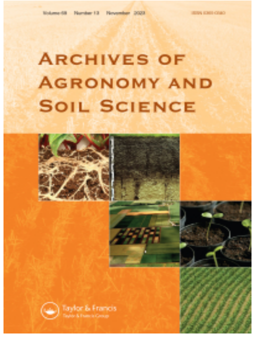

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Medium management intensity supports largest topsoil organic carbon stocks in mountain grassland

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ABSTRACT

Grassland soil organic carbon (SOC) stock constitutes the largest terrestrial greenhouse gas sink. Therefore, we compared the effect of three common mountain grassland management regimes on the SOC stock in the inner-alpine Lower Engadine valley. We hypothesized that higher management intensity (MI), including higher manure loads and higher cutting frequency, increases plant productivity and organic matter (OM) input to the soil, providing the substrate for a higher SOC stock. In our study, we found that the SOC stock (0–20 cm depth) in low MI plots was only 73.1 ± 3.99 t C ha^{-1} and much larger (+23%) in medium MI grassland plots with 89.6 ± 4.2 t C ha^{-1}. Surprisingly, in high MI plots, the SOC stock was also comparatively small with 78.7 ± 5.4 t C ha^{-1} (+8% compared to low MI). Soil pH, C/N ratio, clay content and farmyard manure were no drivers of SOC stock differences. We conclude that, compared to medium MI, in the high MI grasslands, the organic C input from high plant productivity is overcompensated by antagonistic management effects, favoring higher OM decomposition rates. Accordingly, more fertilization and frequent cutting, leading to higher grassland yields, are not necessarily beneficial for SOC sequestration.

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KEYWORDS
SOC stock; FYM; productivity; soil organic matter decomposition

Introduction

Soils are a substantial sink for anthropogenic CO_2 emissions (Schlesinger 1977; Post et al. 1982; Le Quéré et al. 2018). About one third of the total global SOC, equivalent to > 80% of C in the earth's atmosphere, is contained in grasslands (661 Pg C; Jobbágy and Jackson 2000). For Europe under global warming conditions, the climate impact was predicted to cause a decrease of this huge SOC stock by 6–10% by the end of the century, due to increased plant growth being overcompensated by increasing OM decomposition (Smith et al. 2005).

Historical records of the Swiss Federal Office for Meteorology for the lower Engadine valley show that only 100 years ago the April–October mean air temperature was ca. 1.5°C lower than today (Volk et al. 2021). But different from lowlands, rising temperatures in comparatively cold regions can be expected to have antagonistic effects on the SOC stock: Higher temperatures can mitigate thermal growth limitations for plants, thereby increasing OM production. But they can also mitigate thermal limitations of metabolic processes, thereby accelerating decomposition (Volk et al. 2021, 2022). Release of CO_2 and a shrinking sink for atmospheric CO_2 would create a positive feedback loop

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with globally rising temperatures. This prospect makes reliable estimates of present-day SOC stocks essential to optimize management practices that favor a large soil carbon sink (Bossio et al. 2020).

Management practices that increase plant OM input to the soil could increase SOC storage (Poeplau 2021), but they are also likely to increase microbial activity. This may even lead to a decrease in total SOC, as soil microbes transform OM into SOC with a C use efficiency of only 30% (Sinsabaugh et al. 2013). Consequently, during the decomposition process, most of the C contained in OM from green plants and fertilizer (manure) is not stabilized in the form of microbial products but lost to the atmosphere as CO_2.

Grassland management practices usually aim to increase plant growth and fodder quality by optimizing measures such as fertilization, weed control and the number of utilizations (mowing or grazing). As a result, more intense management may lead to a larger soil C stock by supplying larger amounts of OM to the import pathway. Indeed, higher SOC sequestration rates were shown in high-productivity, compared to low-productivity grasslands (Fornara and Tilman 2008; Ammann et al. 2009). In a synthesis of global grassland soil studies on management (improved grazing, fertilization, legume and improved grass species sowing, irrigation), Conant et al. (2017) concluded that improved management tends to lead to increased soil C accumulation. Furthermore, a management regime, including fertilization and moderate mowing/grazing, compared to no management at all, was found to increase SOC content by 15% in only 3 years in an old-field site of agronomic pasture species on Vancouver Island, Canada (Ziter and MacDougall 2013).

However, a large OM import rate is not the only pathway towards SOC stock increases. Our research on subalpine grassland soils (Volk et al. 2018) showed that plant productivity consistently increased with increased nitrogen (N) input, but that maximum soil C accumulation was achieved under medium (14 kg N ha^{-1} yr^{-1} added), rather than maximum productivity (54 kg N ha^{-1} yr^{-1} added). Furthermore, slow decomposition of a small or moderate OM input may lead to considerable SOC accumulation. In a grassland experiment, that first indicated increased SOC storage under intensive management after 6 years, Ammann et al. (2020) found after 10 years that the situation had reversed: SOC was lost under intensive, but SOC was gained under extensive management. In a different study a comparison of extensively managed grasslands of low productivity and high plant species diversity with high-productivity grasslands has shown significantly higher soil C stocks in low-productivity fields (Kohler et al. 2020). Also, De Deyn et al. (2011) demonstrated that the cessation of fertilizer application, reducing overall plant productivity, increased the rate of soil C accumulation. In a recent review Bai and Cotrufo (2022) found that higher plant diversity, that is usually associated with low or medium productivity, favors SOC storage via increased belowground C input and higher microbial necromass.

