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Carbon dioxide fluxes and soil carbon storage in relation to long-term grazing and no grazing in Icelandic semi-natural grasslands

Anna Gudrun Thorhallsdottir[1] | Jon Gudmundsson[2]

[1]Holar University, Saudarkrokur, Iceland

[2]Agricultual University of Iceland, Reykjavik, Iceland

Correspondence
Anna Gudrun Thorhallsdottir, Holar University, 551 Saudarkrokur, Iceland.
Email: annagudrun@holar.is

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Abstract

Question: What is the effect of long-term grazing and no grazing (NG) on carbon dioxide flux and soil carbon storage in Icelandic semi-natural grasslands.

Location: Three farms, with known history of land use, in W Iceland.

Methods: On each farm, we located an intensively and an extensively grazed site, which both had been constantly grazed for centuries, and a parallel site with no grazing for over 50 years. We measured net ecosystem exchange (NEE), ecosystem respiration and normalized difference vegetation index on a regular basis over the growing season. Samples were taken from 60 cm deep soil profiles for analysis of soil organic carbon (SOC).

Results: The grazed sites showed significantly more negative NEE than the NG sites, indicating more carbon dioxide uptake on the grazed sites compared to the NG sites. The normalized difference vegetation index was also significantly higher on the grazed sites. On all farms, the total SOC content was higher in the grazed sites than in the parallel NG sites.

Conclusions: The study indicates that cessation of grazing decreases productivity and carbon dioxide uptake in a semi-natural grassland in Iceland, as well as SOC content in the soil. Historically, all the NG sites in the study had the same grazing history as the continuously grazed sites until grazing exclusion. The measured lower SOC on the NG sites seems to indicate that, without grazing, SOC is lost with time and/or grazing is needed to maintain SOC in these grasslands.

KEYWORDS
carbon dioxide, ecosystem respiration, grazing, historical legacy, Iceland, net ecosystem exchange, no grazing, semi-natural grassland, soil organic carbon

1 | INTRODUCTION

Grasslands cover about 40% of earth's terrestrial surface, mainly within the global grassland biome (Suttie et al., 2005). Outside the global grassland biome are extensive grasslands that have been created and maintained by grazing (mowing and/or fire); evolutionary by wild grazers, but for millennia by livestock (Dengler et al., 2014). Historically, these natural and semi-natural grasslands

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were widespread but are now among the most threatened biomes on earth (Bengtsson et al., 2019; Bardgett et al., 2021), not least in Europe where agricultural intensification and/or abandonment has caused extensive degradation of the semi-natural grasslands (Norderhaug et al., 2023).

One of the last strongholds of N-European semi-natural grasslands are in Iceland, where the open landscape is dominated by moss heathlands and semi-natural grasslands, created by over 1000 years of livestock grazing (Thorhallsdottir et al., 2013). As the native birch (*Betula pubescens*) forest covers less than 1% of the lowlands, there is limited seed dispersal from the native birch (Snorrason et al., 2016). Decreased grazing and grazing exclusion rarely lead to a natural birch forest encroachment in Iceland (Oskarsdottir et al., 2022) like in northern Scandinavia (Speed et al., 2014), but rather a grass–moss–lichen successional dynamic (van der Wal, 2006). Thus, Iceland provides a special stage for studying the effect of long-term livestock grazing on northern semi-natural grasslands.

Grazing is a vital factor maintaining grasslands (Conant et al., 2017). Grazing activates dormant axillary buds and the rapid growth of new tillers in grasses (Briske, 1991; Diaz et al., 2001; Irving, 2015). Grazed grasslands are one of the most productive ecosystems globally, with a very high net carbon gain (Bengtsson et al., 2019). Grazing has been shown to increase grassland production (Mipam et al., 2019). The importance of grasslands for carbon sequestration and its role in world climate regulation has been overlooked (Soussana et al., 2010; Bengtsson et al., 2019).

Soils are the largest terrestrial reservoir of carbon (Chapin et al., 2009). Grassland soils are estimated to store more soil carbon than forest soils (Conant et al., 2017). About 70% of grassland biomass has been reported to be below-ground (Titlyanova et al., 1999). The high below-ground production of grasslands is due to intensive root growth and a high turnover of fine short-lived roots, giving a large input of organic matter into the soil and a high percentage of the carbon below-ground (Ziter & MacDougall, 2013). Total biomass production and biomass allocation to roots is reported to be higher from grazed than ungrazed grasslands (Veen et al., 2014; Wilson et al., 2018). Due to the high root/shoot ratio and the deep root mass in grasslands (McSherry & Ritchie, 2013), the depth of sampling for assessing total soil organic carbon (SOC) is especially important. In a survey of permanent grasslands soils in Great Britain, Ward et al. (2016) detected effects of grazing down to 1 m depth in the soil and that grazing enhanced especially carbon storage in the deep soil.

Historical land use, including grazing, leaves legacies both in plant community composition and soil properties with time (Fox et al., 2015; Vidaller et al., 2022). Changes in land use, like cessation of grazing, take time to induce detectable changes above- and below-ground. Knowledge of the grazing history is therefore important for explaining current plant community composition and soil properties (Ward et al., 2016; Katulanda et al., 2018).

