Received: 19 November 2024 | Revised: 15 January 2025 | Accepted: 19 January 2025

DOI: 10.1111/sum.70028

RESEARCH ARTICLE

Soil Use and Management | BRITISH SOCIETY OF SOIL SCIENCE | WILEY

Changes in soil quality on horse paddock trails and the influence of paddock grids

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Funding information
Stiftung Sandgrueb; Stiftung Pro Pferd; Federal Food Safety and Veterinary Office

Abstract

Paddock trails offer horses the possibility to follow their natural urge to move and to behave interactively in a group association. To create appropriate conditions all year round, the installation of paddock grids is a common solution to avoid muddy trails and to prevent horses from injuries. The impact of horses on the soil on those trails is relatively unknown. In this study, we quantified the impact of horses kept on paddock trails on key soil quality indicators (soil bulk density, microbial biomass and soil organic carbon (SOC)) of the topsoil (0–0.3 m depth), and evaluated possible protective effects of paddock grids in an on-farm study across 17 sites. We found significantly higher soil bulk density at 0–0.1 m depth, significantly lower soil microbial biomass in the 0–0.2 m layer, and significantly lower SOC contents at 0–0.2 m depth in paddock trails compared to ungrazed control sites. Comparing trails with and without paddock grids showed no significant difference in soil bulk density at any sampling depth, but significantly lower soil microbial biomass and a significantly higher soil organic carbon to nitrogen ratio (soil CN-ratio) in trails with paddock grids compared to trails without grids. We could not find any impact of soil texture on the response ratio of the measured soil quality indicators, regardless of the type of trail (with or without paddock grids). Although we found overall lower mean soil bulk densities in trails with paddock grids, the difference to trails without paddock grids was not significant. A trend of an increase in bulk density over time was found for trails without paddock grids but not for trails with paddock grids, indicating that paddock grids might have a protective effect over time. In summary, our results suggest that soil quality is negatively affected by horses on paddock trails but that the effects are restricted to the top 0.2 m of soil. Furthermore, the results indicate that paddock grids were not able to prevent the negative effects of horses trampling but weakened them.

KEYWORDS

horse trampling, microbiology, soil compaction, soil protection

1 | INTRODUCTION

A considerable part of the degradation of grasslands is caused by livestock through overgrazing, compaction and erosion (Steinfeld et al., 2006). Soil degradation caused by horses is of growing concern as more and more horses are kept in greater density on agricultural farms, where they have access to agricultural grassland. The mechanical pressure on soil from horses is presumed comparable to that of bigger livestock during grazing (De Belie & Rombaut, 2003; Gustas et al., 2007) and can have similar impacts as farm vehicle traffic regarding topsoil compaction (Greenwood & McKenzie, 2001).

Modern forms of horse husbandry, such as paddock trails and active stables, grow in popularity as they allow horses to have more social contact with conspecifics (Yarnell et al., 2015). The intention of paddock trails is to promote a safe and natural way of horse keeping and simultaneously improving the hoof care and natural movement according to the horses' instincts (Jackson, 2016). Depending on the breed, feral horses have proved to walk between 3.5 and 16 kilometres per day (Hampson et al., 2010; Kaczensky et al., 2008). By creating spatially separated areas of different functionality (e.g. resting, eating and drinking), similar to feral conditions, paddock trails increase the free horse movement (Jackson, 2016) compared to traditional horse husbandry (Rose-Meierhöfer et al., 2010). But this increased movement has inevitable impacts on the soil with yet unknown extent.

Soil degradation caused by grazing and by the movement of large mammals results from the direct mechanical impact of the hoofs on the soil, which results in soil compaction and soil kneading especially in wet conditions (Cox & Amador, 2018; Roesch et al., 2019). In many cases, the strongest compaction effect caused by trampling is confined to the topsoil (Lai & Kumar, 2020; Vzzotto et al., 2000). Although horses can be similar in size to cattle, soil compaction caused by horses is considered more serious as horse hooves have a smaller soil contact area and hence higher surface stress compared to the claws of cattle (Cox & Amador, 2018). Repetitive trampling also strongly modifies the soil surface, leading to bare spots with disturbed soil organic carbon (SOC) dynamics because of the lack of vegetation and an increase in soil degradation by decreasing soil stability and increasing soil erodibility (Hiltbrunner et al., 2012). Degradation of soil structure by compaction and kneading by mammals may furthermore decrease soil water infiltration, hamper soil aeration (Roesch et al., 2019; Taddese et al., 2002) and impede root penetration, which increases surface water ponding, runoff and erosion (Herbin et al., 2011).

A degraded soil structure caused by soil compaction can also result in a decline in microbial biomass and microbial activity because of the loss of optimal physical conditions and supply of food sources in the soil (Cui & Holden, 2015). A change in soil structure may, therefore, have profound consequences on the microbial community and several soil ecosystem functions may be negatively affected, including nutrient and soil organic carbon (SOC) cycling and water regulation (Creamer et al., 2016). Soil microorganisms are sensitive to changes in their biotope (Thomsen et al., 2012) and therefore often used as an indicator to detect changes in soil systems (Hug et al., 2013).

As paddock trails are usually accessible all year round, the trails often become muddy and uneven, especially during winter and spring. To prevent horses from injuries, and to create horse appropriate conditions all year round, a common solution is to stabilize the trails with so-called paddock grids. Mostly fabricated of recycled plastic, paddock grids are supposed to be long-lasting and easy for installation and later removal. However, the influence of paddock grids on the soil, that is, if and how much they can help protecting the soil, is currently unknown.