In the Engadine valley, the ca. 90 km long, inner alpine valley of the upper Inn River in Switzerland (1800 m to 1000 m a.s.l.), grasslands are the predominant form of agriculture. These grasslands are managed at different intensities. In this study we compared SOC stocks (0–20 cm soil depth) of the three common management regimes of increasing intensity, that cover the full grassland productivity range across management intensities (MIs).

We hypothesized that SOC stocks would be positively correlated with management intensity, because higher MIs provide more plant biomass and OM input from fertilizer (manure), resulting in larger OM resource availability for SOC stabilization and consequently for a higher SOC stock.

Materials and methods

Site description

The studied grassland sites are in Eastern Switzerland, in the Lower Engadine valley, within a ca. 1.5 km perimeter around the village Sent at ca. 1200 to 1600 m a.s.l. (Figure 1). The Engadine is part of the inner-alpine dry zone and the climate shows a certain degree of continentality. Annual mean values for the most recent 1991–2020 averaging period at the nearby

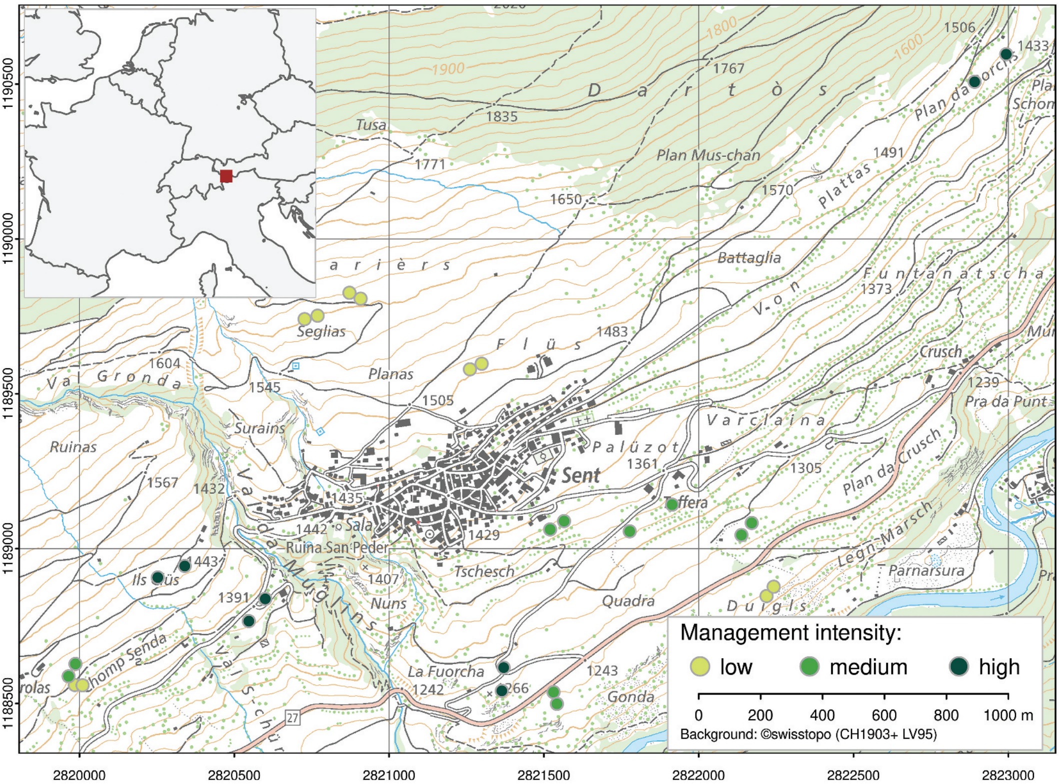

Figure 1. Map of grassland sites around the village of sent in the lower engadine valley. Colors indicate three levels of management intensity.

MeteoSchweiz weather station of Scuol (4 km from Sent at 1304 m a.s.l.) are 704 mm precipitation, a mean temperature of 5.9 °C, 112 days of snow cover and 1785 sunshinenhours. The soils of our sampling area above the Inn River were characterized as shallow Phaeozems (Holliger 2007). The increasing stone content prevented soil sampling with a 5 cm impact probe beyond 20 cm depth.

Global warming effects are apparent on a 10-year scale already: While precipitation and sunshine hours remained almost unchanged over time, the mean temperature during the 1991–2020 averaging period was 0.4 °C higher and snow cover lasted 8 days less, compared to the prior 1981–2010 averaging period.

Experimental sites

We identified 28 grassland sites that had been categorized according to productivity prior to the start of our study. The sites were managed by 13 different farmers, following traditional land use practices for >20 years. Within each of these sites, a randomly chosen 5 × 5 m plot was defined to serve for this soil sampling program.