Grassland carbon sequestration can be determined indirectly by measuring the balance of CO_2 fluxes or directly by measuring changes in SOC (de la Motte et al., 2016). These measurements, i.e., CO_2 flux measurement vs SOC, give very different perspectives, and reflect different time scales and ecosystem processes. The CO_2 flux measurement gives an estimation on the carbon balance at a given time and is a good method for analyzing the effect of certain variables, like grazing, on current carbon balance. The static chamber technique for assessing CO_2 flux is widely used (i.e., Byrne et al., 2005; Rong et al., 2017; Ma et al., 2021; Murphy et al., 2022). As sequestrated carbon is extensively stored in the soil in grasslands, the long-term carbon balance is reflected in the accumulation (or loss) of soil carbon, measured as SOC. When carbon inputs and outputs are in balance, there is no net change in SOC levels. When carbon inputs from photosynthesis exceed C losses, SOC levels increase over time (Ontl & Schulte, 2012). In this study, we could select sites that had a known grazing history for decades, enabling us to evaluate the long-term effect of grazing on both CO_2 flux and SOC.

The aim of this study was to investigate the effect of grazing on carbon balance in Icelandic semi-natural grasslands, by comparing CO_2 fluxes and SOC on long-term permanently grazed sites, to parallel sites that had not been grazed for several decades. We hypothesized that cessation of grazing (no grazing) would lead to less green biomass, and decreased carbon uptake, while sites under extensive grazing would have more green biomass and more carbon uptake than intensively grazed sites. We further hypothesized that, after around 50 years of different grazing regimes, these differences in carbon uptake above-ground might be measurable below-ground, as a difference in SOC levels.

2 | MATERIALS AND METHODS

Since the settlement in the 9th century, most of Icelandic rangeland has been used for grazing. After the middle of the 20th century, interest in forestry grew and many farmers fenced off a smaller section of their rangeland for afforestation purposes. Today, many of these enclosures stand intact within a surrounding grazing land. Some of the enclosures have never been fully planted with trees, resulting in open, intact areas, neither encroached by shrubs nor trees. These sites create a unique opportunity to compare the long-term effect of grazing and no grazing (NG) in the semi-natural grasslands in Iceland.

In this study, we used afforestation enclosures from the 1970s as the NG sites. The timing of the enclosing was confirmed by the landowners. We do not have accurate data on grazing intensity on the sites before the enclosure. However, as sheep roam quite freely in Iceland, they graze over the whole landscape. Therefore, we assume that the NG sites were grazed in a comparable way to the whole landscape and surrounding sites before grazing exclusion and the difference found between the NG and grazed sites can be assigned to the different grazing treatments for the last 50 years.

2.1 | Site descriptions

We located three actively operating farms that had an afforestation enclosure surrounded by an actively grazed rangeland; Holl

(64°31′43″ N, 21°20′58″ W), Oddstadir (64°32′33″ N, 21°19′30″ W) and Reykholt/Breidabolsstadur—hereafter named Reykholt (64°40′13″ N, 21°16′56″ W).

With historical land use information from the farmers, we also localized on each of the three farms a permanent intensive-grazing site (IG) and a permanent extensive-grazing site (EG). All these grazed sites were in close vicinity to an afforestation enclosure that had an open area, thus avoiding side effects from trees, i.e., from shade or roots. On all the farms, the IG sites were 1–3-ha enclosures closer to the farmhouses, used for animals the farmers wanted to keep close, like older animals and riding horses. All the EG sites were extensive hillsides, 2000–3000 ha, where the main livestock flock grazed through the summer and fall. Neither the IG nor the EG sites had been fertilized and, in all cases, they were lying side by side in the landscape. Both Holl and Oddstadir had sheep and horses on their grazing land, while Reykholt had mainly horses and only an occasional sheep passing through.

On each farm, we marked a permanent 10 m long transect 5 m from the fence dividing NG from either IG or EG. CO_2 flux measurements were taken at 2, 3, 4, 5, 6, 7, 8, and 9 m along the transect during each data collection. We used the static chamber method (see Wickland et al., 2001), using a CPY-4 fully transparent chamber from PP systems (Amesbury, MA, USA) with installed photosynthetic active radiation (PAR) sensor. The chamber was connected to an infrared gas analyzer (EGM-4, PP systems), equipped with software calculating the changes in CO_2 concentration applying a quadratic function in case of small leakage of the chamber–soil interface. An installed fan running continuously during the measurements ensured constant mixing of air within the chamber. Readings of changes in gaseous CO_2 as g CO_2 m^{-2} h^{-1} and PAR over the time of measurements were obtained directly from the EGM-4 software. EGM-4 settings include max time for each measurement, which in most cases was 2 min. If stable rise or decline in CO_2 concentration was not reached within that time limit, the time settings were revised. Net ecosystem exchange of CO_2 (NEE) was measured under ambient light conditions for 2 min max (or until equilibrium stable changes in CO_2 concentration were as reached within the chamber). Respiration (*R*) was measured, on the same plot, immediately after NEE by fully covering the chamber with non-transparent cloth and excluding incoming PAR, and thereby halting photosynthesis. Photosynthesis (*P*) was calculated as the difference of NEE and R ($P = \text{NEE} - R$). The measured *R* includes respiration from living plants, microbes, and microfauna, and decomposition of soil, litter, and standing dead biomass. CO_2 fluxes and related factors were measured six times for each grazing category (site) on all farms, evenly distributed over the growing season, from June 19 to September 18, 2015. Each round of measures was conducted within three days.

