) and (D) after the experiment was finished and the trails were not used by the horses for 7 weeks (May 2025). The information in the blue boxes represent the mean areal percentage with standard deviations (in brackets) of the vegetation for each treatment across all four paddock trails.

the paddock trails was significantly lower compared to all treatments with and without paddock grids.

Focusing on a specific period in September and October 2023, with changing wet—dry—wet weather conditions revealed differences between treatments in the dynamics of soil wetting and drying (Figure 6). We measured an increase in volumetric soil water content during both rain events and a decrease during the dry period between these events in the horse-excluded control area, but much lower increases and decreases in the soil of all treatments. For the treatments, we noticed a stable and elevated volumetric water content after the first rain and consequently, a smaller change in water content during the following precipitation and dry phases. This was especially clear in the soil of the REINFORCED$_{\text{Wood_Stones}}$, with a lower dynamic and a higher degree of saturation in the soil. Specifically, during a 47-day period, the horse-excluded control area had a lower mean (0.25 m^3/m^3) and more dynamic volumetric water content (range: 0.21–0.32 m^3/m^3) than all treatments used by horses (mean: 0.34 m^3/m^3; range: 0.27–0.40 m^3/m^3) (Figure 5).

3.5 | Paddock Grid Material Stiffness and Height Influence Protective Effect

The simulations indicated that soil stress decreases when the height of the paddock grid increases and/or when the Young's modulus of the grid material increases (Figure 7). For example, our analysis shows that the stress under a paddock grid of 5 cm height and a Young's modulus of 10^6 kPa (corresponding to HDPE, similar to the grids used in the study; Figure 7 red strip) is 10%–20% of the stress reaching the soil without paddock grid at 10 cm soil depth and 30%–40% at 30 cm depth (Figure 7 green area). In other words, stress is reduced by a 5 cm thick paddock grid by 80%–90% at 10 cm depth and 60%–70% at 30 cm depth.

4 | Discussion

4.1 | Decrease of Soil Quality of Paddock Trails With and Without Paddock Grids

The findings of this study suggest harmful consequences of horse paddock trails on the physicochemical properties of both top- and subsoil after a 15-month period, confirming our hypothesis of horse-induced soil degradation and the results from the on-farm study from Hiltebrand et al. (2025). Comparing treatments with and without paddock grids revealed no clear answer about the suitability of paddock grids because we found degrading effects in soil and vegetation for all treatments, some effects stronger and others weaker. The significant increase in soil bulk density, as well as the significant decrease in air permeability (Table 1) and gas diffusion (Table S2) in all treatments indicate compaction due to the

