ORIGINAL ARTICLE

Rotational pasture management to increase the sustainability of mountain livestock farms in the Alpine region

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Abstract

Over the past 30 years, farming in the Alpine region has undergone important changes: the average number of animals per farm and the use of external inputs have increased while the diversity of farming practices has decreased, becoming similar to intensive farming. This change has led to a reduction in the supply of agroecosystem services and the sustainability of the mountain livestock sector. In this study, we investigated rotational grazing as alternative to continuous grazing to improve the sustainability of mountain farming practices. Greenhouse gas (GHG) emissions such as carbon dioxide, methane and nitrous oxide were measured together with soil properties (bulk density, saturated hydraulic conductivity, organic carbon content and plant biomass) for two grazing seasons using static chambers. The results showed that rotational grazing had a positive impact on plant biomass: minimize soil disturbance, reduce compaction and GHG emissions of the soil and increase water infiltration. Therefore, this practice has revealed clear benefits in terms of soil protection and climate change mitigation and adaptation.

Keywords Agroecology · Carbon cycle · Greenhouse gas emissions · Rotational grazing · Soil carbon stock

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Introduction

Sustainable land and soil management practices are central to improve our food systems, maintain a healthy environment and ensure European rural development (Recanati et al. 2019). Soil has numerous functions including food production, nutrient and water storage, filtering, buffering, as well as breaking down and storage and turnover of organic matter. It also plays a central role in the protection of water and in the natural exchange of gas with the atmosphere (FAO 2018). It is crucial for nature, agriculture and all human beings as the foundation of our health and our wealth (Adhikari and Hartemink 2016). Soil also constitutes a source of greenhouse gas (GHG) emissions mainly from intensive agriculture (Oertel et al. 2016), which accounts for about 25% of the global anthropogenic annual emissions (Smith et al. 2014). It represents a key tool for climate change mitigation (Bennetzen et al. 2016); by changing management practices, soil can provide a wide range of services that bear significant environmental advantages for sustainable development (Stavi et al. 2016).

Conventional agriculture can degrade soil in terms of loss of soil organic matter (SOM) and reduction of nutrient

content (Doran and Parkin 1997); moreover, it also lowers the microbial diversity and biochemical activity (Saha 2010). Within agricultural sectors, livestock contributes nearly 80% of all agricultural emissions (Steinfeld et al. 2006), mainly derived from enteric fermentation (methane-CH_4 emissions) and manure management, CH_4 and nitrous oxide-N_2O (O'Mara 2011). Agricultural and livestock practices, including pasture management, have a tremendous impact on long-term soil health and soil functions, it is, therefore, important to develop and implement practices that guarantee the durability and resilience of the resources in order to obtain long-term benefits, e.g. water conservation and carbon stock accumulation (Altieri et al. 2015). To ensure the sustainability of productive grazing systems, it is crucial to improve and maintain soil health (Derner et al. 2018).

Faced with a rapidly growing demand for livestock products, the mountain cattle sector has undergone important changes in the last 20 years. The number of mountain farms has decreased and their average size has increased, becoming similar to the intensive farms located in the plains, breaking the traditional link between livestock and grasslands already threatened by the widespread desertion of mountain areas (Ramazin and Battaglini 2014). Furthermore, in many summer alpine pastures, the breeding rates are managed at suboptimal levels (Sturaro et al. 2013).

The grass protects the soil from erosive agents (e.g. water and wind) and supports its biological activity, e.g. the decomposition of organic matter and the accumulation of soil organic carbon. However, grazing removes the photosynthesizing leaves of plants, influences the natural physicochemical processes of the soil and triggers soil erosion especially when it is not properly managed (Bilotta et al. 2007). If grazing pressure is excessive, muddy conditions and soil compaction can occur, which together with the decline of desired grazing species; it favours the spread of weeds that tolerate such conditions (Drewry et al. 2008). On the other hand, if the grazing pressure is too low, the biomass production will increase because the animals eat as much as they want, but the net profit suffers because the forage (input) is wasted due to selective grazing. The optimal grazing pressure, thus defined when the grass is grazed at the optimal height (15 cm) which allows the maximum yield of fresh grass and the regrowth of grazing plants, and which provides the animals with the greatest quantities of grass with the value optimal nutritional (Voisin 1959), is obtained by adopting a pastoral plan; in this way, the food demands of the livestock can be met, the minimum possible amount of forage is wasted and soil degradation is prevented (Gusmeroli 2004). Adequate management of domestic herbivores is therefore important to maintain good soil coverage and the botanical composition of alpine meadows (Probo et al. 2014).

The aim of our study was to evaluate the impacts of continuous grazing, which is the practice of turning livestock out on a piece of pasture for the whole grazing season, versus rotational grazing for two consecutive years. Rotational grazing has been adopted as an innovative agroecological practice, with the aim of maximizing sustainability and promoting the multifunctionality of grazing. This practice allows, in fact, an efficient use of grazing resources, since the animals remain on each plot of pasture only for the time necessary for an optimal consumption of grass. The study assessed the effect of agroecological practice in terms of soil disturbance, soil organic carbon and complete annual soil carbon and GHG budget. This was achieved by measuring soil bulk density, soil water infiltration capacity, soil carbon stock, pasture production and soil greenhouse gas emissions (CO_2, N_2O and CH_4).