Farmers were interviewed annually in November/December about the management of their fields in the past year. They reported the dates of grazing and cutting as well as the fertilization activities. Quality and quantity of organic fertilizers were recorded as solid manure, liquid manure, urine-rich manure and bedding manure. Annual N and C loads were calculated based on Richner et al. (2017), assuming a dilution of 1:2 for liquid and urine-rich manure and bulk density of solid

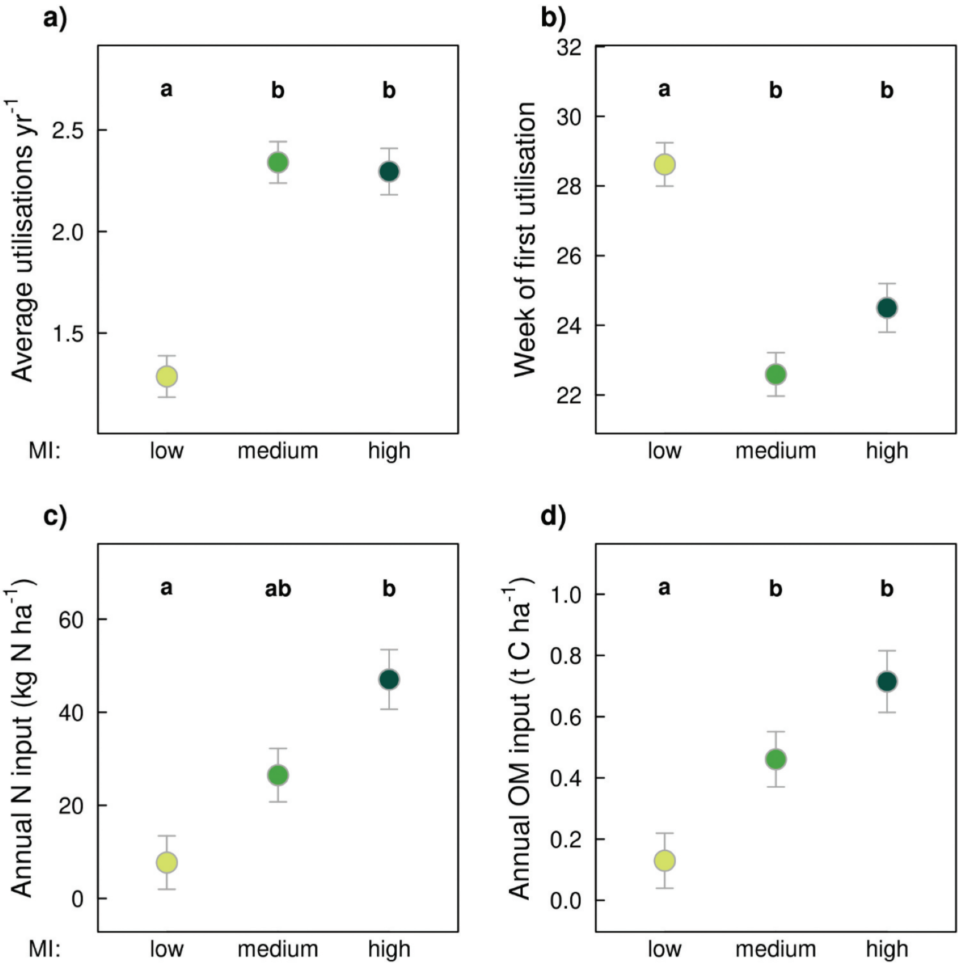

Figure 2. Management descriptors of grasslands in different management intensity (MI) categories. Circles indicate 12 year means (2010–2021) for individual sites ±1 SE. Lowercase letters in each panel indicate significant post-hoc comparisons of means using Tukey contrasts.

manure of 0.6 t m^{-3} as well as contents of 3.9 kg total N m^{-3} and 40.6 kg C m^{-3} for liquid manure, 4.5 kg total N m^{-3} and 23.2 kg C m^{-3} for urine-rich manure and 4.5 kg total N t^{-1} and 87 kg C t^{-1} for solid and bedding manure.

Low management intensity (MI) sites ($n = 10$) were characterized by one main utilization per year (Figure 2(a)), either by mowing or grazing. Mowing takes place in mid-July (week 29) (Figure 2(b)), often set to a specific date by a management contract between the farmer and the cantonal administration. In wetter years, there may be an occasional light grazing in autumn by sheep or cattle (0.05–0.15 LU ha^{-1}) to consume the regrowth before the onset of snowfall. Low-intensity grasslands are usually unfertilized except for a low amount of farm-yard manure applied on some fields bi- or tri-annually (7.7 kg N ha^{-1} year^{-1}; Figure 2(c)). Organic matter C input (0.13 t C ha^{-1} year^{-1}, Figure 2(d)) is significantly lower compared to medium and high MI. Average plant species richness on 25 m^2 is 46 and significantly higher compared to medium and high MI. Indicator plant species for low-intensity grasslands were *Brachypodium pinnatum*, *Galium verum*, *Bromus erectus*, *Thymus serpyllum* and *Asperula cynanchica*.

Medium MI sites ($n = 10$) are characterized by two utilizations per year (Figure 2(a)), mostly spring grazing and a late hay cut. The first utilization was earlier (week 22) than low or high

MI, because many were grazed in the beginning of May (Figure 2(b)). Fertilization (26.5 kg N ha^{-1} $year^{-1}$; Figure 2(c)) took place by farmyard manure in late fall or (exceptionally) early spring and provided an organic matter C input of 0.46 t C ha^{-1} $year^{-1}$ (Figure 2(d)). In spring, manure is often crushed and distributed using a harrow. Average plant species richness on 25 m^2 is 31 and significantly lower compared to low MI and similar to high MI. Indicator species are *Trisetum flavescens*, *Festuca pratensis*, *Centaurea scabiosa* and *Carum carvi*.