The motivation of this study was to quantify the impact of horses kept on paddock trails on the soil in comparison to ungrazed soil, and to investigate possible changes in key soil quality indicators over time. The objectives of this study were to (1) quantify the overall influence of horses kept on paddock trails on the soil, and to evaluate (2) whether paddock grids have a protective effect on soil quality compared to trails without paddock grids, (3) if and how effects are influenced by soil texture and (4) if there is an accumulated negative effect on soil quality over time. We measured soil bulk density, microbial biomass (carbon and nitrogen), SOC, pH, texture and the soil CN-ratio. Each measurement should detect changes in soil quality in paddock trails with and without paddock grids and in ungrazed control areas (grassland next to trails). We hypothesized that (i) soil quality is lower in paddock trails compared to ungrazed control areas in terms of higher soil compaction, lower SOC content and lower microbial biomass, (ii) trails without paddock grids have a higher soil bulk density, lower SOC content and lower microbial biomass compared to trails with paddock grids, (iii) soil texture influences the severeness of the effect horses have on the soil by altering soil bulk densities and microbial biomass, and that in summary (iv) trails with paddock grids exhibit less soil degradation over time compared to trails without paddock grids.

2 | MATERIALS AND METHODS

2.1 | Site descriptions

2.1.1 | Soil and site selection

An online survey (via Google Forms; free licence) was performed in Switzerland, Germany, Luxemburg and

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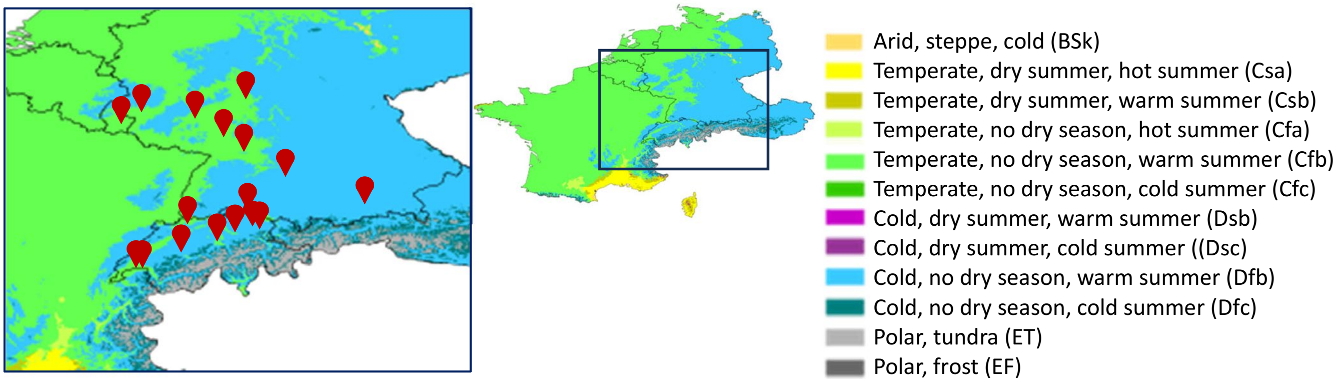

FIGURE 1 Climate classification according to Köppen-Geiger (1980–2016) and the location of the 17 study sites of this study (Beck et al., 2018).

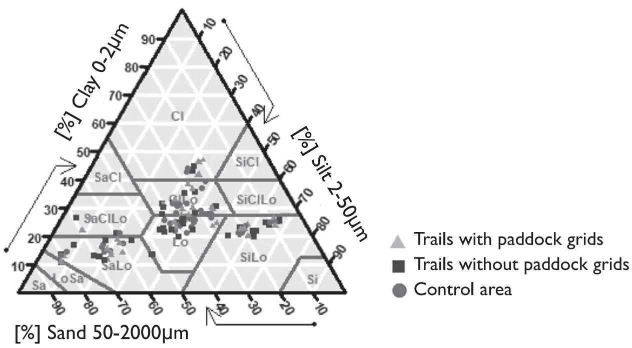

FIGURE 2 Soil texture triangle created by the R package 'soiltexture' and according to USDA standards indicating the different soil textures of the 17 study sites. The soil texture is given for the paddock trails with paddock grids, paddock trails without paddock grids and the ungrazed control areas.

France to find participants with suitable study sites with existing paddock trails. We included farms that had trails with paddock grids, trails without paddock grids, or both in our study. To avoid interference of additional material, we excluded trails with any type of substruction (e.g. wood chips, sand, grit, etc.) between paddock grid and soil. An ungrazed control area next to a trail was another key aspect of the selection to assure a comparison between grazed and ungrazed soil within the same study site. In total, we received 237 answers from the online survey, and 17 study sites across Germany (8), Luxemburg (1) and Switzerland (8) (Figure 1) fulfilled all the selection criteria. In addition to the different soil textures (Figure 2), the local climate varied between sites in terms of mean annual temperature and precipitation, from 9.5 to 11.9°C and 618 to 1748 mm, respectively. Main Köppen-Geiger climate types of the investigated regions ranged from temperate, no dry season and warm summer (Cfb) to cold, no dry season with warm summer (Dfb) (Figure 1).