Material and methods

Study area

The study area was in the AgriLife farm (www.agrilife.bio), an organic donkey dairy farm, located in Comano Terme, Trentino Alto Adige Region (Lat. 46° 00′ 10.44″ N; Long. 10° 52′ 12.88″ E; elev. 508 m a.m.s.l.) (Fig. 1), within the UNESCO Biosphere Reserve of Ledro and Judicaria Alps. The farm raises around 40 dairy donkeys (Amiatina, Martina Franca and Ragusana breeds) that graze outdoors from May to October in the two hectares of pasture near the stables. The limited surface of the pasture determined a high animal pressure of six Animal Unit Month per hectare (AUM ha^{-1}) with consequent depletion of soil and grassland quality, impairing the sustainability of the current management. The surveyed area was a pasture located next to the donkey barn, whose growing season is generally from May to October; it was a valley floor grassland. During the study, meteorological data (minimum and maximum air temperatures, precipitation) were obtained from a meteorological station located in Campo Lomaso (http://meteo.fmach.it/meteo/). Annual average air temperature was 12 °C. Maximum and minimum average annual temperature during the period of the measurement was −5 °C in January and 27 °C in July, respectively; total annual precipitation was 1147 in 2018 and 1394 mm in 2019 respectively. From the pedological point of view, AgriLife farm was located in a glacial plain on glacial deposits covered by heterogeneous croplands; dominant soils were classified as Cutanic Luvisols, coarse loamy (IUSS Working Group WRB, 2015), formed on Tertiary limestone and Mesozoic dolomite, and on Holocenic alluvial deposits.
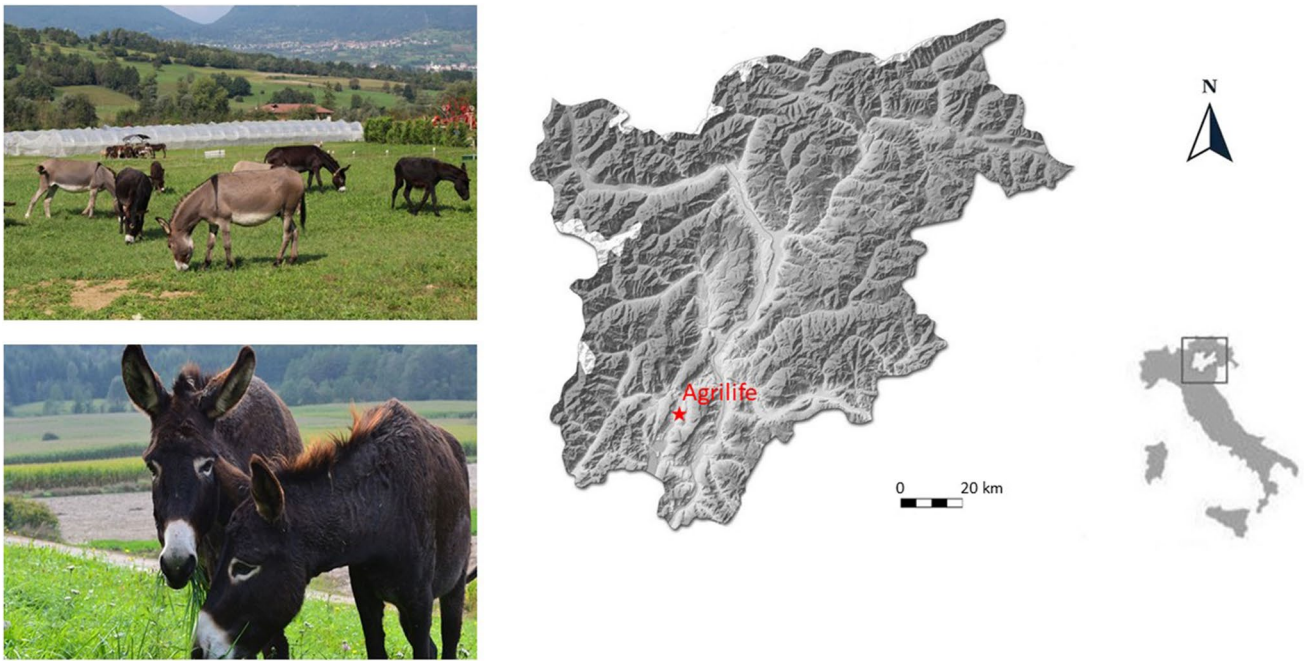
Fig. 1 The study area in Trentino Alto Adige Region (Northern Italy)

Experimental plots (grazing systems)

In the first year of the project (2017), the pasture, usually managed as continuous grazing, was divided in two different plots of one hectare each, equal in terms of soil type, texture and vegetation composition. The grassland pasture, analysed at the start of the study, was dominated by grass species (*Festuca arundinacea S.*, *Phleum pratense S.*), with variable proportions of legumes (*Trifolium repens L.*, *Trifolium pratense L.*, *Lotus corniculatus L.*) and forbs (*Plantago major L.*, *Taraxacum officinalis L.*). The soil was slightly gravelly in the surface horizon and very gravelly in the subsoil horizons. According to the classification, soils are characterized by a relative desaturation of the exchange complex and deep clay illuviation, characteristics that result in a reduced availability of nutrients.