High MI sites ($n = 8$) are used up to three times per year (Figure 2(a)). They are mown or grazed and regularly fertilized with slurry and/or farm-yard manure (FYM), resulting in an input of 47.0 kg N ha^{-1} $year^{-1}$ (Figure 2(c)) and an organic matter C input of 0.71 t C ha^{-1} $year^{-1}$ (Figure 2(d)). Harrowing in spring is carried out regularly. Fields are sporadically overseeded with commercial multi-species mixtures without ploughing to improve species composition and forage quality. Average plant species richness is 28 and slightly below medium MI sites. Oversowing has only a small effect on species richness, since most sown species are not completely absent beforehand, but just decreased in abundance. Indicator plant species are *Heracleum sphondylium*, *Anthriscus sylvestris*, *Taraxacum officinale*, *Vicia sepium* and *Crepis biennis*.

Soil sampling and analysis

In October 2018, five soil cores each were obtained in all 28 grassland sites, systematically covering the 5 × 5 m sampling plot. A 5 cm inner diameter Humax impact probe (Martin Burch AG, Rothenburg, Switzerland) with PVC insert sleeve was hammered perpendicularly to the surface into the ground to produce an intact 20 cm soil core. This core was split in four 5 cm depth increments in the lab. All samples were dried and sieved (2 mm). Stones and plant parts were separated to obtain bulk fine soil. The plant material that was retrieved when sieving the soil cores served as proxy for total belowground plant material ('roots'). Using 2.65 for rock fragment density and 0.34 for root density, fine soil bulk density ($BD_{fine\ soil}$) was determined individually for every single increment sample according to

$$BD_{fine\,soil} = \frac{mass_{sample} - mass_{rock\,fragments} - mass_{roots}}{volume_{sample} - \frac{mass_{rock\,fragments}}{\rho_{rock\,fragments}} - \frac{mass_{roots}}{\rho_{roots}}}$$

We measured soil organic C and N contents in bulk soil by elemental analysis (oxidation of C-CO_2 and N-NO_2 in an O_2 stream and subsequent reduction of NO_2-N_2 by a copper–tungsten granule). Separation of CO_2 and N_2 was accomplished by gas chromatography–thermal conductivity detector (GC-TCD) and quantification using acetanilid as an external standard (Hekatech Euro EA 3000, Wegberg, Germany). Samples were free of carbonate, so total C equals organic C.

SOC stock per depth increment ($SOCstock_i$) was then calculated according to

$$SOCstock_i = SOCcon_{fine\,soil} \times BD_{fine\,soil} \times depth_i$$

where $SOCcon_{fine\ soil}$ is the concentration of organic C in the fine soil (%) and $depth_i$ is the depth of the respective soil layer (cm).

Soil pH was determined in 1 : 2.5 soil-water suspension according to Swiss reference method pH (https://ira.agroscope.ch/de-CH/publication/45991).

Clay content was determined for a particle size ≤2 µm using the pipette method according to Swiss reference method KOF (https://ira.agroscope.ch/de-CH/publication/45990).

Statistics

Data were analyzed using linear models with Gaussian likelihood followed by Tukey post-hoc tests of means using package *emmeans* in R 4.4.1 (R Core Team 2024). Error bars shown in all graphs are standard errors of the mean.

Results

SOC stock peaks at medium management intensity

Across all four depth increments, the maximum SOC stock was always found in the medium MI, but depth increments showed differences between MIs only in the top 10 cm (Figure 3). The total SOC stock (0–20 cm) was significantly different between MIs: 73.1 ± 3.99 t C ha^{1} in low MI plots, largest in medium MI grassland plots with 89.6 ± 4.2 t C ha^{-1} (+23%) and comparatively small with 78.7 ± 5.4 t C ha^{-1} (+8%) in high MI plots (Figure 3).

Belowground plant material not significantly different between MIs

Belowground plant material (BGP) C mass was largest (ca. +7%) in the low MI compared to high MI, but differences were not significant between MIs (Figure 4). Averaged across sampling depths, BGP C means were 2.28 (±0.260), 2.11 (±0.173) and 2.13 (±0.205) t C ha^{-1} at low, medium and high MI, respectively.

Organic matter C/N ratio is not significantly different between MIs

A rising C/N ratio of OM can be an indicator for poor decomposability of soil organic matter, but the C/N ratio of the soil samples in this study did not differ significantly between MIs or depth increments. Averaged across sampling depths, C/N ratio means were 11.2% (±0.34), 11.8% (±0.75) and 10.0% (±0.44) at low, medium and high MI, respectively (Figure 5).