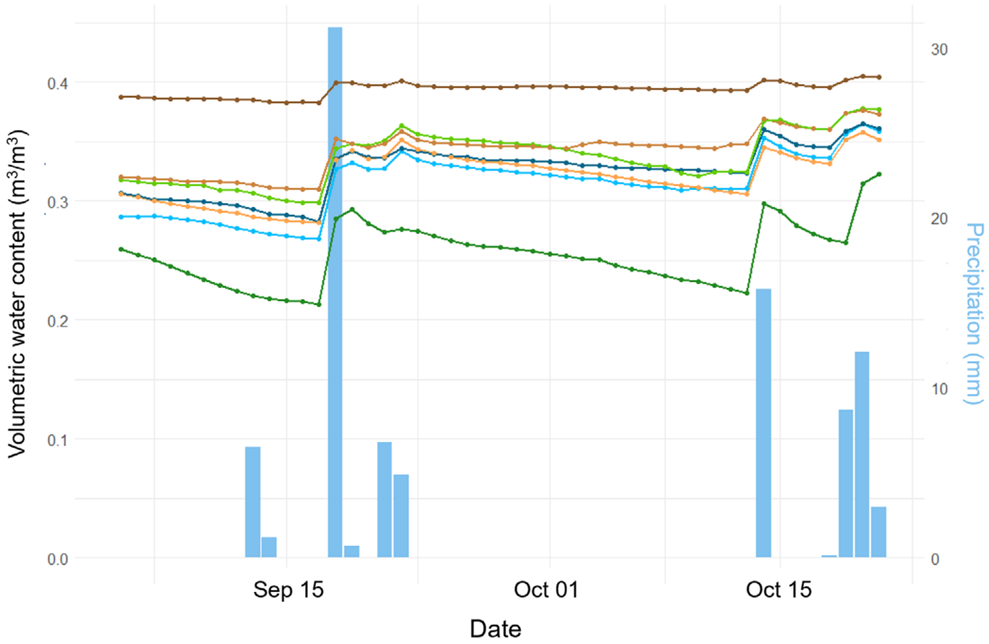

FIGURE 6 | Daily precipitation (blue bars; mm/m^2) and mean daily volumetric water content (m^3/m^3) of all treatments and horse-excluded control areas next to the trails during a wet—dry—wet weather condition in September and October 2023. The curves represent averages of the six treatments over the four paddock trails.