Across all study sites, soil clay content varied from 11% to 47%, with loam, clay-loam, silt-loam and sandy-loam being the most prominent texture classes (Figure 2). At each site, we ensured that soil texture between trails with paddock grids, trails without paddock grids and ungrazed control area did not differ.

2.1.2 | Farm management

Farm management is used here as a term for additional factors that might influence the soil response to horse trampling and grazing. We assessed the length and width of the trails, the age of the trails, and the number of horses to calculate the stocking density, which we defined by the number of animals per area [animals/m^2]. Stocking density was used as an index of the trampling impact from horses. Trail age ranged from 0.5 to 10 years, with a mean age of 5.2 years (standard deviation 2.7 years) for trails with paddock grids, and 5.0 years (standard deviation 2.8 years) for trails without grids. The mean stocking density of all study sites was 0.01 (standard deviation 0.01) and ranged from 0.002 to 0.057 (Table S1). The type of paddock grid (i.e. grid brand) was not considered in our analyses. Moreover, we did not assess the impacts of hoof care (e.g. shoed and unshoed horses) or feeding management.

2.2 | Soil sampling and analysis

2.2.1 | Sampling design

Soil sampling of the top 0–0.3 m of soil took place within 2 weeks in May 2022, and the sampling design was identical across all study sites. At each site, three locations were sampled on the paddock trail (which either had paddock grids, no paddock grids, or both). An ungrazed control area was sampled next to each location. Most trails showed a landscape patchiness (e.g. topography, vegetation, etc.) and the sampling locations were selected according to the following criteria: (i) a relatively even topography with a maximal inclination of <4% slope steepness to avoid inference from soil erosion or deposition, (ii) trails which are frequently used, (iii) sampling areas at least 1 m away from any fence or construction and (iv) the possibility for comparison to a close control area not used as a paddock trail. If a paddock trail was covered with paddock grids, the grid was removed, and samples were taken from underneath the grid. This ensured that samples from trails with paddock grid, trails without paddock grids and control areas were taken from the same depths and could be compared. From each sampling location, we collected soil samples for measurements of soil texture, SOC content, total nitrogen content, pH, bulk density and microbial biomass (carbon and nitrogen).

2.2.2 | Soil bulk density

Undisturbed soil core samples were taken using a tube sampler (diameter: 0.035 m; height: 0.4 m) and split into three layers (0–0.1, 0.1–0.2 and 0.2–0.3 m). Five soil cores were taken within 1 m^2 at each location and later pooled to one composite sample per location and depth. A total of 153 samples (each consisting of five core samples) were collected from trails without paddock grids, 153 samples from the ungrazed control area and 72 samples from trails with paddock grids. All samples were packed in plastic bags and then stored in a cool storage room (4°C) until further processing.

To calculate the soil bulk density of the fine earth, all samples were weighed, sieved to 2 mm, oven dried (105°C) for at least 48 h, and weighed again ($M_{<2mm}$). The weight of particles larger than 2 mm (M_{scel}) was used for the calculation of the volume of gravel (V_{scel}; $V_{scel} = M_{scel}/\rho_{scel}$), using a value of 2.4 g/cm^3 for gravel density (ρ_{scel}) according to the procedure of the Swiss National soil monitoring programme (Schwab & Gubler, 2018). The soil bulk density of the fine earth (BD) was calculated as $BD = M_{<2mm}/(V_{tot} - V_{scel})$ [g/cm^3].

2.2.3 | Microbial biomass

For each location, 20 soil cores from the topsoil (0–0.2 m) were collected using a Pürckhauer drill (diameter: 0.02 m), which resulted in ca. 2 kg of composite soil samples per location. A total of 51 samples (each consisting of ca. 2 kg of soil) were collected from trails without paddock grids, 51 samples from ungrazed control areas and 24 samples from trails with paddock grids. Each sample was packed in labelled plastic bags and transported in cooling containers until arriving at the laboratory and stored in a cool storage room (4°C) until further processing. Visible living or unprocessed organic matter (plant material and earthworms) and stones were removed, and each field-fresh sample was sieved to 2 mm. Microbial biomass was quantified using the fumigation extraction method where the soil is fumigated with chloroform for 24 h following Vance et al. (1987). The remaining material after fumigation was then used to calculate the amount of microbial biomass carbon and microbial biomass nitrogen, by comparing fumigated and non-fumigated soil of each sample. The analysis was repeated three times for each sample, and results are given as microbial biomass carbon per soil dry matter [mg C(FE)/kg soil dry matter] and microbial biomass nitrogen [mg N(FE)/kg soil dry matter], with an accuracy of 1 mg. This measurement was executed according to the reference methods of Agroscope (Agroscope, 2020). We interpret the microbial biomass carbon (MBC) as the representation of microbial biomass because the incorporation of organic carbon into an organism by microbes is understood as the process of biomass growth (Mason-Jones et al., 2023). The microbial biomass nitrogen (MBN) reflects the efficiency of soil microbial N-mineralization (Huang et al., 2013; Li et al., 2020). The CN-ratio of microbial biomass (MBC:MBN) was calculated by dividing the microbial biomass carbon by the microbial biomass nitrogen of each sample and interpreted as possible influences on the decomposition efficiency (Huang et al., 2013) and consequently the C- and N-cycle in the soil.