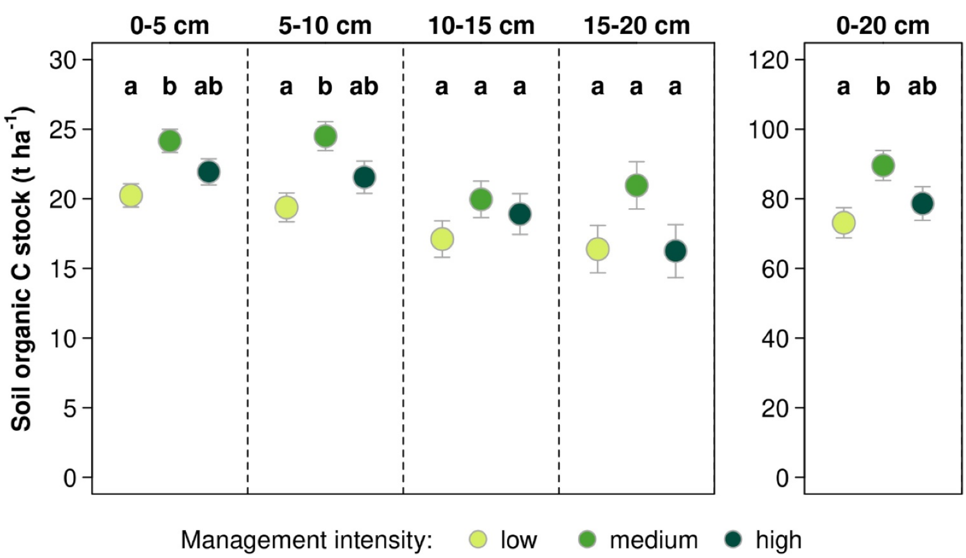

Figure 3. Mean bulk soil OC stock values (SOC t C ha^{-1}), grouped by management intensity (MI), plotted over depth increment (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm and 0–20 cm). Brown indicates low, bright green medium and dark green high MI. Bars indicate ±1 SE of the mean.

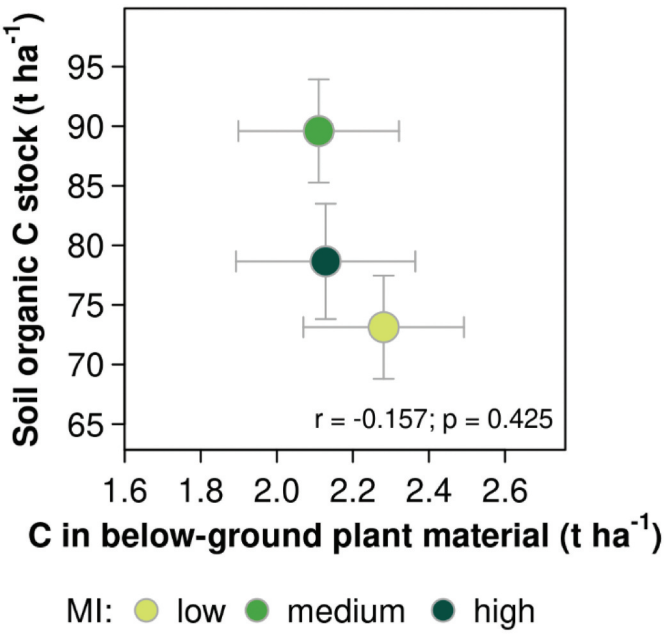

Figure 4. Mean belowground plant material OC mass values (0–20 cm, t C ha^{-1}) plotted against mean bulk soil OC stock values (0–20 cm, SOC t C ha^{-1}), grouped by management intensity (MI). Bars indicate ± 1 SE of the mean, r is Pearson's product moment correlation coefficient between all observation and p its significance.

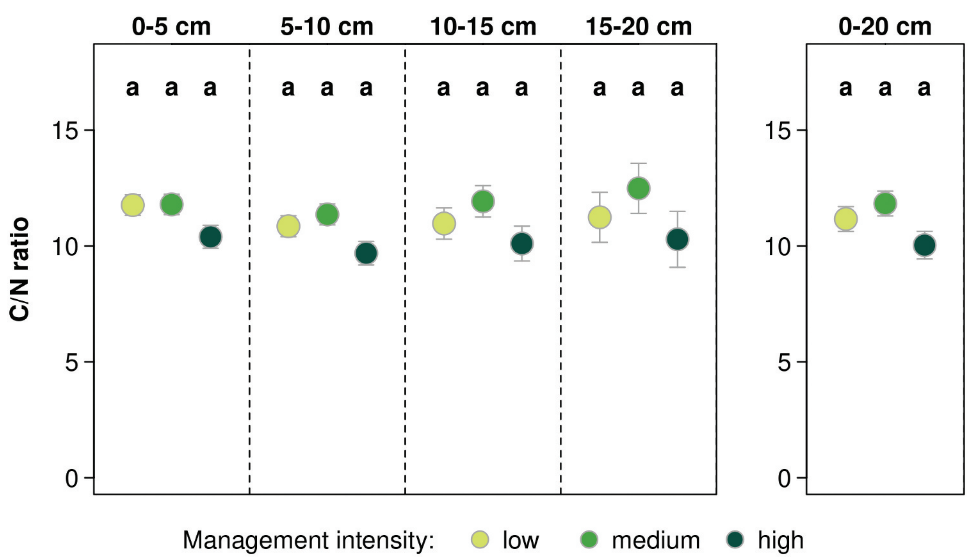

Figure 5. Mean bulk soil organic matter C/N ratio values (C/N) grouped by management intensity (MI), plotted over depth increment (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm and 0–20 cm). Bars indicate ±1 SE of the mean.