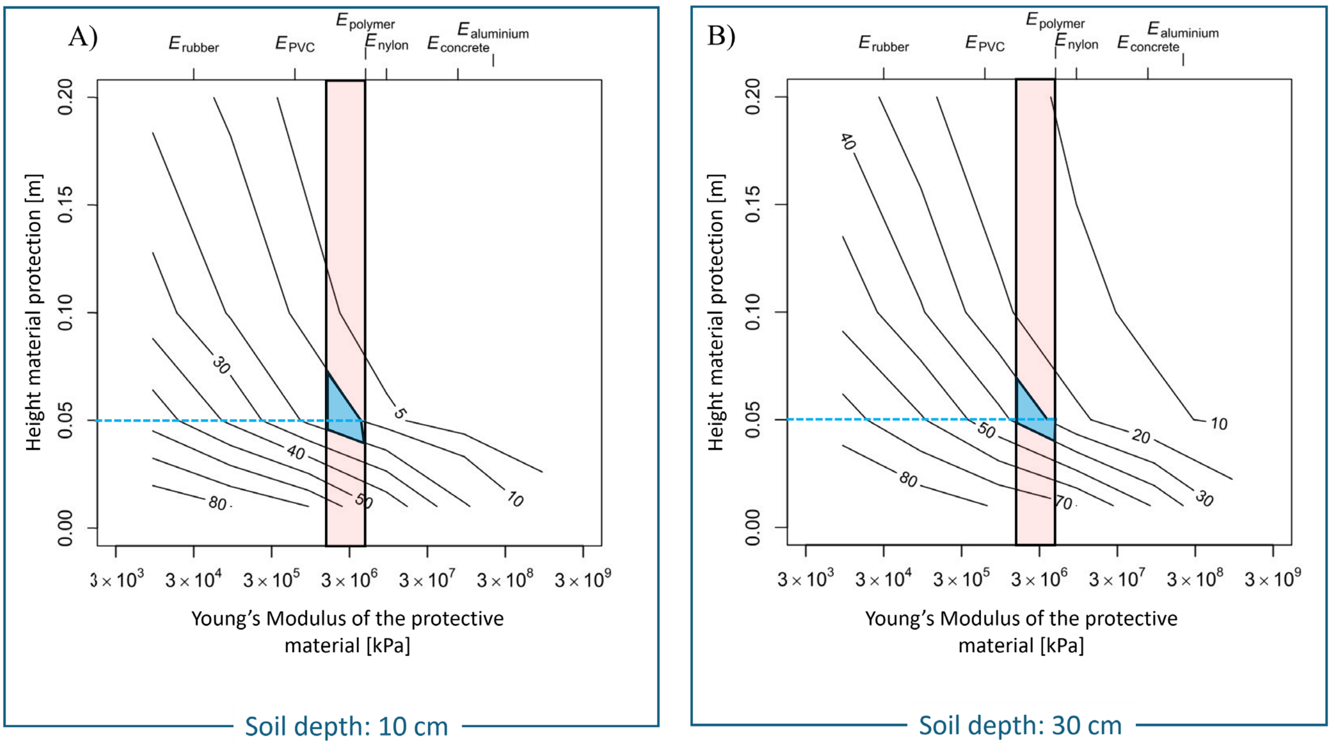

FIGURE 7 | Percentage (%) of relative vertical stress reaching (A) 10 cm depth and (B) 30 cm depth with the use of protective material (paddock grids) in relation to the soil without protection (unprotected trails) (i.e., $\sigma_{material}/\sigma_{soil}$) for a given material height (m) and Young's Modulus (kPa). The Young modulus of the protective material (as a reference, $E_{soil} = 3 \times 10^3$ kPa) and the corresponding stiffness of common materials (Ashby and Jones 1980) are represented on the *x*-axis. The vertical red bar indicates the Young Modulus of High-Density-Polyethylene (HDPE) (4.5×10^5–1.5×10^6 kPa (Tebeta et al. 2020); COMSOL Multiphysics)—a material similar to the paddock grids used in this study. The blue area represents the vertical stress transmitted to the soil at 10 cm and 30 cm depth, beneath a 5 cm-thick protective material (paddock grids) as implemented in our experimental setup.

construction of the paddock trails and horse trampling during the 15 months of the experiment, leading to a disturbed continuity and connectivity of soil pores. These changes are likely to negatively impact important soil processes and functions such as water and gas transport, biological activity and root growth (Deubel et al. 2011). Looking at the timeline of these structural changes in soil showed, that the increase in bulk density was not constant throughout the length of the study, as we measured lower, yet non-significant, bulk densities in spring than in the preceding autumn (Table S1). This may be associated with a higher mean precipitation in winter and subsequently swelling of clay particles (Fernandes et al. 2015) and partial loosening of the soil until spring, leading to lower bulk densities in spring. Additionally, we measured an overall lower mean daily distance walked by the horses during the winter months (October until March) (Figure S2). Therefore, treatments observed a lower pressure over the winter, possibly leading to a lower soil bulk density in spring than the preceding autumn. Notably, all treatments had this seasonal variation except the unprotected trail, for which we measured a continuous increase in bulk density from 2022 to 2024.

The negative influence of soil compaction on water infiltration is well known (Horton et al. 1994; Ngo-Cong et al. 2021). This in turn can induce ponding and potentially flooding (Khaerudin et al. 2017; Hidayati et al. 2021). Ponding was only observed in the unprotected trails in this study, although the soil bulk density, air permeability, gas diffusion and volumetric soil water content were similar to the treatments with paddock grids. The ponding in the uncovered treatments is likely caused by soil kneading from horse trampling to about 30–40 cm soil depth, resulting in an impermeable soil layer. In fact, extreme ponding, disruption of wet soil through trampling, and freezing of the soil made the unprotected trails inaccessible during winter 2023/2024 and all unprotected trails had to be rerouted because the horses refused to pass it due to the muddy and frozen conditions. As a result of rerouting, treatments without paddock grids used more than twice the land area during winter compared to those with paddock grids, which remained traversable under winter and wet conditions. A disrupted water infiltration in the soil of all treatments, possibly caused by the increase in soil compaction and trampling, was also demonstrated during the wet-dry-wet weather condition in 2023, where we measured stable and elevated soil moisture contents. This indicates a high degree of saturation in the soil and a disturbed ability of drying and rewetting of the soil.

Although we found no significant difference in soil structural properties between the two types of paddock grids, the FEM simulations indicate that the combination of height and stiffness of the material has a great influence on the stress reaching the soil and ultimately, the degree of protection. This aligns with the lower bulk density found for the reinforced paddock grid, which was bigger in size (height) and had a higher material stiffness compared to the basic paddock grid. Simulations suggest that a 5 cm-thick paddock grid (similar to the ones we used in this study) reduces the soil stress by 80%–90% in the topsoil and by 60%–70% in the subsoil in relation to the soil without protection (Figure 7), however, such a strong difference was not reflected in our measurements of soil bulk density. According to the FEM results, even a material with low stiffness can protect the soil if the protecting material (paddock grid) has sufficient height. However, high paddock grids with low material stiffness might not be feasible in practice due to a high price per paddock grid and low durability because of abrasion. Differences between stress simulations and measured soil impact (i.e., bulk density) may in part be explained by the fact that simulations were performed using a solid plate although paddock grids are perforated. A perforated material has a lower Young's modulus than a solid material (Cepkauskas and Jianfeng 2005) which would influence the pressure distribution of the horses on the soil and transmission of stress in the soil.