2.2.4 | Physico-chemical soil parameters

The remaining of the samples (0–0.2 m depth) not used for analysing microbial biomass was oven dried (40°C) for 24 h, sieved to 2 mm and used for the following analyses. Soil pH was measured with a water suspension test and a soil:water ratio of 1:2.5. Soil organic carbon content (SOC) was determined by the wet combustion technique, which determines the total SOC content using potassium dichromate and sulphuric acid (ISO 10694) (Walkley & Black, 1934) with an accuracy of 0.03%. Soil texture was measured using the pipette method and classified according to the USDA classification (USDA, 1993). Total carbon (C) and total nitrogen (N) in the soil were measured using the Dumas combustion method with an elementary analyser (ISO 13878). The carbon to nitrogen ratio (C:N ratio) was calculated by dividing total C by total N for each sample.

TABLE 1 Mean values and standard deviations (in brackets) of soil organic carbon content (SOC), soil C:N-ratio, pH, microbial biomass carbon (MBC) and soil bulk density of paddock trails with and without paddock grids and corresponding ungrazed control areas.

	SOC [g/kg]	Soil C:N-ratio	pH [in H_2O]	MBC [mg/kg soil]	Bulk density [g/cm^3]		
Sampling depth [m]	0–0.2				0–0.1	0.1–0.2	0.2–0.3
Trails with soil grids	22.0 (12.0)	12.10 (3.68)	7.50 (0.53)	547 (568)	1.03 (0.25)	1.15 (0.24)	1.21 (0.33)
Trails without soil grids	20.5 (11.1)	10.50 (2.60)	7.19 (0.70)	653 (448)	1.14 (0.19)	1.20 (0.21)	1.27 (0.16)
Control area	24.9 (12.0)	10.40 (2.50)	7.05 (0.70)	899 (572)	0.89 (0.21)	1.07 (0.18)	1.18 (0.21)

2.3 | Calculations and statistical analysis

To compare soil responses in paddock trails across sites, differences between paddock trails and the corresponding ungrazed control area were expressed by response ratios. For this, we divided the value of a certain soil quality indicator (i.e. bulk density, microbial biomass, SOC) from the paddock trails by the respective value of the control area for each site. Response ratios greater than one indicate higher values in the paddock trails than in the corresponding control area, and response ratios smaller than one indicate lower values than in the control area.

All statistical analyses were carried out using the R 4.1.1 software (R Core Team, 2021). The comparison of soil properties between paddock trails and control area was analysed by ANOVA using a linear mixed model y ~ fixed effect + (1|random intercept$_1$) + … + (1|random intercept$_n$), where y is either the response ratio or the soil bulk density, microbial biomass, pH, C:N-ratio, SOC content or sand content. The fixed effects consider the soil coverage (i.e. trail with paddock grid, trail without paddock grid, control area) and sampling depth. The random intercepts consider the different study sites and different sampling locations within each study site.

Correlations between the dependent soil quality indicators soil bulk density, microbial biomass and SOC content and the independent soil parameters (pH, C:N-ratio and sand content), farm management (age of trail and stocking density) or climatic conditions (mean annual precipitation and mean annual temperature) were calculated with either Pearson (soil bulk density and SOC content) or Spearman rank correlation coefficients (microbial biomass) depending on their distribution, with a ggscatter plot (package ggpubr) illustration. For all of the above analyses, statistical significance was defined at $p = .05$.

3 | RESULTS

Microbial biomass carbon (Table 1) and microbial biomass nitrogen (Table S2) were both highest in the ungrazed control area followed by trails without paddock grids and trails with grids. Variation in microbial biomass (carbon and nitrogen) between sites, represented by standard deviations was high, indicating strong influence of site characteristics (soil, climate). The CN-ratio of microbial biomass (MBC:MBN) showed no significant difference between ungrazed control area (6.4 (0.8)), trails with paddock trails (6.8 (2.5)) and trails without paddock grids (6.6 (1.8)) (Table S2). The highest mean SOC contents were found in the ungrazed control areas, followed by trails with paddock grids and trails without grids. All SOC contents showed high values of standard deviations ranging from 7.1–52.2 g/kg SOC in the control areas, 6.8–51.3 g/kg SOC in trails with paddock grids and 3.1–50.6 g/kg SOC in trails without paddock grids. The soil C:N-ratio showed higher mean values in the control areas compared to the paddock trails regardless of the installation of paddock grids or not. The soil pH was neutral for most soils and the mean pH was highest in trails with paddock grids, followed by trails without grids and the ungrazed control areas.

Microbial biomass carbon was significantly correlated with SOC in the ungrazed control area ($r = 0.91$, $p < .001$), trails with paddock grids ($r = 0.93$, $p < .001$) and trails without paddock grids ($r = 0.89$, $p < .001$) (Figure S2). The relationship between microbial biomass carbon and SOC was similar in trails with paddock grid, trails without paddock grids, and in the ungrazed control area.