2.2 | Environmental factors

Normalized difference vegetation index (NDVI) was recorded by Sky Portable Spectrosense2 Systems at three spots along each transect, at 1, 5, and 10 m, each measurement day for every site. Soil temperature (soil *T*) at 10 cm depth was recorded at each measurement point at the time of measurements. PAR was recorded simultaneously with each CO_2 flux measurement.

2.3 | Above-ground biomass (above-ground carbon)

Above-ground biomass was estimated on the last day of flux measurements by taking sward samples, using a 10 × 10 cm frame with a sharp edge that cut down through the sward. The samples thus contained all living and dead biomass and litter above the topsoil layer at the time of sampling. On each transect, five sward samples were taken at 2, 4, 6, 8, and 10 m and at 2 m distance to the side of the transect. The samples were dried at 60°C, separated to particles less, and larger than 2 mm and each part weighted. The organic matter (OM) content of the less than 2 mm part, mixture of litter and soil particles, was determined by loss on ignition. The part larger than 2 mm was treated as only including OM and amount determined through weighting. Carbon content was then calculated assuming 50% C content of OM.

2.4 | Soil organic carbon

Soil samples were obtained at each site on the last day of CO_2 flux measurements on each site. For estimation of SOC content in the soil, the soil profile was excavated. The depth of the profile was 60 cm, which was enough to reach the underlying glacial material on most of the sites. At sampling, the soil profile was divided at 10-cm depth intervals, first sample from 0 to 10 cm, then 10 to 20 cm etc., down to 60 cm. Bulk density (Bd) samples were taken at two depths in each profile, one for the upper part of the profile and one for the lower part. The samples were obtained with a cylinder of 7.5 cm in diameter and 7.5 cm in height, driven vertically into the profile. A few profiles were too stony to drive the cylinder into the profile. I these cases, a size-measured cubic was carefully excavated with a sharp knife and used for a Bd assessment, correspondingly. Each profile was described according to stratification and stoniness of each layer. The two Bd samples of each profile were assigned to depth intervals according to soil stratification recorded in the field. Soil samples were oven-dried at 40°C, separated to particle size categories (<2 mm, 2–4.75 mm, and >4.75 mm), the weight of all size categories determined, and the volume of particles larger than 2 mm measured. The Bd of particles less than 2 mm was then determined through the remaining volume, and weight of particles less than 2 mm in the Bd samples. The content of SOC in samples (w/w % C) was determined with dry combustion. SOC in the samples was analyzed as Total Carbon (TC), as inorganic C is generally very low in Icelandic soils (Oskarsson et al., 2012). Coarse Fragment ratio (CF) was estimated from the volume of fragments larger than 2 mm included in the soil samples compared to the volume of particles less than 2 mm,

and the estimated ratio of coarse fragments as recorded in a profile description in the field. The amount of carbon per volume of soil is calculated from % C in sample less than 2 mm, the Bd and estimated CF, according to the equation:

$$g\,C\,cm^{-3} = \frac{\%\,C * Bd_{<2\,mm}\left[g\,cm^{-3}\right] * (1 - CF)}{100}$$

The carbon stock in g C cm^{-2} at the profile was calculated by the summing up the carbon content (g C cm^{-3} * interval depth in cm) of each depth layer.

2.5 | Statistical analyses

The significance of difference in averages of Soil *T*, PAR, NEE and NDVI between grazing categories within each farm and for all the farms, was analyzed using single-factor ANOVA and a two-tailed t-test (Microsoft Office Professional Plus 2016 –Excel, 2016 Data Analyses). Likewise, the same test was applied for comparing SOC at depth levels and whole profile between grazing categories. Only one soil profile (except for the IG site on one farm with two profiles) was excavated at each site and accordingly statistical comparison of grazing categories within individual farms is not possible. The linear correlation of NEE and SOC was tested with pearson's correlation coefficient and *R*-squared (R^2).

3 | RESULTS

3.1 | Carbon fluxes, NEE and environmental factors

The CO_2 fluxes (g CO_2 m^{-2} h^{-1}) are presented as NEE, *R* and photosynthesis (*P*). Figure 1 shows the average CO_2 flux in each grazing category on all three farms, for each measurement round, through the growing season. For the grazed sites, NEE is more negative earlier in the season, indicating a more active biomass with a higher CO_2 uptake earlier in the growing season. The NEE for the NG sites is less negative in the early season, indicating less active biomass in the earlier part of the growing season (Figure 1). Throughout the whole growing season, the CO_2 flux amplitudes are higher at both the IG and EG sites than NG, i.e., higher on grazed sites than the not-grazed sites.

Average CO_2 flux for the three grazing categories over the growing season is shown in Figure 2. The NG sites have a less negative NEE than both grazed sites, IG and EG, as well as less *R* and *P*.

Statistical comparison of the measured environmental parameters and NEE are presented in Table 1. Averages for all the farms as well as averages within each farm are given. For all the farms, the difference in NEE between the grazed sites (including both IG and EG) and the NG sites is significant, with more negative NEE on the grazed sites, indicating a higher net carbon uptake on the grazed sites than the NG sites. Within each farm, there is always a significant difference between NEE of all the grazed sites (IG and EG) and the NG sites (NG), with one exception. On the farm Oddstadir, the NG site is only significantly different from the IG site but not from the EG site. There is however a significant difference between the grazed sites, EG and IG. On the other two farms, there is not a statistical difference between measured NEE on IG and EG sites.