A decrease in MBC from 2022 to 2024 was found for all treatments, despite the unchanged SOC, a common resource for soil microbiota to grow. This suggests that the impairment of MBC was influenced by other factors like the degraded soil structure, creating less suitable environments for soil microbiota, including a decrease in porosity (an increase in bulk density), disturbed continuity and connectivity of soil pores, which reduces soil aeration and results in higher soil moisture (Cui and Holden 2015) as also found in this study (Table 1, Figure 6).

The significant decrease in $C{:}N_{mic}$ we found for all treatments, indicates a shift in soil microbial community composition (from fungal to bacterial community) and biomass, which can further have an impact on N cycling (Huang et al. 2013), and on the decomposition of soil organic matter and carbon sequestration (Bhattacharyya et al. 2022). Low significances in chemical parameters between treatments could be the result of a short experimental period, as 15 months might not have been long enough to observe significant changes in these properties.

4.2 | Effect of Paddock Grids on Vegetation Cover

A notable decrease in vegetation cover was measured in all treatments. A similar rapid decrease in vegetation was previously described by Hiltbrunner et al. (2012), who studied the effects of cattle trampling on soil properties and the vegetation cover. Although we found no difference in vegetation cover between treatments during the study, we found notable differences in the vegetation recovery 7 weeks after the horses were removed from the trails (Figure 5D). The reinforced paddock grid enabled a faster vegetative recovery than the basic paddock grid when installed directly on soil. The lower soil bulk density observed under the reinforced paddock grids compared to the basic paddock grids may have facilitated a more rapid recovery after the horses were removed from the paddock trails. In contrast, no vegetation recovery was measured in the unprotected trail, indicating a severe disturbance of vegetation on this treatment. This is consistent with the soil analysis data, as we found the second highest soil bulk density, a low air permeability, and the only significantly lower MBC in the unprotected trail, which might have negatively influenced the vegetation recovery additionally to the constant trampling and grazing of the horses during the trial. This partially confirms our hypothesis about the slower vegetation recovery of unprotected trails, although we could not confirm the overall lower soil quality compared to treatments with paddock grids.

4.3 | No Protective Effect of Wood Chips Buffering Layer on Soil Properties but Negative Effect on Vegetation Cover

No evidence was found in our study that could demonstrate an additional protection of the wood chips under the paddock grids against soil compaction, even though the FEM simulations suggest a lower soil stress in case of a higher protective material (Figure 7). Positive effects of wood chips amendments on soil quality have been reported in the literature (Barthès et al. 2010; Fontana et al. 2023). The only significant influence we found in our study that can be associated with the wood chip buffering layer is the increase in SOC we found for both types of paddock grids (Table 1), probably through slow decomposition of the wood chips and continuous input of SOC into the soil. This might be similar to the finding of Fontana et al. (2023), who determined positive influences of ramial wood chips amendments on carbon storage and soil physical properties and found increased SOC levels in their study.

We found the wood chips buffering layer to have a significantly negative impact on the vegetation regrowth in June 2023 (after reseeding and before the horses were on the trails) and after 1 year of exposure to horses, with a vegetation cover of approximately 0% for both types of paddock grids (Figure 5). The reason for this is likely that the wood chips layer underneath the paddock grids acted as a barrier for plant roots, preventing them from growing deeper roots, which lowers the plant's stability and also reduces aboveground biomass (Li et al. 2023). We found no evidence that the slow degradation of the wood chips buffering layer under the paddock grids influenced soil pH, and hence, differences in vegetation recovery between treatments were not explained by soil pH. Our hypothesis, that an additional wood chips buffering layer can further reduce the pressure reaching the soil could not be confirmed from the soil measurements, but the wood chips buffering layer was unfavourable for vegetation growth.

5 | Conclusion

This study demonstrated that soil quality of paddock trails was generally negatively affected by horse trampling, independent from the design or presence of paddock grids. We measured an increase in soil bulk density, a decrease of microbial biomass and SOC, as well as impacts on soil water dynamics. Vegetation on paddock trails quickly diminished on all trail treatments but trails with paddock grids showed a faster recovery when horses were removed from the trails. Numerical simulations indicated that reinforced paddock grids can distribute the weight of the horses more effectively due to its design (height and material stiffness), which result in less vertical stress reaching the soil and should result in lower soil compaction. This was not reflected in the soil bulk density measurements. However, the vegetation recovery was more productive on reinforced paddock grids than on basic paddock grids. A layer of wood chips under the paddock grids could not further reduce soil compaction and was found to negatively influence vegetation cover.