Continuous grazing was divided into two experimental plots; one plot was managed with rotational grazing (RG) by dividing the area in five paddocks of 2.000 m^2 each. The animals were moved every 4 days from one paddock to another, after grazing up to an appropriate degree (AgriLife personal communication) allowing the grazed paddock to recover. In the RG plot, grass was grazed at the inflorescence emergence, providing the animals with a balanced supply of proteins, carbohydrates, vitamins and minerals. This treatment was managed by a pastoral plan which included two operations every 20 days: grooming of the upper soil layer (0–5 cm) with spreading of manure and topping of pasture residuals in the growing season (May to September) to maintain pasture quality.

The second 1 ha plot was managed, maintaining the existing management on the farm, with continuous grazing although it included a visibly degraded area due to the presence of drinking and feeding stations. For this reason, the plot has been divided into two sub-portions of about 0.5 hectares each, one considered to be continuous grazing (CG) and one, the most visibly degraded area due to trampling of animals, considered to be continuous stepped grazing (CSG).

The two sub-portions were not physically separated, and animals could freely move from one to another. The herd of donkeys, with their respective foals, were split (AgriLife personal communication) into three groups of 12 animals respecting relations of friendship between animals. The first group was for RG, the second group for CG and the third group for CSG. Each group grazed 8 h/day during the summer and 4 h during the spring (May), returning to the stable in the evening. The first group in RG only fed by grazing, the second and the third group in CG and CSG, respectively, got 4 kg/head/day of hay in addition to outdoors grazing.

Pasture and soil analysis

To evaluate the effect of animal trampling on the pasture production in terms of biomass, every month from May to October during the whole project, three randomized samples

of plant pastures were clipped at ground level in each treatment from a square of 100×100 cm. The samples were dried in an oven at 80 °C until dry constant weight (approximately 48 h). Pasture production was expressed as g of dry matter per square metre (g DM m^{-2}). To assess the effect of animal trampling on soil, the physical and chemical properties of the soil in each treatment were analysed. Soil samples were collected in autumn (October–November) both years (2018 and 2019). In each plot, soil samples (about 150 gr) in three replicates (9 in total for each samples date) were taken at 0–15 cm depth and stored at 5 °C before the analysis in laboratory. For the chemical analyses, soil samples were air-dried and sieved at 2 mm. The soil reaction (pH) was measured in a soil-distilled water solution (1:2.5 w/w). Soil mixtures were stirred and let stand for 1 h. Then, they were centrifuged for 10 min at 3800 rpm. pH was measured using a probe with selective sensors (XS Instruments, Carpi, MO, Italy).

Total carbon (C_{tot}) and total nitrogen (N_{tot}) contents of soil (%) were determined by dry combustion elemental analyser (Carlo Erba Instruments, mod 1500 series 2). Total organic carbon (C_{org}) was determined, also, by a dry combustion elemental analyser (Thermo Fisher Scientific Inc. USA) after the complete removal of inorganic carbon from soil with 0,5 M HCl.

The soil bulk density (BD, Mg m^{-3}) was measured at the end of each grazing period (October–November) for each plot to assess the effect of trampling on soil compaction.

The BD of the upper layer (0–10 cm) was determined with the core method using metallic cylinders of 100 cm^3 volume 50 mm $\times$ 54 mm cylindrical coresat (Grossman and Reinsh 2002). Three samples of soil cores, taken near the previous soil sampling sites, were placed in plastic bags and stored into an insulated bag to avoid evaporation during transportation to the laboratory. Then, samples were weighed at field conditions, oven dried at 105 °C for 48 h and reweighed for calculating the moisture content. Bulk density was calculated as ratio between the dry weight and the volume of the sample. Samples were weighed at field conditions (FW), oven dried at 105 °C for 48 h and reweighed (DW) for calculating the gravimetric soil moisture content (g g^{-1}) as:

$$[(FW - DW) \div DW] \tag{1}$$

and BD (Mgm^{-3}) as:

$$[DW \div V] \tag{2}$$

Water regulation

The amount of water that infiltrates depends on various factors, among others, the conditions of humidity, the soil structural characteristics (including clods due to tillage) as well as the land cover and the duration and intensity of precipitations (Hillel 1998). The infiltration process depends mainly on three soil parameters: the saturated hydraulic conductivity (K_{sat}, mm h^{-1}), the dimensional distribution of the pores, and the soil saturation conditions. As a first approximation, the water potential infiltration had been estimated measuring K_{sat} in the different area (continuous, continuous-stepping and rotational grazing), using a Guelph permeameter (soil moisture equipment Corp. 2012). At all the sites, the Guelph permeameter was operated at two different heads, namely 5 and 10 cm. Different solutions were adopted to estimate the K_{sat} given the measured flow rates (cm/min) at single heads (Amoozegar and Warrick 1986; Reynolds and Elrick 1990) or using the two readings jointly (Reynolds et al. 1983). Given the extreme field variability and the substantial violation of the theoretical assumptions of computational approaches, the average K_{sat} values obtained from using all the approaches are considered more representative and robust than a single value, in agreement with the so-called ensemble approaches used in climate and hydrological modelling (Cichota et al. 2013; Guber et al. 2006).