3.1 | Impact of paddock trails on soil quality and the influence of paddock grids

Soil bulk density was significantly higher in trails with paddock grids than the ungrazed control area at the 0–0.1 m depth ($p = .001$), as shown by a response ratio significantly larger than 1. There was a trend for higher bulk densities at 0.1–0.2 m depth ($p = .06$) and 0.2–0.3 m depth ($p = .31$) in trails compared with ungrazed areas (Figure 3d). Trails without paddock grids had significantly higher soil bulk densities at 0–0.1 m ($p < .001$) and 0.1–0.2 m depth ($p = .007$) than the ungrazed control area, with corresponding response ratios significantly larger than 1 (Figure 3d). No significant difference between ungrazed control areas and paddock trails was found for the

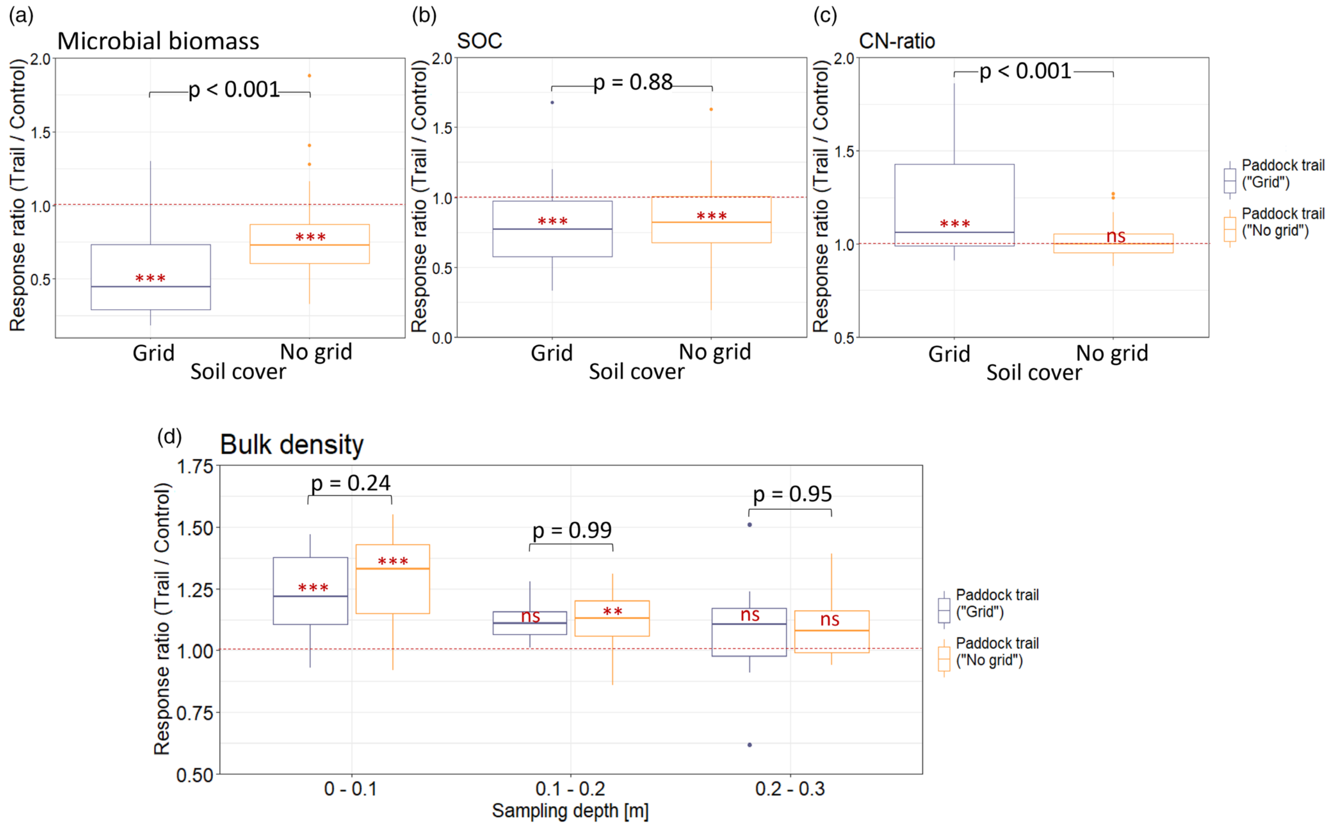

FIGURE 3 Response ratio of (a) microbial biomass carbon, (b) soil organic carbon (SOC) content, (c) carbon to nitrogen-ratio (C:N-ratio) and (d) soil bulk density of paddock trails with paddock grids (Grid, $n = 24$) and without paddock grids (No grid, $n = 51$) in relation to the ungrazed control areas. p-values show the level of significance between the paddock trails (with and without grids) and the stars indicate the level of significance between the paddock trails (with and without grids) and the ungrazed control areas (ns = $p > .05$, * = $p \leq .05$, ** = $p \leq .01$, *** = $p \leq .001$).

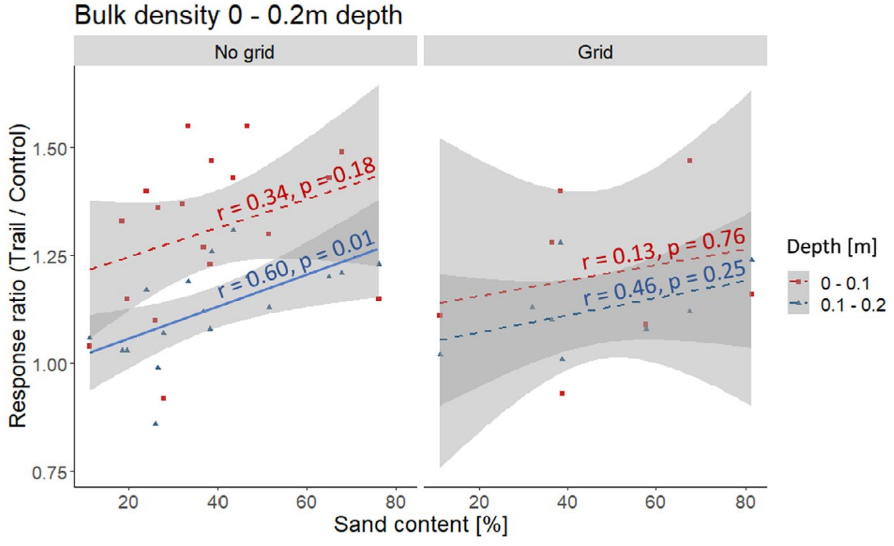

FIGURE 4 Impact of sand content on the response ratio of soil bulk density for the soil layers 0–0.1 m (red) and 0.1–0.2 m (blue) for trails without (No grid, $n = 51$) and with paddock grids (Grid, $n = 24$).