SOC clay content not significantly different between MIs

The clay content (0–20 cm depth mean), an important factor favoring organic C stabilization, was uncorrelated with SOC stock ($r = 0.12$, $p = 0.56$). Highest clay content was 25.9% ± 1.97 at high MI, where SOC stock was intermediate, and not at the medium MI (clay 22.9% ± 0.95 and highest SOC

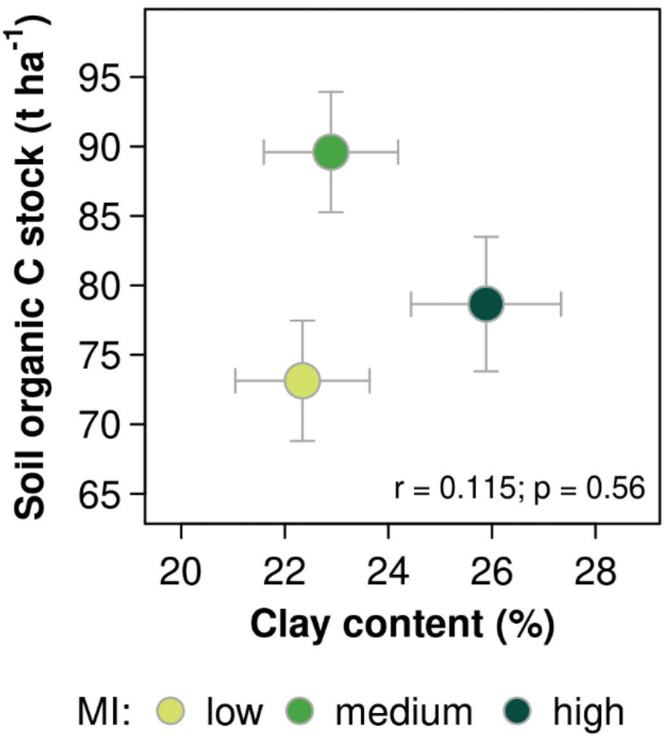

Figure 6. Mean bulk soil clay content percentage values (0–20 cm, clay content (%)) plotted against mean bulk soil OC stock values (SOC t C ha^{-1}), grouped by management intensity (MI). Bars indicate ±1 SE of the mean, r is Pearson's product moment correlation coefficient between all observation and p its significance.

stock) or low MI (clay 22.3% ± 1.17 and lowest SOC stock). Differences in clay content between MIs are not significant (Figure 6).

Soil pH positively correlated with SOC stock

The mean soil pH at low MI was 6.2 (±0.18), at medium MI 6.7 (±0.07) and at high MI 6.3 (±0.09), qualifying the soils as slightly acidic to neutral. Soil pH correlated positively with soil organic C stocks (Figure 7).

Discussion

Challenges in assessing SOC stocks

As a consequence of global climate change, the Alps are an area of intensive warming (Gobiet et al. 2014; Rottler et al. 2019). Plant productivity in high elevation environments is often limited by thermal energy, both in terms of temperature and length of the growing season. Thus, warming can strongly favor plant growth and consequently the potential input of organic C into the soil (Grigulis and Lavorel 2020; Volk et al. 2021). This observation is supported by monitoring data of the Swiss Federal Office for the Environment (FOEN, 2023. Supplementary information Table S1 and Figure S1). They show that SOC stocks in Swiss grasslands below 1200 m a.s.l. altitude were decreasing over 31 years (1990–2021), presumably as a result of increased soil respiration. However, in grasslands above 1200 m a.s.l., hence at elevations with stronger thermal limitation, SOC stocks increased over the same

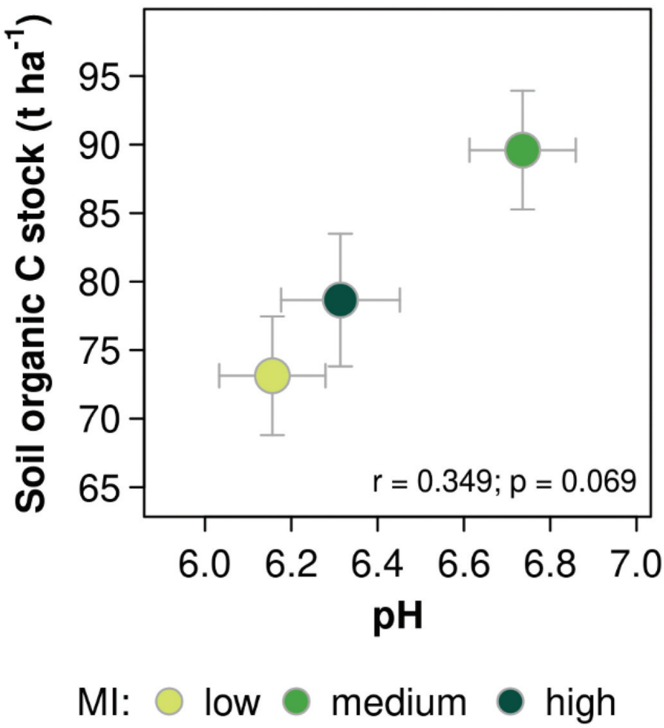

Figure 7. Mean bulk soil pH values (pH) plotted against mean bulk soil OC stock values (SOC t C ha^{-1}), grouped by management intensity (MI). Bars indicate ±1 SE of the mean, r is Pearson's product moment correlation coefficient between all observation and p its significance.

period (Supplementary information Table S1 and Figure S1). On the other hand, in a subalpine grassland warming experiment close to the Sent research site of this study, Volk et al. (2022) found only negative effects of warming (loss of C) on the net ecosystem C balance. Regardless of the direction of change, recent responses of the soil C stock to global warming are likely to be reflected in the data presented here, because grassland SOC loss can be expected to be rapid and restricted to topsoil (Verbrigghe et al. 2022). Lacking a time series of soil sampling data we cannot decide whether the grassland sites in our study are in a steady state today. This leaves the possibility for an undetected management intensity × warming interaction in the data.