In summary, soil quality underneath paddock grids was not better protected than in unprotected trails despite the faster vegetation recovery.

Acknowledgements

Many thanks go to Vladimir Milojevic (Sandgrueb-Stiftung) and Rainer Schulin (ETH, prof. emeritus) for initiating the project in the first place. Special thanks go to the farm managers and researchers of Haras National Suisse (Inès Lamon, Samuel Schär, Margaux Barbey, Georges Nussbaumer, Hervé Sapin, Raphaël Fresnau, Emilie Martorell, Clément Lheureux, Xavier Ringli, Sébastien Fischer, Willy Béroud, Laurent Corminboeuf, Samuel Schaer, Margaux Barbey, David Barras, Cyril Magne, Flavian Boute, Laureen Michod, Jason Kindler Johner, Miriam Baumgartner, Sabrina Briefer, Marianne Cockburn), who monitored and oversaw the health of the horses and the state of the infrastructure. We extend our gratitude to Maria Vorkauf, Olivier Heller, Alejandro Romero-Ruiz, Philippe Tschanz, Valerio Volpe, Noemie Shavit (all Agroscope, Switzerland), Michelle Martin, Tomoya Sagara, Clive Hotz and Daniel Krebs who helped take and prepare soil samples on numerous occasions. Additional thanks go to Béla Glavitsch (Agroscope), Klaus Jarosch (Agroscope), Diane Bürge (Agroscope), Andrea Bonvicini (Agroscope) and Marlies Sommer (Agroscope) for their support in lab analysis. Research funding for this study was provided by the Stiftung Sandgrueb, Stiftung Pro Pferd, and the Federal Food Safety and Veterinary Office (FSVO), which is gratefully acknowledged. Open access publishing facilitated by Agroscope, as part of the Wiley - Agroscope agreement via the Consortium Of Swiss Academic Libraries.

Funding

Stiftung Sandgrueb, Stiftung Pro Pferd and the Federal Food Safety and Veterinary Office (FSVO).

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Mean values and standard deviations (in brackets) of soil bulk density [g/cm^3] of the trail treatments with the basic paddock grid (BASIC) directly installed on the soil ($BASIC_{Grass}$) or on a wood chip buffering layer ($BASIC_{Wood}$), the reinforced paddock grid (REINFORCED) directly installed on the soil ($Grass_{REINFORCED}$), with integrated cobblestones installed directly on the soil ($REINFORCED_{Grass\_Stones}$) or with integrated cobblestones on a wood chip buffering layer ($REINFORCED_{Wood\_Stones}$), and the unprotected trail (UNPROTECTED) for the collection dates in autumn 2023 and spring 2024. The percentage change [%] represents the increase (+) or decline (−) of the parameters from autumn 2022 and the collection date. The asterisks indicate the statistical significance (APA) of the difference between 2022 and the collection date. **Table S2:** Mean values and standard deviations (in brackets) of gas diffusion of the treatments with the basic paddock grid (BASIC) directly installed on the soil ($Grass_{BASIC}$) or on a wood chip buffering layer ($Wood_{BASIC}$), the reinforced paddock grid (REINFORCED) directly installed on the soil ($Grass_{REINFORCED}$), with integrated cobblestones installed directly on the soil ($Grass_{REINFORCED\_Stones}$) or with integrated cobblestones on a wood chip buffering layer ($Wood_{REINFORCED\_Stones}$), and the unprotected trail (UNPROTECTED). The percentage change [%] represents the increase (+) or decline (−) of the parameters from autumn 2022 to autumn 2024. The asterisks indicate the statistical significance (APA) of the difference between 2022 and 2024. **Figure S1:** (A) Illustration of the geometry of the problem considering the boundary conditions of the study. (B) soil domain with the presence of a paddock grid as protective material and the boundary (0.07 m radius) stress (σ) on the top of the grid. (C) soil domain of unprotected soil with a boundary (0.07 m radius) stress (σ). **Figure S2:**: mean daily distance walked of all horses housed on the four paddock trails in this study from June 2023 until July 2024.