0.2–0.3 m depth for trails without grids. Comparing the response ratios for soil bulk density between trails with and without paddock grids showed the highest difference at the 0–0.1 m depth, but no significant differences between the two types of trails could be found (Figure 3d).

The response ratios for microbial biomass carbon indicate that microbial biomass carbon of both trail types (i.e. with and without grids) was significantly lower than in the ungrazed control areas ($p < .001$). Comparison between trails with and without paddock grids shows a significantly

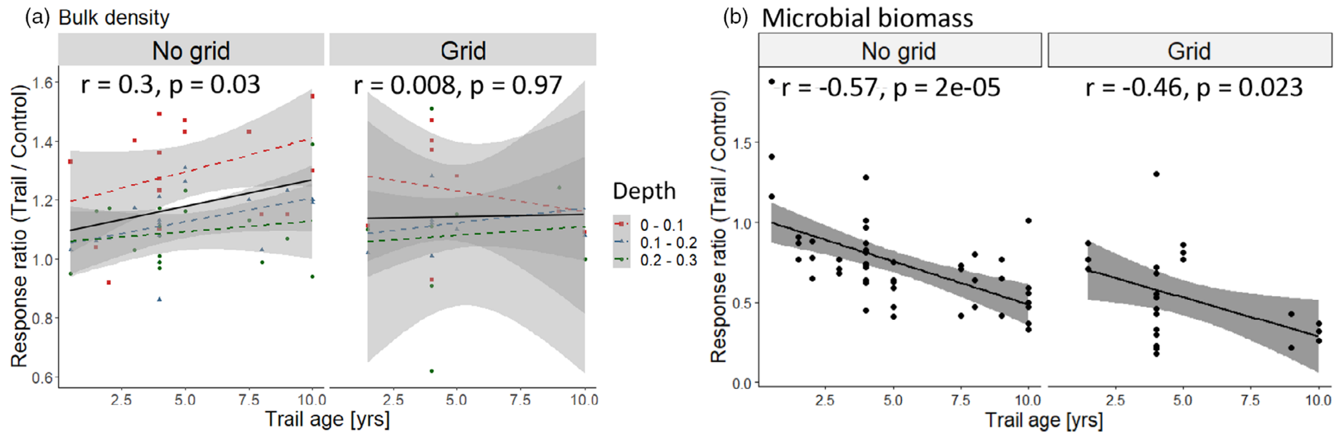

FIGURE 5 Impact of trail age on the response ratio of (a) soil bulk density for the soil layers 0–0.1 m (red), 0.1–0.2 m (blue), 0.2–0.3 m (green) and combined 0–0.3 m (black) and (b) microbial biomass carbon (0–0.2 m depth) for trails with paddock grids (Grid, $n=24$) and trails without paddock grids (No grid, $n=51$).

lower microbial biomass carbon in trails with grids than in trails without grids ($p<.001$), indicating that trails without paddock grids are more comparable to the microbial biomass carbon in the ungrazed control areas than trails with paddock grids (Figure 3a). The response ratios for microbial biomass nitrogen showed similar results with significantly lower microbial biomass nitrogen in both types of trails (i.e. with and without paddock grids) than in the ungrazed control area ($p<.001$) and significantly lower microbial biomass nitrogen in trails with grids than in trails without grids ($p<.001$) (Figure S1a). The response ratio for the CN-ratio of microbial biomass (MBC:MBN) showed no significant difference between the ungrazed control area and trails with paddock grids ($p=.88$) and trails without paddock grids ($p=.97$). No significant difference was found for the CN-ratio of microbial biomass (MBC:MBN) between trails with and without paddock trails ($p=.95$) (Figure S1b). SOC content was significantly lower in trails with paddock grids ($p=.002$) and trails without grids ($p=.0003$) than in control areas. No significant difference was found in SOC content between trails with and without grids ($p=.88$) (Figure 3b). Paddock grids showed influence on the C:N-ratio in the soil with significantly higher C:N-ratio in trails with grids compared to trails without grids and ungrazed control areas ($p<.001$; Figure 3c).

Considering the influence of different soil textures of the top 0–0.2 m depth on soil bulk density shows a significantly positive relationship between the response ratio of bulk density and sand content for paddock trails without paddock grids (No grid) at 0.1–0.2 m ($p=.01$; $r=0.60$) but not at 0–0.1 m depth ($p=.18$; $r=0.34$) (Figure 4 left panel). No significant relationship between texture and bulk density was found for trails with grids at 0–0.1 m ($p=.76$) and 0.1–0.2 m depth ($p=.25$) (Figure 4 right panel). Response ratios of microbial biomass carbon and SOC were not affected by soil texture (Figure S3).