Soil carbon stock

The soil carbon stock (CST, Mg ha^{-1}) was calculated based on organic carbon content (C_{org}) in volume (%) and BD (Mg m^{-3}) for the first 15 cm of soil, which is the layer most susceptible to human disturbance:

$$CST_m \left(\text{Mg} \bullet \text{ha}^{-1} \right) = \text{Corg}m(\%) \times \text{BD}m \times (1 - gGm) \times tm \times 0.1$$

where CST_m (Mg C ha^{-1}) is the soil organic carbon stock of depth interval m; Corg_m (mg C g^{-1} fine earth) is the organic carbon content of the fine earth fraction (< 2 mm) of the depth interval (m); BD_m (g soil cm-3 soil) is the mass of soil per total volume of the soil sample of the depth interval m; gG_m (g coarse fragment g^{-1} soil) is the mass fraction of coarse mineral fragment (> 2 mm), thus (1-gGi) is the mass fraction fine earth (g fine earth g^{-1} soil) of the depth interval m; tm is the thickness (depth, in cm) of the depth interval m; 0.1 is a factor for converting mg C cm^{-2} to Mg C ha^{-1}.

Greenhouse gas fluxes from soil

Greenhouse gas fluxes from soil were measured approximately four times over 2 years (in May, July, September and October 2018 and in May, July and October 2019) using polyvinyl chloride (PVC)-closed chambers (Adviento-Borbe et al. 2013). Six vented closed opaque chambers (30 cm in diameter) were placed in each treatment, for a

total of 18 chambers. Before sampling, each chamber was covered with a lid with a reflective insulation and equipped with an outlet tube with a gas sampling valve and an internal fan to mix the headspace air. During each gas sampling event, the chambers remained closed for 45 min, allowing four gas samplings (at 0, 15, 30 and 45 min). Simultaneously with each GHG flux measurement, soil temperature and volumetric soil water content were measured, at 10 cm, using a portable sensor (STP-1, Soil Temperature Probe, PP Systems, Hitchin, UK) and theta probe (Ml2x, Delta-T devices Ltd., Cambridge, UK). Headspace gas samples were collected with air-tight 30 mL propylene syringes and were immediately pressurized into pre-evacuated 12 mL glass Exetainer® vials (Labco Ltd. Buckinghamshire, UK). The gas samples were analysed within 4 weeks from collection. GHG concentrations were analysed using a GC-2014 gas chromatograph (Shimadzu Scientific) with a thermal conductivity detector (TCD) for CO_2, a ^{63}Ni electron capture detector (ECD) for N_2O and a flame ionization detector (FID) for CH_4. Chamber gas concentrations were converted to mass per volume units using the Ideal Gas Law and measured chamber air temperatures and volumes. Fluxes of CO_2, N_2O and CH_4 were calculated using the slope of linear regression of gas concentration versus chamber closure time and the enclosed soil surface area. Daily fluxes were expressed on yield basis (kg of dry matter) and global warming potential (GWP) was calculated as kg C-CO_2eq kg^{-1} d^{-1} using the climate warming factor on 100-year horizon equal to 34 and 298 for CH_4 and N_2O, respectively (Myhre et al. 2014).

Statistical analysis

Statistical analysis was made using Statistica (Release 12, StatSoft, Inc. 1984–2014). Sample normality was tested using the Shapiro–Wilk test. One-way and two-way analysis of variance (ANOVA) was followed by least significance difference (LSD) test for post hoc comparison of means to identify the statistical differences between the three treatments in terms of pasture production, gas emissions and physio-chemical soil properties at $p < 0.05$. Tukey's test for post hoc comparison of means was performed for the comparison of more than two samples, e.g. soil parameters during the 2 years of the trial. Differences among treatments on GHG fluxes were analysed by a two-way ANOVA followed by Bonferroni post hoc test, using the statistical software Prism 4 (GraphPad Software, Inc.).

Table 1 Pasture production (g of DM m^{-2}) on the three treatments in different seasons during grazing in the two-year study

	Spring	Summer	Autumn
2018			
CSG	10.3 ± 2.5 b	8.2 ± 2.4 c	20.5 ± 2.5 c
CG	98.4 ± 10.3 b	100.2 ± 9.5 b	105.6 ± 8.3 b
RG	104.6 ± 7.5 a	134.3 ± 10.3 a	315.3 ± 12.4 a
2019			
CSG	15.4 ± 1.5 c *n.s*	8.1 ± 1.1 c *n.s*	28.3 ± 1 c *
CG	94.5 ± 12.5 b *n.s*	70.5 ± 10.3 b *n.s*	107.5 ± 9.4 b *n.s*
RG	277.3 ± 28.3 a **	112.5 ± 8.3 a *n.s*	291.5 ± 17.4 a *n.s*

DM dry matter, *CSG* continuous stepped grazing, *CG* continuous grazing, *RG* rotational grazing

Mean ± standard deviation (+/−) are reported ($n=3$). Different letters indicate significant differences between different treatments within the season, identified by the LSD as post-hoc test for the comparison of means at $p < 0.05$. Statistical differences between the two years are indicated by asterisks next to the values of the year 2019: * at $p < 0.05$; ** at $p < 0.01$ and *n.s.* if not significant

Results

Pasture production

The pasture production was significantly different in the three treatments (Table 1). In CSG, being a very degraded area, pasture production was almost non-existent throughout the year in both 2018 and 2019. At the first sampling date (spring 2018), no significant statistical differences were observed between RG and CG with a value of 104.6 ± 7.5 g of dry matter per m^2 and 98.4 ± 10.3 g of dry matter per m^2 in RG and CG respectively, while in summer and autumn, RG recorded significant higher values. The greatest differences between the two treatments occurred in 2019, when throughout the year, the differences between the two treatments were statistically significant. In the spring, dry matter in RG was 194% greater ($p < 0.01$) than in CG. The difference between the two treatments decreased during the summer, as dry matter in RG was 44.6% greater than in CG, but it raised again in autumn when the pasture production in RG was 171% greater as compared to that in CG. No significant differences were observed in the production during the three seasons within the same treatment. Comparing the 2 years, only in the case of the RG treatment, mean dry matter production increased by 266% in 2019.