Measured soil *T* is the same for all the grazed sites on all the farms (IG and EG), showing a significantly different soil *T* than on the NG site on the same farm. On two farms, the grazed sites have higher soil *T* than the NG sites, while at Reykholt it is the opposite; soil *T* on both IG and EG sites is significantly lower than on the NG site (Table 1).

Averaged over all the sites, NDVI or the greenness, is significantly less on NG sites than grazed sites, both IG and EG (Table 1). Within individual farms, all the grazed sites also have a higher NDVI than the NG site, except for the EG site at Holl and the IG site at Reykholt.

There is no difference in PAR, measured coincidentally with the CO_2 flux measurements, with one exception. Measured PAR on the NG site at Oddstadir is significantly lower at the time of CO_2 flux measurements than on both the IG and EG sites on that farm.

3.2 | Carbon in above-ground biomass and soil

Carbon in above-ground biomass on each farm varies from site to site, with overall range 0.24–0.85 kg C m^{-2}. Averaged over all the

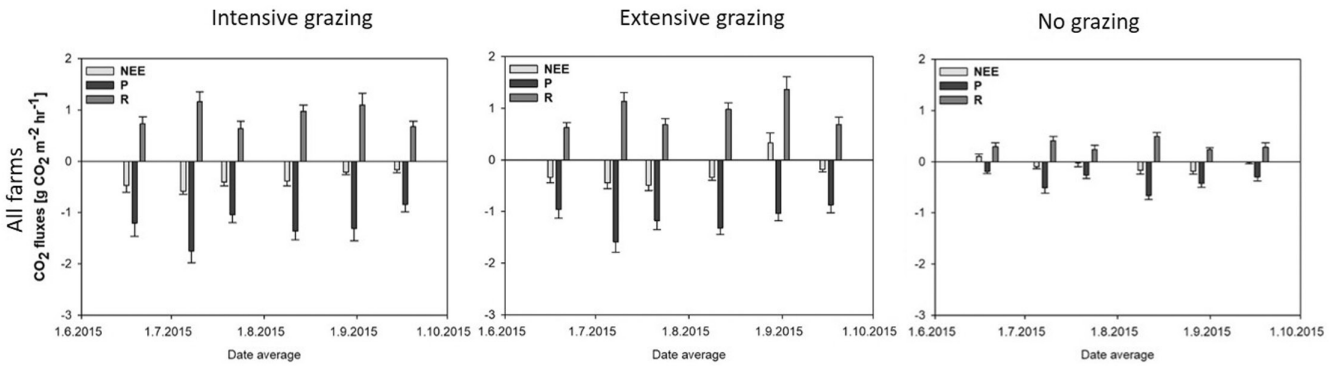

FIGURE 1 Results of CO_2 flux measurements; net ecosystem exchange (NEE), respiration (*R*) and calculated photosynthesis (*P*). Average for the three and calculated photosynthesis (*P*), averaged for each grazing category on the three farms. Error bars are standard error (SE).

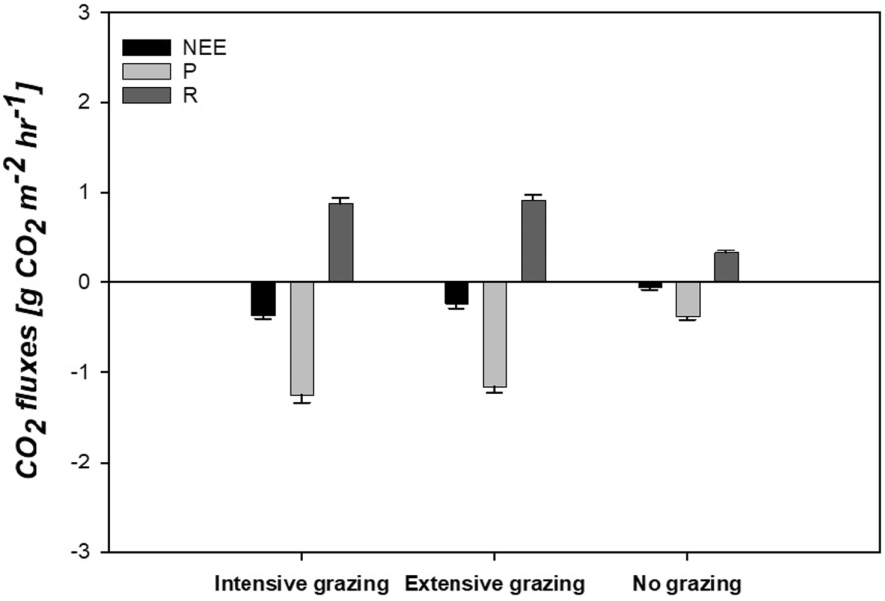

FIGURE 2 Results of CO_2 flux measurements; respiration (*R*), net ecosystem exchange (NEE) and calculated photosynthesis (*P*) on all sites, averaged for all farms and dates, in relation to the different grazing categories. Error bars are standard error (SE).

TABLE 1 Environmental parameters.