3.2 | Impact of stocking density and trail age on soil quality

Stocking density did not impact soil bulk density in any sampling depth of trails with paddock grids ($p=.32$) and trails without grids ($p=.18$) (Figure S4a), microbial biomass carbon of trails with grids ($p=.16$) and trails without grids ($p=.43$) (Figure S4b), or SOC content for trails with grids ($p=.37$) and trails without grids ($p=.072$) (Figure S4c). A significantly positive correlation between trail age and the response ratio of soil bulk density of the top 0–0.3 m depth was found for trails without paddock grids (Figure 5a left panel) but not for trails with paddock grids (Figure 5a right panel). Looking at each soil layer individually showed no significant correlation between soil bulk density and the trail age for trails with or without paddock grids. Moreover, we found a significantly negative impact of trail age on soil microbial biomass carbon in both trails (with and without paddock grids) (Figure 5b), indicating a decrease over time in microbial biomass carbon under paddock trails compared to ungrazed control areas. We found no evidence that paddock grids protected the decline in soil microbial biomass carbon over time. We found no significant impact of trail age on SOC content for both trails with paddock grids ($r=-0.2$, $p=.35$) or trails without grids ($r=-0.19$, $p=.19$).

4 | DISCUSSION

4.1 | Influence of horse paddock trails on soil quality

The findings in this study show an overall increased soil bulk density, reduced microbial biomass carbon and nitrogen, and reduced SOC content under paddock trails with and without grids compared to ungrazed control areas. The constant ratio of microbial biomass carbon per unit SOC across soil covers suggests that the reduced microbial biomass carbon is driven by the decline in SOC (Figure S2). The significant increase in soil bulk density on both types of trails demonstrates a considerable pressure of the horses on the soil. Lai and Kumar (2020) estimate in their meta-analysis an increase in soil compaction at 0–0.1 m depth caused by livestock of around 11% in heavy grazing and 8% in moderate grazing (relative to ungrazed). Our findings suggest an overall increase in soil bulk density caused by horses of around 15% in trails with paddock grids and 28% in trails without paddock grids at 0–0.1 m depth in comparison to ungrazed control areas.

The soil bulk density of both paddock trails with and without paddock grids was significantly higher at the 0–0.1 m soil depth compared to the ungrazed control area as shown by response ratios greater than 1. No difference in bulk density between trails (with and without paddock grids) and ungrazed control areas could be found at the 0.2–0.3 m layer (Figure 3d). This indicates a high influence of the horses on the topsoil but little direct impact on the subsoil.

4.2 | Limited protective effect of paddock grids

Although trails with paddock grids showed overall lower mean soil bulk densities compared to trails without grids, differences were not significant in any of the investigated soil depths. This indicates that paddock grids have only a small protective effect against soil compaction. Our data further indicate that this protective effect is highest in the top 0.1 m depth but shows no impact in lower soil layers. Soil texture showed only limited influence on the soil bulk density (Figure 4a) for both trails with and without paddock grids. Microbial biomass carbon and SOC were also unaffected by texture, and paddock grids showed no influence on both parameters (Figure S3). A larger data set would be needed to systematically test whether the impact of horses in paddock trails on soil quality indicators is influenced by soil texture.

Lai and Kumar (2020) associate influences on soil quality changes by livestock to animal grazing activities with trampling of the soil, grazing of plant materials including roots, and the addition of animal excretes to the soil. Trampling and grazing leads to a reduction in standing plant material and a faster litter decomposition on the trails (Wang et al., 2016). The lack of vegetative cover on pasture tracks caused by horses is also reported by Farmer et al. (2023), who indicate a decrease in plant cover and greater sediment deposition by runoff on horse tracks. Visual inspection on our study sites showed little or no vegetation cover on paddock trails, with little difference between trails with and without grids. The reduction in plant biomass on the paddock trails supports our findings of lower SOC contents compared to the ungrazed control areas. Besides trampling, a lack of plant cover and therefore less soil pores could be a reason for the increase in bulk density. The significantly lower SOC in paddock trails (with and without paddock grids) compared to the ungrazed control areas might also be explained by the lack of plant cover and the physical breakdown of the plant material because of grazing.

Significantly lower soil microbial biomass carbon and nitrogen was found in both types of paddock trails compared to the ungrazed control areas. The ratio of microbial biomass carbon to SOC was not affected by paddock grids (Figure S2), which suggests that the decline in microbial biomass carbon was mainly driven by the decline in SOC rather than the presence of paddock grids. Our results demonstrate a strong negative influence of the trampling and grazing of horses on soil microbial biomass carbon (Figure 3a) and nitrogen (Figure S1) in the soil, indicated by response ratios significantly lower than 1 in both types of trails (with and without paddock grids). A disturbed soil microbiology was also found by Hiltbrunner et al. (2012) who negatively correlate soil porosity and the reduction in plant cover with microbial biomass in sub-alpine pastures grazed by cattle. The significantly lower soil microbial biomass (carbon and nitrogen) in trails with paddock grids compared to trails without paddock grids ($p < .001$) indicate that the soil microbiota was not protected or supported by paddock grids. This finding was surprising as we assumed that better soil physical conditions because of lower soil bulk density would lead to more favourable conditions for soil microorganisms. Despite the change in microbial biomass carbon and nitrogen, the CN-ratio of microbial biomass we found in this study showed no significant difference between the ungrazed control areas and both types of trails (i.e. with and without paddock grids). Studies have demonstrated that changes in the composition of soil microbial communities (indicated by changes in CN-ratios of microbial biomass) (Huang et al., 2013) and microbial biomass itself can influence ecosystem nitrogen cycling (Fraterrigo et al., 2006). As we found a significant difference in the soil CN-ratio but not in the CN-ratio of microbial biomass, data on the specific microbial composition would be needed to know whether paddock trails alter the C- and N-processes in the soil.