Assessing management-dependent SOC stocks can be further complicated by the fact that the soil profile varies between sites and is not fully covered by the analysis (Wiesmeier et al. 2012). In the shallow soils of our study area, the 20 cm sampling depth that we investigated can be expected to cover the largest part of the SOC stock, but it needs to be kept in mind that our results reflect the most dynamic part of the SOC stock (Jenkinson and Coleman 2008; Rumpel and Kögel-Knabner 2011). This layer is not only directly exposed to human management, but also under the influence of both aboveground litter and roots, and heterotrophic lifeforms including mice, arthropods, fungi and microbes. Excluding the possibility of deepening root growth under climate warming (Jia et al. 2019), in this management intensity trial, we make the simplified assumption that in unplowed grassland subsoil (>30 cm depth) OM content changes follow the faster topsoil dynamics, only with a lag phase and smaller amplitudes. We, therefore, consider our findings a valid proxy for the total soil organic C storage.

Edaphic factors do not confound MI effects on SOC stock

Providing protection of OM from decomposition, clay content is often considered to be the most important factor determining the potential C storage capacity (Matus 2021). If clay content was correlated with MI, this could then lead to a confounding of factors. However, findings from our study show that the maximum SOC stock is associated with the medium clay content, not the highest clay content (Figure 6). From studies that differentiate the process of SOC formation into a climate-driven formation of particulate OM (non-mineral associated) and soil property driven formation of mineral associated OM (Doetterl et al. 2015; Mitchell et al. 2021), we deduce that both with respect to our 'topsoil only' sampling scheme and the regional warming situation, SOC sequestration in our study is likely not clay-content driven.

Another important factor affecting OM decomposition is soil pH. A meta-analysis on the common agricultural practice of liming indicated strongly increased CO_2 emissions from soils with increased pH (Zhang et al. 2022). Indeed, the regulatory role of soil pH on decomposition rates varies by a factor of four in the pH range from 4.0 to 6.0 (Walse et al. 1998; Leifeld et al. 2008). Accordingly, soil carbon loss through increased decomposition can be a consequence of increasing soil pH (Malik et al. 2018), following alleviation of acid retardation of microbial growth in land use change processes. Also in a grassland environment similar to ours, decreasing acidity strongly accelerated OM decomposition (Leifeld et al. 2013). But surprisingly, in our study, we found SOC stock to be positively correlated with decreasing soil acidity, not suggestive of accelerated OM decomposition due to alleviated acid retardation of microbial growth (Figure 7). This lets us assume that the acidity levels of all MIs in our study (pH 6.2–6.7) were all well above the acid retardation threshold. Thus, pH is non-limiting for microbial activity in our MI series and not a factor that is driving the C stock size.

Plant organic matter input does not drive SOC stock differences

As one component of increased MI, we observed increased N inputs (Figure 2(c)), promoting grassland plant productivity. In an Austrian study at ca. 730 m a.s.l. on the effect of very high fertilization rates (up to 240 kg N ha^{-1} $year^{-1}$, a factor of 5 above our high MI N input), Gruber et al. (2006) found that with up to three cuts, annual DM yield always increases with increasing N input. This extreme comparison makes us confident, that in the N input range applied in our study, higher N input always yields higher productivity. It is also plausible to assume that overall plant productivity is a valid proxy for plant derived OM input to the ecosystem, even if higher soil C contents may be mostly a product of root rather than shoot material (Rasse et al. 2005). It was often reported that SOC stocks rise with rising plant productivity (e.g. Mitchell et al. 2021; Bai et Cotrufo, 2022). As higher yields increase the potential for higher input of OM into soils (Conant et al. 2017), this led us to hypothesize that higher plant productivity coincides with higher SOC stocks, all other factors (climatic, edaphic) being very similar.

This hypothesis was not confirmed in our study, as we found the largest SOC stocks at the medium MI (Figure 3). This finding is similar to an earlier experiment, showing maximum SOC stock at medium N input (Volk et al. 2018), Our working hypothesis implies a linear relationship between MI and SOC stock. This may result from an overrepresentation of studies that focus on the restoration of degraded grasslands (Bardgett et al. 2021). In the degraded situation, SOC stock and OM input are both at a minimum, making differences in C input more important, whereas a short mean residence time of SOC does not play an important role (Lützow et al. 2006). In our study, however, sites are usually under the same management for decades and may be close to their specific SOC sequestration potential, with OM input and decomposition in a steady state, only modulated by annual weather conditions.

The mean mass of belowground plant material in our experimental plots and the corresponding C content (2.2 t C ha^{-1} ±0.21; ca. 1400 m a.s.l.) was smaller compared to the data for subalpine grassland that was only grazed, unfertilized and at higher altitude in the same region, as reported in

Leifeld et al. (2013); 4.2 t C ha^{-1} ±1.10; ca. 2100 m a.s.l.) and Volk et al. (2022); 8.9 t C ha^{-1} ±1.33; ca. 2170 m a.s.l.). This confirms a general trend of lower allocation to root mass compared to shoot mass at lower elevation (Qi et al. 2019) and in high-productivity systems (Li et al. 2015).