		Soil *T*			PAR			NEE			NDVI		
Farms	**Grazing category**	**Average**	**EG**	**NG**	**Average**	**EG**	**NG**	**Average**	**EG**	**NG**	**Average**	**EG**	**NG**
All farms	Intensive	11.1	ns	ns	931	ns	ns	−0.37	*	***	0.810	ns	***
All farms	Extensive	11.2		*	969		ns	−0.24		**	0.777		***
All farms	No grazing	10.8			859			−0.06			0.664		
	ANOVA	ns			ns			***			***		
Holl	Intensive	11.1	ns	***	818	ns	ns	−0.30	ns	*	0.833	***	***
Holl	Extensive	11.2		***	931		ns	−0.28		*	0.691		ns
Holl	No grazing	9.8			968			−0.16			0.661		
	ANOVA	***			ns			*			***		
Oddstadir	Intensive	11.1	ns	*	1022	ns	**	−0.62	**	***	0.896	**	***
Oddstadir	Extensive	11.1		*	991		*	−0.15		ns	0.835		***
Oddstadir	No grazing	10.5			739			−0.16			0.677		
	ANOVA	*			**			***			***		
Reykholt	Intensive	11.0	ns	***	954	ns	ns	−0.19	ns	***	0.701	***	ns
Reykholt	Extensive	11.2		***	983		ns	−0.29		***	0.806		***
Reykholt	No grazing	12.3			870			0.13			0.655		
	ANOVA	***			ns			***			***		

Note: Soil temperature (soil *T*), photosynthetic active radiation (PAR), net ecosystem exchange (NEE) [g CO_2 m^{-2} h^{-1}] and normalized difference vegetation index (NDVI) on all farms, average for the three grazing categories intensive grazing (IG), extensive grazing (EG) and no grazing (NG). Level of significance for the difference of the averages (single-factor Anova and two-tailed *t*-test); ns = not significant ($\alpha < 0.05$); * = significant at $\alpha = 0.05$; ** = significant at $\alpha = 0.01$; *** = significant at $\alpha = 0.001$.

farms, there was no significant difference (ANOVA) found in the above-ground biomass between grazing categories (Table 2).

Results of the soil measurements are shown in Table 3. On the IG site of Oddstadir farm, two profiles were taken and the results from both are included in Table 3. The average of calculated SOC, in each depth interval of the two profiles, is used in all comparison of grazing categories.

SOC is the main carbon stock on all sites (see Tables 2 and 3). On all the farms, there is overall less SOC in the whole soil profile on the NG sites. On two farms, more SOC is found in the intensively grazed sites than the extensively grazed sites while at Oddstadir the extensively grazed site has least SOC, lower than the NG site. A considerable portion (%) of the SOC is in the deeper part of the soil profiles (Table 4).

Above-ground biomass [kg C m^{-2}]	Intensive grazing (IG)	Extensive grazing (EG)	No grazing (NG)	All grazing categories
Holl	0.62 ± 0.11	0.85 ± 0.39	0.74 ± 0.26	0.74 ± 0.17
Oddstadir	0.24 ± 0.05	0.65 ± 0.23	0.57 ± 0.20	0.45 ± 0.13
Reykholt	0.43 ± 0.14	0.36 ± 0.08	0.55 ± 0.09	0.45 ± 0.08
All farms	0.43 ± 0.20	0.62 ± 0.18	0.58 ± 0.13	0.54 ± 0.09

TABLE 2 Average above-ground biomass measured in each grazing category on each farm with ±95% confidence limits.

The overall average of SOC stock of grazing categories shows a trend, from most SOC in IG sites, less in EG sites and least SOC in NG sites (Figure 3).

Linear fitting of observed SOC to measured NEE at same site is weak ($R^2 = 0.55$), using a second-order polynomial gives $R^2 = 0.60$, indicating a weak relationship of these two variables in the study.

4 | DISCUSSION

In this study, we hypothesized that the cessation of grazing would lead to less green biomass, i.e., less active biomass, and subsequent decreased carbon uptake compared to permanently grazed sites. We found an overall difference between the grazed sites on the one hand and the NG sites on the other; measured as significantly less active green biomass (NDVI) and significantly less carbon uptake (NEE) on sites that had not been grazed for decades. However, our prediction that extensive grazing would have more green biomass and more carbon uptake than intensively grazed sites was not confirmed. We did not find more green biomass in the extensive grazing, and found significant more uptake on the IG than the EG site, although less above-ground biomass on two of the IG sites. We further found indications that the long-term different grazing regimes were leaving measurable differences in the carbon content below-ground, with more SOC in the grazed sites compared to the long-term non-grazed sites.

4.1 | NEE and NDVI in relation to grazing

Overall, NEE of both EG and IG was larger (more negative value) than at NG sites, indicating that grazing stimulates net CO_2 uptake (Figure 3). This difference was statistically significant (Table 1). This negative effect of grazing abandonment on carbon uptake has also been found elsewhere.

Schmitt et al. (2010) studied land use (mowing and grazing) effects on NEE and its components in six mountain grasslands in Austria. They found that decreased land use, and particularly land abandonment, led to a decrease in carbon uptake. Other more recent studies have also found that grazing prevails over non-grazing for shifting the ecosystem from a negative to a positive carbon balance, or from a carbon source to a carbon sink (Kang et al., 2013; Gomez-Casanovas et al., 2018). In our study we found significantly more uptake on the IG than the EG sites. Owensby et al. (2006) studied carbon flux from grazed and ungrazed tall-grass prairie in Kansas, US. They found most carbon uptake where grazing utilization was highest. Owensby et al. (2006) concluded that reduced ecosystem respiration, more open canopy structure and the presence of young, highly photosynthetic active leaves were responsible for the increased net carbon uptake. We found that the amplitudes of the fluxes, both *R* and NEE, were higher on the grazed sites than on the NG sites, showing increased ecosystem respiration under grazing. This agrees also with the findings of Xun et al. (2018). The higher flux amplitudes on the grazed sites are also a measure of an overall increased activity of the ecosystem, were *P* increased more with grazing than *R*. NDVI measures the greenness of the vegetation and is a measure of photosynthetically active biomass. Overall, NDVI was significantly higher on both IG and EG sites than on NG sites (Table 1), thus supporting the results from the CO_2 flux measurements.