Table 2 Soil chemical and physical characteristics of the study sites

Treatments	CSG- Continuous Stepped Grazing		CG- Continuous Grazing		RG-Rotational Grazing	
Experimental plots description	Plot Surface: 0.5 ha; Management: Continuous grazing; (May-September); Stocking density: 12 animals; Soil texture: coarse loamy		Plot Surface: 0.5 ha; Management: continuos grazing; (May-September); Stocking density: 12 animals; Soil texture: coarse loamy		Plot Surface: 1ha (5 paddocks of 2.000 m^2 each); Management: rotational grazing with 5 days grazing-stay on each paddock (May-September); Stocking density:12 animals; Soil texture: coarse loamy	
Year	2018	2019	2018	2019	2018	2019
C_{tot} (%)	4.45±0.00 a	3.46±2.21 a *n.s.*	2.18±0.05 b	3.17±0.72 a *n.s*	2.14±0.00 b	2.42±0.08 a **
C_{org} (%)	1.78±0.00 a	3.28±1.98 a *n.s.*	1.05±0.06 b	2.37±0.34 a *	1.21±0.23 b	2.21±0.06 a **
Soil Carbon Stock (Mg ha^{-1})	37.83±0.13 a	69.13±41.39 a *n.s.*	21.11±0.25 b	45.20±6.47 a **	24.36±0.37 c	41.64±1.19 a **
N_{tot} (%)	0.394±0.00 a	0.387±0.15 a *n.s.*	0.240±0.05 b	0.377±0.05 a *	0.230±0.00 b	0.367±0.01 a **
pH	7.58	7.68	7.40	7.64	7.20	7.05
Bulk Density (Mg m^{-3})	1,42±0.07 a	1,40±0.08 a *n.s.*	1,33±0.00 a *n.s.*	1,27±0.06 a *n.s.*	1,34±0.07 a *n.s.*	1,26±0.07 a *n.s.*
K_{sat} (mm h^{-1})	0,233±0.25 a **	0,642±0.22 b **	1,335±0.33 c	1,913±0.18 a **	1,864±0.31 a	2,701±0.19 b **

Each value represents the mean of 3 replicates sampling. Means±standard deviations are reported for each year. Statistical differences were identified by the LSD as post-hoc test for the comparison of means at $p < 0.05$. Different letters indicate significant differences between the treatments within the same year. Significant differences between the two years within the same treatment are indicated by asterisks: * at $p < 0.05$; ** at $p < 0.01$ and *n.s.* if not significant. C_{tot} total carbon, C_{org} organic carbon, N_{tot} total nitrogen, K_{sat} saturated hydraulic conductivity

Soil properties as affected by grazing intensity

Soil was classified as Cutanic Luvisols, coarse loamy (clay 18%; silt 45% and sand 40%) (IUSS Working Group WRB 2015) in each treatment.