The significantly higher microbial biomass carbon in trails without grids could derive from higher input of excrete per area. Cleaning the trails from horse excretes is, according to the practitioners in this study, more difficult on trails without grids, as the excretes mix with soil. This leads to a higher input of nutrients into the soil of trails without grids, and hence more nutrients available for soil microbes.

Soil grids are produced of recycled plastics of unknown origin, and future studies should investigate the occurrence and migration of microplastics into soil. Microplastics are emerging contaminants in the water and soil environment, entering agricultural soils via multiple sources (Corradini et al., 2019; He et al., 2019; Steinmetz et al., 2016; Weithmann et al., 2018). Visual observations of paddock grid fragments on the trails and the lack of plant cover on most trails with grids suggest that horses have a high impact on the stability and abrasion of the grids. Once in the soil, soil quality as well as the plants and the horses on these trails could be negatively affected by plastic fragments.

4.3 | Soil quality declines over time on paddock trails

We found a significant impact of trail age on soil quality indicators. Soil bulk density over the top 0–0.3 m depth increased with trail age in trails without paddock grids but not in trails with grids (Figure 5a). This suggests that paddock grids could help minimize the impact of horses on the soil by keeping topsoil compaction levels lower over time. We also analysed the correlation between soil bulk density and trail age including only study sites which had both trails with and without paddock grids ($n=24$), and this still showed an increase in soil bulk density in trails without paddock grids, but the increase was not significant any longer (Figure S5). Further studies including a higher number of study sites with both trails with and without paddock grids at the same sites could further investigate a possible protective effect of paddock grids against compaction over time. Soil microbial biomass carbon decreased with trail age in both types of trails (Figure 5b). As discussed by Liu et al. (2017), this could be explained by the lower litter quality that accumulates over time caused by a reduction or lack of vegetation. An increase in soil bulk density over time might additionally reduce suitable habitats for soil microbes, resulting in an overall lower microbial biomass carbon with time (Cui & Holden, 2015). The constant ratios of the microbial biomass carbon per unit SOC between both types of trails suggest that the decline in SOC is the main driver for the decline in microbial biomass carbon.

Although cow stocking rates have been shown to have a negative influence on bulk density in the topsoil (Pulido et al., 2018), stocking density in this study had little impact on soil bulk density. Plausible reasons for this are that stocking densities were generally low in our study (1–6 horses per hectare). Additional farm management aspects that could not be considered in this study may also influence soil response on paddock trails. For example, it has been shown that feeding management affects horse movement. Hampson et al. (2012) show that automated feeding systems promote horse movement compared with stationary feeders, and Seabra et al. (2023) state that the time horses spend walking is significantly lower in an ad libitum treatment compared to an automated box feeding system. Future studies could therefore investigate the impacts of feeding management and monitor the horses, for example, using GPS-trackers, to link actual horse movement to changes in soil quality.

5 | CONCLUSION

We found horses to have a considerable impact on the topsoil of paddock trails, quantified by a significant increase in soil bulk density, a significant decrease in soil microbial biomass (carbon and nitrogen), and a tendency for reduced SOC content. No significant differences in soil bulk density between paddock trails and ungrazed control areas were measured at 0.2–0.3 m depth, suggesting that the impact of horses on paddock trails is limited to the topsoil. Soil texture showed no considerable influence on the impacts on the soil quality parameters. Although we could not find a significantly negative correlation between stocking density and soil quality, we showed that soil bulk density, and microbial biomass carbon deteriorated with increasing trail age. The impact of paddock grids on soil quality was not unambiguous. We measured lower bulk density on trails with paddock grids than on trails without grids, but the differences between them were not significant. The protection effect of paddock grids against soil compaction seems therefore minimal and restricted to the top 0–0.1 m depth. However, soil bulk density tended to increase with trail age in trail without paddock grid but not in trail with paddock grids, suggesting that paddock grids might help minimizing soil compaction over time. SOC contents did not differ between trails with and without grids but were significantly lower compared to the ungrazed control areas. However, soil microbial biomass (carbon and nitrogen) was significantly lower in trails with grids than in trails without grids, indicating a potential trade-off of paddock grids.

ACKNOWLEDGEMENTS

Many thanks go to Sabrina Martin, Marie Roig-Pons, Anja Zollinger (Swiss National Stud Farm SNSF of Agroscope) and Thorsten Hinrichs (HIT Active Stable) for the distribution of the media call to find suitable study sites. We extend our gratitude to Virginia Hart, Anna Lena Klein, Raffaele Lanini (ETH Zurich), Daniel Krebs (Eversys) and

Michelle Martin (University of Zurich) who helped take and prepare soil samples. 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. Special thanks go to all the practitioners participating in this project for providing detailed information and for the possibility of doing research on their farms.

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 at the end of this article.

How to cite this article: Hiltebrand, C., Keller, T., Bachmann Rieder, I., & Doetterl, S. (2025). Changes in soil quality on horse paddock trails and the influence of paddock grids. *Soil Use and Management*, *41*, e70028. https://doi.org/10.1111/sum.70028