Grazing pressure is often difficult to define, especially in heterogeneous landscapes with free-roaming animals. Under these conditions, grazing pressure can vary considerably within sites, despite the same stocking rate. In our study, we defined IG and EG sites on each farm based on information given by farmers. It was not possible to obtain the exact grazing pressure, as we were working with long-term use of natural sites, but not an experimental setup. The grazing-pressure categories in this study were ranked within each farm but could not be ranked within each category. Thus, within grazing categories, some sites were grazed more and some less. For example, it seemed obvious that the IG site at Reykholt had the most grazing pressure of the three intensively used sites in the study. Overlapping, in terms of grazing pressure, between the IG and EG grazing categories on different farms cannot be excluded. This is unlikely however given the difference in size and long-term use of sites in the study, as reported by the farmers. The overall difference between the grazed sites on the one hand and the NG sites on the other is however clearly reflected in our results.

Grazing intensity is an important factor influencing ecosystem CO_2 fluxes in grasslands (Owensby et al., 2006). Moderate grazing is reported to have the highest NEE while heavy grazing results in lower NEE, like NG (Zhu et al., 2015; Rong et al., 2017). In our study, we found overall significantly higher NEE under IG than under EG (Table 1), but when testing the differences between the grazing categories within each individual farm, we found a significant difference between IG and EG only in case of Oddstadir (Table 1). This could indicate that the IG sites were closer to grazing optimization than the EG sites (Mipam et al., 2019). On the other two farms, we did not find significant

TABLE 3 Results of the soil profile parameters for each depth interval and calculated SOC for each site on each farm.

		Depth interval (cm)						
Farm grazing category	**Factor**	**0–10**	**10–20**	**20–30**	**30–40**	**40–50**	**50–60**	**SOC (kg C m^{-2})**
Holl Intensive (IG)	% C	12.23	6.01	5.18	7.09	2.00	0.64	
	$Bd_{<2mm}$	0.60	0.60	0.47	0.47	0.47	0.47	
	CF	0.03	0.09	0.20	0.10	0.10	0.03	
	kg C m^{-2}	7.08	1.54	1.33	1.82	0.84	0.29	12.91
Holl Extensive (EG)	% C	10.03	8.41	7.22	6.40	5.86	5.68	
	$Bd_{<2mm}$	0.62	0.62	0.62	0.50	0.50	0.50	
	CF	0.28	0.36	0.19	0.23	0.02	0.13	
	kg C m^{-2}	3.43	2.88	2.47	1.76	1.61	2.48	14.64
Holl No grazing (NG)	% C	11.32	7.13	4.31	1.02	0.40	0.15	
	$Bd_{<2mm}$	0.50	0.50	0.50	1.52	1.52	1.52	
	CF	0.15	0.63	0.47	0.37	0.31	0.36	
	kg C m^{-2}	4.82	1.32	1.14	0.98	0.42	0.14	8.82
Oddstadir Intensive (IG-1)	% C	8.29	8.85	4.28	5.29	5.47	5.46	
	$Bd_{<2mm}$	0.54	0.54	0.54	0.66	0.66	0.66	
	CF	0.00	0.22	0.17	0.03	0.11	0.01	
	kg C m^{-2}	4.48	3.76	1.93	1.74	3.20	3.57	18.69
Oddstadir Intensive (IG-2)	% C	12.96	7.61	7.07	5.58	4.70	2.66	
	$Bd_{<2mm}$	0.66	0.66	0.66	0.66	0.77	0.77	
	CF	0.10	0.69	0.16	0.03	0.15	0.31	
	kg C m^{-2}	7.79	1.59	3.94	3.61	3.08	1.41	24.15
Oddstadir Extensive (EG)	% C	12.18	2.55	2.04	2.64	5.02	5.48	
	$Bd_{<2mm}$	0.71	0.71	0.71	0.59	0.59	0.59	
	CF	0.37	0.24	0.29	0.15	0.16	0.15	
	kg C m^{-2}	5.46	1.37	1.04	1.32	2.49	2.74	14.42
Oddstadir No grazing (NG)	% C	11.39	8.22	5.83	5.10	5.04	5.58	
	$Bd_{<2mm}$	0.65	0.65	0.65	0.63	0.63	0.63	
	CF	0.02	0.20	0.02	0.07	0.20	0.10	
	kg C m^{-2}	4.85	3.50	2.48	2.07	2.05	2.27	17.22
Reykholt Intensive (IG)	% C	15.79	5.77	2.14	0.91	0.92	0.55	
	$Bd_{<2mm}$	0.86	0.86	0.86	0.86	0.88	0.88	
	CF	0.08	0.13	0.05	0.14	0.15	0.24	
	kg C m^{-2}	12.51	4.32	1.75	0.67	0.69	0.37	20.31
Reykholt Extensive (EG)	% C	16.24	7.28	4.12	1.95	0.57	0.47	
	$Bd_{<2mm}$	0.42	0.42	0.42	1.03	1.03	1.03	
	CF	0.05	0.21	0.15	0.13	0.17	0.13	
	kg C m^{-2}	6.39	2.40	1.46	1.73	0.48	0.42	12.88
Reykholt No grazing (NG)	% C	1.18	0.55	0.13	0.11	0.09	0.09	
	$Bd_{<2mm}$	1.51	1.51	1.23	1.23	1.23	1.23	
	CF	0.19	0.11	0.09	0.01	0.12	0.21	
	kg C m^{-2}	1.45	0.73	0.15	0.13	0.10	0.09	2.66

Note: Bd = bulk density of particles < 2 mm; CF = volume/volume ratio of course fragments (>2 mm).

differences in NEE between the two grazing categories, indicating little difference between the grazing categories on these farms.