The soil chemical characteristics are reported in Table 2. Total soil carbon content (C_{tot}, %) and soil organic carbon content (C_{org}, %) were significantly different in 2018 comparing CSG to CG and RG. In 2018, the mean C_{tot} values were equal to 4.44 ± 0.001%, 2.17 ± 0.053% and 2.13 ± 0.001% for CSG, CG and RG respectively. In 2019, however, values of both C_{tot} and C_{org} were evidently higher in CSG than in CG and RG, even if the differences were not statistically significant, given the high variability observed in CSG. Statistically significant differences in C_{tot} and C_{org}, were however observed within the same treatment in both in 2018 and 2019. In the CSG treatment, the values decreased from 2018 to 2019, while they increased in both CG and RG. Statistically, significant differences in N_{tot} soil content (%) were detected only in 2018, with higher values in CSG (0.394 ± 0.001%) compared to CG (0.24 ± 0.045%) and RG (0.23 ± 0.001%). Significant differences between the mean values of CSG treatment were not detected in the 2 years of observations. On the other hand, N_{tot} increased in CG and RG treatments, with statistically significant differences between the 2 years. The pH values did not exhibit any statistically significant difference among mean values, neither between plots nor between years. Moisture content (g/g) did not exhibit any statistically significant differences among mean values, neither between treatments nor between years, ranging between 0.20 and 0.23 g g^{-1} BD values (Table 2), pooled over the 2 years of observation, were significantly higher ($p < 0.05$) in the CSG treatment (1.42 ± 0.02 Mg m^{-3}) with respect to the CG (1.30 ± 0.04 Mg m^{-3}) and the RG treatments (1.29 ± 0.06 Mg m^{-3}). Significant differences ($p < 0.05$) between the mean values of the same treatment were not detected in the 2 years of observation. This trend was similar for the saturated hydraulic conductivity (K_{sat}, mm h^{-1}, Table 2), but in this case, RG (320.9 ± 125.0 mm h^{-1}) showed significantly higher values ($p < 0.05$) than CG (56.9 ± 17.4 mm h^{-1}) and CSG (3.40 ± 1.0 mm h^{-1}). Furthermore, in the case of the RG treatment, mean K_{sat} values for 2018 (89.4 ± 18.5 mm h^{-1}) were significantly lower ($p < 0.05$) than the values observed in 2019 (552.3 ± 70.2 mm h^{-1}). The highest values in terms of CST (Mg ha^{-1}) were recorded in CSG showing statistically significant differences with respect to CG and RG. Statistically significant differences were only found in 2018 (37.83 ± 0.134 Mg ha^{-1}, 21.119 ± 0.25 Mg ha^{-1} and 24.36 ± 0.379 Mg ha^{-1}for CSG, CG and RG respectively). In 2019, despite finding the highest values in the CSG, the differences between treatments were not statistically significant.
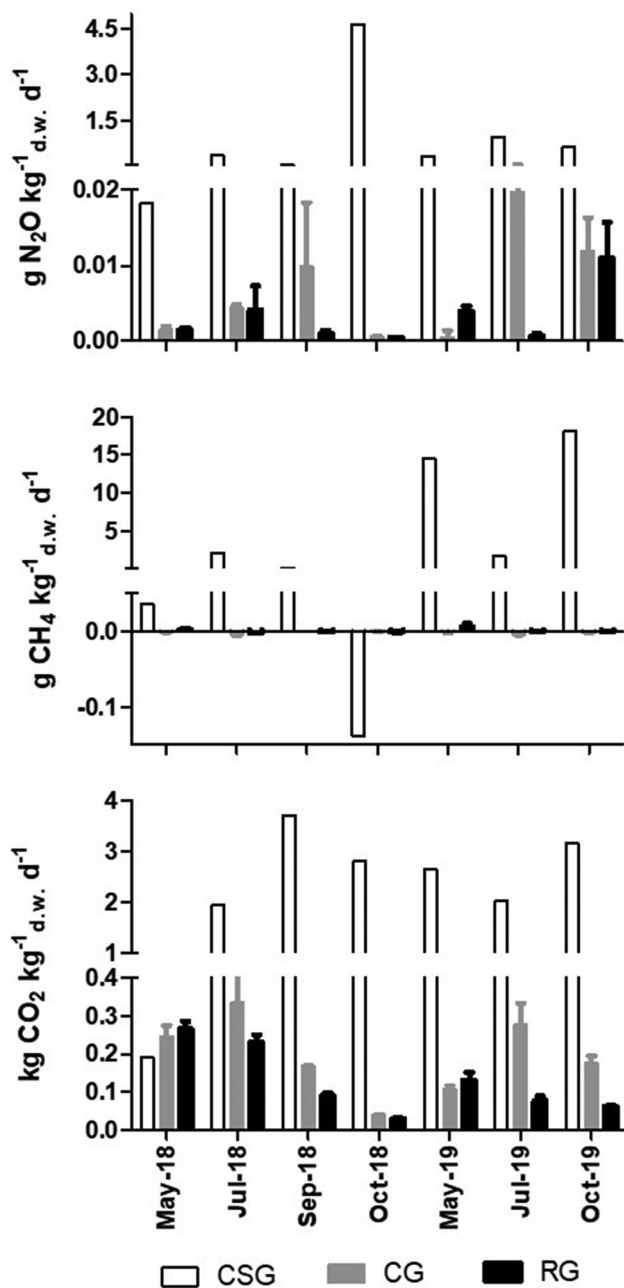
Fig. 2 Nitrous oxide-N_2O (top), methan-CH_4 (middle) and carbon dioxide-CO_2 (bottom) fluxes from soil, in the tree treatments during 2018 and 2019. Daily fluxes are expressed on plant biomass basis (kilogram of dry weight). Average values ($n = 6$) ± standard error. *CSG*, continuous stepped grazing; *RG*, rotational grazing; *CG*, continuous grazing

Greenhouse gas fluxes

Fluxes of the three GHGs monitored were significantly affected by both sampling dates and grazing treatments when expressed on yield basis ($p < 0.001$).

N_2O emissions (Fig. 2, top) were significantly higher in the CSG treatment with respect to CG and RG in all dates except for September 2018. In CSG treatment, values reached the highest peak in October 2018. CG showed higher N_2O emissions than RG in July 2019 only ($p < 0.01$).

CH_4 fluxes (Fig. 2, middle) showed the highest values of both emissions (May–September 2018 and 2019) and consumption (October 2018) in the CSG treatment. CH_4 fluxes in CG and RG treatments were always similar and close to zero.

CO_2 emissions (Fig. 2, bottom) were always higher in the CSG treatment, except for May 2018. In July and October 2019, CO_2 emissions were higher in CG than in RG treatment.

GWP (Fig. 3) followed the trend of CO_2 emissions: being that it was higher in the CSG treatment throughout the monitored period, except for May 2018, and it was higher in CG than in RG treatment in July and October 2019 ($p < 0.01$). Carbon dioxide contributed to the GWP for more than 90% throughout the monitoring period in CG and RG treatments. In CSG, N_2O contributed for 33 and 12% in October 2018 and July 2019, respectively and CH_4 for 15 and 16% in May and October 2019, respectively.