We observed that under high MI belowground biomass C mass is smaller compared to low MI (Figure 4, not significant). We assume a two-factor effect of increasing nutrient availability in more productive fields: 1) High nutrient supply often results in a lower root/shoot (R/S) ratio, because a proportionally smaller resource allocation is necessary for nutrient acquisition (Davidson 1969; Boot and Mensink 1990; Cong et al. 2019) and 2) high cutting frequencies shorten the regrowth period available to plants, possibly leading to smaller individual plants with lower root mass (Gruber et al. 2006). Therefore, increased belowground productivity must be excluded from the potential drivers of increased SOC storage.

The SOC stock size or stock size changes are frequently associated with the C/N ratio of plant material or of soil organic matter, as an indicator of substrate quality. This is because the substrate C/N ratio has a strong influence on microbial OM decomposition. A smaller C/N ratio under high N supply conditions may allow for higher SOC storage, presumably favored by improved microbial C use efficiency (CUE) as described by Poeplau et al. (2018). On the other hand, Riggs et al. (2015) and Riggs and Hobbie (2016) did not find increased microbial CUE with increased N input, but instead reduced microbial biomass and coincidingly reduced microbial respiration were hinting at larger SOC stocks. This association of low C/N with high SOC storage cannot be found in our study. Here, the C/N ratio peaks at the maximum SOC stock (medium MI), so that high C/N ratios (Figure 5) seem to coincide with high SOC stocks. This observation supports the assumption that high C/N ratios in litter cause low decomposability (Berg 2000), thus increasing turnover times of soil OM and SOC storage. But all MIs taken together, there is no correlation of C/N with SOC stock, so that OM C/N ratio is apparently unrelated to SOC storage.

FYM input does not drive SOC stock differences

Grassland management in highly productive lowland areas usually includes a substantial proportion of mineral fertilizer, supplying a large amount of plant nutrients, but no organic C. In contrast, the mountain grasslands of our study are solely fertilized using slurry or FYM, consisting of cattle feces and barn bedding material. This leads to a substantial input of organic C into the ecosystem with a linear increase of factor 5 between MIs (Figure 2(c)). FYM fertilization has often been shown to promote SOC buildup, depending on the decomposability of FYM OM (Hoffmann et al. 2006; Šimon et al. 2013). Comparison of OM input (Figure 2(d)) and SOC stocks (Figure 3) shows that such a buildup of SOC stocks depending on FYM input is not observed in our study. Thus, our findings contrast many long-term studies that report large SOC gains under FYM fertilization (e.g. Poulton et al. 2018; Li et al. 2021). Such C gains may be observed when untypically large amounts of FYM are applied, exporting OM from one site, only to import it to the next site (Schlesinger 2000). Also, valid comparisons can only be made in grassland experiments (Shi et al. 2024), since in arable land the permanent disturbance of the soil structure and the lack of plant cover generally result in low SOC stocks, making soils more suitable for fast replacement of previously lost C. In contrast, our MIs on grassland all apply a comparatively low C input with FYM (0.13–0.71 t C ha^{-1}), that is only ca. 10% of the FYM C input of arable cropland studies (Buyanovsky and Wagner 1998; Kong et al. 2005; Autret et al. 2016), that documented SOC enhancements after annual FYM C inputs of 5.4–8.9 t C ha^{-1}. For a comparable amount of C input with FYM (0.35–0.4 t C ha^{-1} year^{-1} + mineral fertilizer) Hopkins et al. (2009) found no change in SOC stock after 109 years at the Palace Leas site (Cockle Park Farm, North-east England) and a SOC stock increase in the FYM treatment of 12 t C ha^{-1}, compared to 12.3 t C ha^{-1} year^{-1} in the control treatment after 126 years in the Park Grass Experiment (Rothamsted Research, South-east England). Similarly, Keel et al. (2019) found no effect of organic amendments on SOC stock in 11 long-term field trials in Switzerland (cropland and permanent grassland). Based on the evidence above, we suspect that the long-term effectiveness of FYM treatment for SOC stock increases is often prematurely concluded.

Conclusion

None of the drivers commonly associated with SOC stock size (above- and belowground plant productivity, FYM input, soil clay content, soil pH, SOC C/N ratio), explained the differences in SOC stock between the three management intensities (MIs) under investigation. Therefore, the finding that maximum SOC stock is associated with medium MI demands an alternative explanation.

We deduce by way of exclusion, that not above- or belowground OM input ultimately determined the SOC stock, but that the antagonistically acting OM decomposition rate must have overcompensated the larger OM input to high MI fields. Thus, there is substantial OM input at medium MI, but the decomposition rate is reduced compared to high MI.

Accordingly, more intensive management, leading to higher grassland yields, is not necessarily beneficial for SOC sequestration, because this management may favor OM decomposition more than OM stabilization.

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Data availability statement

Data used in this study are available at Volk, M. (2025). Intermediate management intensity supports largest topsoil organic carbon stocks in mountain grassland [Data set]. Zenodo. 10.5281/zenodo.14917543.

Authors’ contributions

MV and MKS designed the experiment and analyzed the data. MV, MH and RG conducted field work. MV and MKS wrote the manuscript.

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