4.2 | Environmental factors

Soil temperature (soil *T*) is an important driving variable for soil respiration (Lloyd & Taylor, 1994). Higher soil *T* results in more soil respiration and, assuming other factors being equal, less negative NEE. Comparing the average soil *T* of each grazing category, both IG and EG sites had higher soil *T* in the growing season than the NG sites, and counteract the difference observed in NEE between grazing categories. On the other hand, changes in vegetation cover can change the soil thermal isolation and thereby the temperature fluctuation in the soil. Grazing can, accordingly, affect soil *T* through vegetation cover (Yan et al., 2018). Thus, one causal effect of grazing on NEE could

Farm	Grazing category	% kg C m^{-2} 0–10 cm	% kg C m^{-2} 10–30 cm	% kg C m^{-2} 30–60 cm
Holl	Intensive IG	54.9	22.3	22.9
Holl	Extensive EG	23.5	36.5	40.0
Holl	No grazing NG	54.6	28.0	17.4
Oddstadir	Intensive IG	28.1	26.7	45.2
Oddstadir	Extensive EG	37.9	16.7	45.4
Oddstadir	No grazing NG	28.2	34.7	37.1
Reykholt	Intensive IG	61.6	29.9	8.5
Reykholt	Extensive EG	49.6	29.9	20.4
Reykholt	No grazing NG	54.6	33.2	12.1
All farms	Intensive IG	48.2 ± 16.4	26.3 ± 3.5	25.5 ± 17.1
All farms	Extensive EG	37.0 ± 12.1	27.7 ± 11.8	35.3 ± 0.3
All farms	No grazing NG	45.8 ± 14.1	32.0 ± 3.3	22.2 ± 12.2
All farms	All categories	43.7 ± 8.8	28.7 ± 3.8	27.7 ± 8.9

TABLE 4 Relative distribution (%) SOC in the whole profile on each site; average of grazing categories (±95% confidence limits).

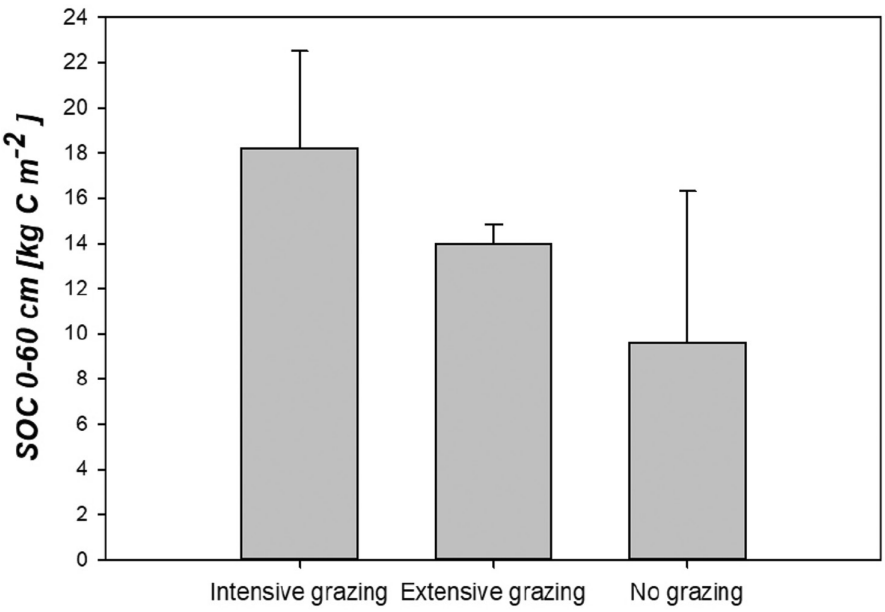

FIGURE 3 SOC for 0–60 cm depth. Error bars are 95% confidence limits.

be that higher soil *T* increases decomposition rate, resulting in less negative NEE and less net carbon uptake. On two of the farms, NEE was more negative on the IG and EG sites than on the NG sites. At the NG site in Reykholt, soil *T* was on average higher than on the corresponding IG and EG sites. This difference was significant for both IG and EG sites. At the other two farms, soil *T* on the NG sites was significantly lower than on the corresponding IG and EG sites (Table 1). In our study, soil *T* thus seems to respond differently to no grazing.

At the time of measurements, incoming PAR was measured lower on the NG site at Oddstadir than on all other sites (Table 1). There is both diurnal and seasonal variation in PAR (Zhang et al., 2000). Our measurements on the Oddstadir NG site has thus, by coincidence, been made at times with less PAR. The cause of this bias is not clear. In theory, this bias could contribute to the observed difference in NEE between grazing categories. However, we found the correlation of *P* to PAR to be weak, with $R^2 < 0.11$ for all grazing categories. Accordingly, PAR is explaining only a small part of the variability of NEE. It is thus unlikely that the Oddstadir NG site PAR bias is affecting the main results.