Discussion

There are two methods of pasture management: the first through a pastoral plan which involves shifting and improvement processes, and the second which does not include management plans, but only continuous grazing (Gusmeroli 2004). In general, in rotational grazing with paddocks, the distribution of animal load, as in our study, tends to be more uniform because of the amount of grass suitable for the nutritional needs of the animals, without the need of supplementary hay feeding. In contrast, continuous grazing with its extreme continuously stepped variant entails the presence of hay distributors in the pasture, causing heavy soil trampling nearby, as evident in the CSG treatment of our study. The comparison between the different pasture treatments in this study was based on the fact that the topographic, vegetation and climatic conditions of the study treatments were similar during the 2 years of study (2018–2019). Annual precipitation varied by only 22% during the study years, and summer precipitation varied by 10%. The temperature regimes in 2018 and 2019 were also similar.

This study highlighted the beneficial effects derived from the implementation of a pastoral plan to manage the rotation among paddocks, eliciting the increase of pasture production, decreasing soil compaction and GHG emissions from the soil.

Pasture production

Our results showed that in the CSG treatment, there was almost an absence of plant cover with a value of 0.12 kg ha^{-1} of dry matter in 2018 and 0.17 kg ha^{-1} in 2019. It also showed that the transition from unmanaged continuous grazing (CG) to managed pasture (RG) increased pasture productivity with an average of 114% from CG to RG during 2018 and 2019. Highly intensive grazing can decrease net primary productivity (Wardle 2013) and result in the loss of palatable, larger-leaved species causing domination of unpalatable small-leaved species, which produce litter of low quality for soil microbes and fauna (Pavlů et al. 2007). In April, at the beginning of the study, the pasture production in RG and CG were similar (Table 2), but after only 4 months (August 2018), the production in the RG had increased by 34% in the summer sampling and doubled in the autumn sampling. The differences also remained in 2019. As suggested by Probo et al. (2014), the implementation of the rotational grazing proved to be a more sustainable and practical management system in the Alps.

Grassland management practices can also support farmers to counter-act the negative impacts of climate change on livestock production and soil quality (Rojas-Downing, et al. 2017). In fact, in recent years, the shortening of grass growth during spring has been observed (Van Oijen et al. 2018) with consequent increase of costs for providing animals with supplementary feed during this season. Experiments in other climatic regions have shown that the management of grazing can increase the organic carbon levels of the soil in grasslands (Machmuller et al. 2015), although its storage is highly dependent on the type of climate (Abdalla et al.

2018), therefore specific experiments as in our study are important to better evaluate the effects of pasture management in alpine environments.

Agroecology, which aims to improve environmental sustainability through the implementation of different ecosystem management strategies, is probably the most promising strategy for increasing resilience and maximizing ecosystem services in Alpine grasslands.

In general, wild and semi-wild farms often do not apply adequate pasture management practices, with consequent impoverishment of the feed production and an increase of issues such as soil compaction and loss of biodiversity, particularly in situations of high animal load (Pisseri 2019). Pasture improvement and rotation methods can be successfully applied to all domestic herbivores: cattle, sheep, goats and horses, through the elaboration of the pastoral plan.

Soil properties

As reported in other studies (Abril and Bucher, 1999; He et al. 2011; He et al. 2011; Zhang et al. 2017), in CSG and CG, we found a higher bulk density of the soil and a lower Ksat caused by excessive trampling of animals.

Mountain grasslands are generally rich in soil organic carbon, but the typically high spatial variability of mountain environments, together with the different management systems, makes their soil carbon content highly variable. Recent studies have suggested that intensive livestock management lead to carbon loss, threating to transform the grassland into a carbon source rather than a sink (Wohlfahrt et al. 2008), with soil GHG emissions (Ciais et al. 2010, Janzen et al. 2006, Powlson et al. 2011). An innovative aspect of this

Fig. 3 Global warming potential (GWP), calculated as kg C-CO$_2$eq kg^{-1} d^{-1} on plant biomass basis (kilogram of dry weight). Average values ($n = 6$) ± standard error. *CSG*, continuous stepped grazing; *RG*, rotational grazing; *CG*, continuous grazing
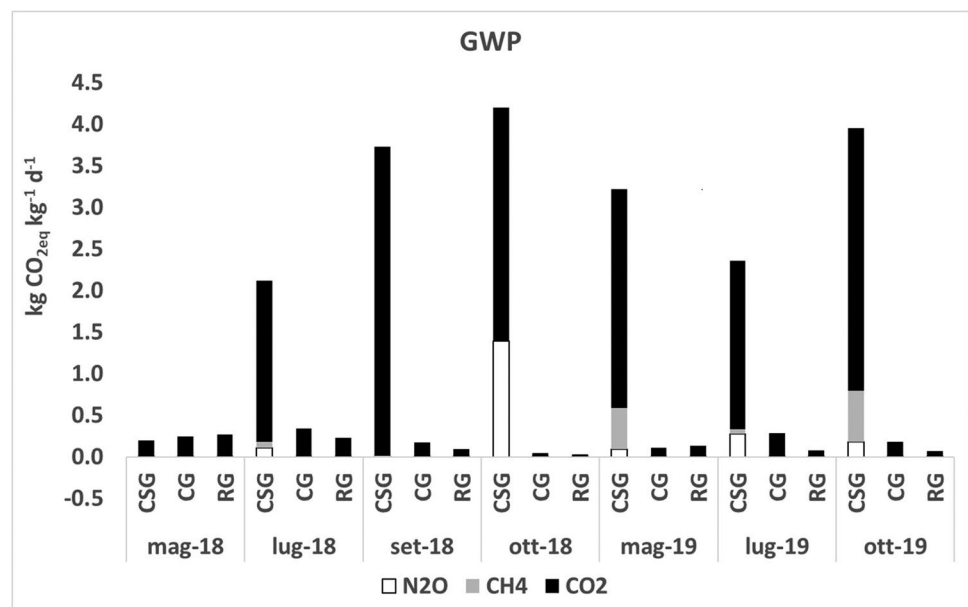
study was that it compared the effects of different livestock management practices on soil carbon stock while most studies are focused on the comparison of grazed and non-grazed areas. In this study, we observed increases and decreases of soil organic carbon in response to increased grazing pressure, which might be due to the short monitoring period. Smith (2004), using a modelling approach, it demonstrated that a change in soil organic carbon may not be detectable in the first 10 years from the beginning of the practice implementation and he assumed an increase in soil carbon input of 20–25% in 7–10 years. Therefore, well-monitored long-term experiments would be very useful to measure changes in the carbon stocks caused by management changes. Grazing intensity has the potential to modify the soil structure and the capacity to store organic carbon and could significantly affect grassland C stocks (Cui et al. 2005). As soil organic carbon (SOC) has a major influence on the soil's physical structure and a range of ecosystem services (e.g. nutrient retention, water storage and pollutant attenuation), its reduction could lead to reduced soil fertility and consequently, land degradation (Rounsevell et al. 1999). However, in our study, CSG generally showed high soil carbon stock, differing from the results of other studies (e.g. Lu et al. 2017 and Zhou et al. 2017 among others). The higher soil carbon stock values in CSG can be caused by the considerably higher bulk density values in CSG than in CG and RG caused by compaction due to continuous trampling and, to the considerable presence of dung near foraging stations found only in CSG. This treatment, as well as CG, did not consider manure management as RG did, therefore, it could alter the results. The direct effects of intensive grazing such as high organic matter input in the form of dung and compaction, but also the reduction of above ground biomass, can lead to short-term accumulation of organic matter which is quickly mineralized (Kuzyakov et al. 2000). Hence, contrasting effects resulted from intensive grazing; on one hand, the increase in fresh organic carbon (i.e. faeces) increases the microbial decomposition of native soil organic matter, thus nutrients available to plants. However, on the other hand, the excess of trampling and continuous overgrazing exert pressure on plant growth leading to an increase of bare soil areas and risk of soil erosion (Waters et al. 2017).

Greenhouse gas fluxes

As for the analysis of pastures as sources of greenhouse gas fluxes, we found that mechanical disturbances of soil such as compaction due to livestock trampling significantly alter gaseous flows from soils, as reported in other studies (Hansen and Jensen 1993; Linn and Doran 1984;). In fact, the fluxes of the three GHGs were more than one order of magnitude higher in the CSG plot than in the others,

highlighting a strong effect of either soil compaction or the accumulation of dung patches.

Compaction reduces the total volume of pores, especially larger ones. This in turn reduces aeration, creating anaerobic sites where denitrification or methanogenesis can occur, which consequently increases the production of N_2O (Bakken et al. 1987) or CH_4 (Serrano-Silva et al. 2014), respectively. N_2O and CH_4 emissions were indeed always higher in the GSG plot compared to the CG and RG plots, with the exception of October 2018, when CH_4 consumption was observed, suggesting a prevalence of oxidative conditions and nitrification (Butterbach-Bahl et al. 2013).

CH_4 is produced in the soil under anaerobic conditions by microbial decomposition of organic materials, whereas CO_2 production results from oxidation of soil organic materials by heterotrophic microorganisms and the respiration of plant roots. In our study, the CH_4 fluxes showed the highest values of both emissions (May–September 2018 and 2019) and consumption (October 2018) in the CSG plot. The highest emissions of CH_4 from CSG pastures may also result from the decomposition of dung patches from the animals, but in literature, studies addressing this effect on real pasture systems are very rare. We found that soil CH_4 emissions had a significant impact on the soil GHG balance of the studied pastures. The annual CH_4 emissions from our study were usually rather small compared to drained peat pasture soil, but taking the strong global warming potential of CH_4 into account (GWP for an averaging period of 100 years including climate carbon feedbacks) (34 CO_2-eq) the effect on the GHG budget is still notable. Optimized grassland management is therefore a potential cost-effective mitigation strategy to reduce atmospheric CO_2 concentrations (Soussana et al. 2010) by improving the CO_2 sink strength and thereby increasing the carbon stock in the soil. In addition to the large emissions resulting from the CSG treatment, RG's management showed lower emission rates than CG in July (N_2O and CO_2) and October 2019 (CO_2). Lower GHG emissions combined with a greater amount of dry matter produced indicate that rotational grazing (RG) is the most effective in mitigating greenhouse gas emissions from the soil and promoting the multifunctionality of farms.

Conclusion

The livestock sector will have to face important changes in company management in the coming years to increase environmental protection. Therefore, a growing sense of responsibility among operators towards significant GHG reductions is desirable to address climate change and other environmental crises. The application of a pastoral plan with rotational grazing, as in our study, has had important

environmental benefits such as an increase in grazing production and a reduction in greenhouse gas emissions and soil compaction, thus increasing the sustainability of the agricultural company in the short and long term. Rotational grazing can be applied to any livestock farm even with limited grazing extension and encouraging the implementation of this system on a larger scale will certainly provide numerous ecosystem services, supporting the environment as also indicated by the future common agricultural policy. Finally, with regard to the Alpine agricultural system, much more research is needed to evaluate the suitability and replicability of the innovative practice in different contexts.

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