4.3 | Carbon above-ground and SOC

The measurements of above-ground biomass do not show any statistical difference between the grazing categories in above-ground carbon. Our sampling method did not differentiate between standing dead and green biomass. The measured lower NDVI values on the NG sites indicate that the portion of the above-ground green biomass was less on NG sites than on grazed sites. Thus, a bigger portion of the above-ground biomass on NG sites was dead standing biomass. This is in line with the results from the CO_2 flux measurements.

We took only two soil profiles on one of the sites, at Oddstadir, while at Holl and Reykholt we were only able to take one profile on each site. Thus, the results only give an indication whether there might be any measurable difference in the amount of SOC after 50 years of different grazing regimes. Interestingly, the results show a clear trend, with most SOC on the IG sites and least SOC on the NG sites (Figure 3). Further, the trend measured in SOC is in parallel with the observed difference in NEE between grazing categories. Shi et al. (2013) found that grazing exclusion decreased SOC and Guo et al. (2018) found that grazing exclusion increased soil CO_2 emissions as well as decreasing carbon sequestration, leading to a decreasing SOC with time. Many other studies have reported a positive effect of grazing on SOC (i.e., He et al., 2011; McSherry & Ritchie, 2013; Wang et al., 2016). These studies show that light and moderate grazing prevails over NG or heavy grazing for maintaining carbon balance, increase carbon sequestration and carbon storage (i.e., Martinsen et al., 2011; Olsen et al., 2011; Teague et al., 2011; Peichl et al., 2012; Kang et al., 2013; Shi et al., 2013; Ziter & MacDougall, 2013; Rui & Xiuqin, 2016). Other factors, e.g., soil depth, livestock type, ecosystem type and climatic conditions have been reported to influence the relationship between grazing and SOC (Derner et al., 2006; Pineiro et al., 2009; Martinsen et al., 2011; Luan et al., 2014; Zhou et al., 2017). In our study, about 30% of the total SOC, from 0–60 cm depth, is at 30–60 cm depth (Table 4). This result agrees with Zhang et al. (2022) who found that SOC decreased under long-term grazing exclusion, especially in the lower layers of the soil profile. These results emphasize the need to include the lower part of the soil profile when comparing effects of grazing on SOC, missed by standard 30-cm carbon inventories (Jandl et al., 2014; Ward et al., 2016; Maillard et al., 2017).

Our study reveals differences between the IG and EG sites on the one hand and NG sites on the other, both above-ground and below-ground, in carbon sequestration. Over the growing season, the NEE of the NG sites was significantly less than at the IG and EG sites. Further, the SOC on the sites showed a trend, from highest SOC on the IG sites, to lowest SOC on the NG sites. According to the historical land use information given by the farmers, all the grazed sites had been grazed comparably for the last decades as in the present. Therefore, the observed difference in SOC between grazed and NG sites is not likely to be the result of more accumulation on the grazed sites only. Part of the observed difference can also be that SOC, that had been built up by long-term grazing, decreased after grazing exclusion. Grazing exclusion, in general, led to the slowing down of soil nutrient cycling and reduced microbial biomass and activity (Medina-Roldán et al., 2012), as reflected in lower *R* fluxes on the NG sites in our study. Wright et al. (2010) found that grazing resulted in lower nitrogen mineralization and higher decomposition rates and pointed out that in the absence of labile nutrient forms (dung/urine) the soil microbial community would have to seek alternative sources of nutrition. In the study by Olsen et al. (2011), grazing increased the amount of carbon segregated into microbial biomass and, consequently, immobilized in long- and medium-term storage pools. Xun et al. (2018) studied the influence of grazing on the soil microbial community. They found that under grazing the microbial community shifted from slow-growing, fungi-dominated communities, mainly responsible for decomposition of recalcitrant SOC, to fast-growing, bacteria-dominated communities, primarily responsible for decomposition of labile SOC (Xun et al., 2018). This agrees with higher *R* on the grazed sites in our study (Figure 1). In a recent study, Naidu and co-workers (2022) found that grazing exclusion (14 years) led to increased interannual fluctuations in soil C, which undermined the stability of the highly dynamic soil C, and led to losses in soil C. Roy and Bagchi (2022) studied the effect of grazing exclusion (12 years) on soil microbial processes and found also that grazing exclusion led to an increase in recalcitrant C. They hypothesized that grazing reduced peroxidase activity, thus lengthening the residence time for soil C to yield net soil C sequestration. In their study they did not however find any differences in SOC after 12 years of grazing exclusion. Other short-term grazing exclusion studies have not found any changes in soil C stock (Speed et al., 2015). Taken together, grazing seems to increase SOC over time, but long-time grazing exclusion is needed for these changes to become detectable. Naidu et al. (2022) concluded that grazers exert a strong influence on both the stability and the size of the soil C pool and that their persistence was essential to protect the soil C pool and achieve natural climate solutions.

In our study, the SOC on IG and EG sites is 8.6 and 4.4 kg C m^{-2} respectively, larger than on the NG sites. Accordingly, the annual change over the 50 years in soil carbon stock is 0.14 and 0.07 kg C m^{-2}, for the grazed sites (IG and EG sites) and NG sites respectively (Table 3). These numbers, 1.4 and 0.7 t C ha^{-1} $year^{-1}$, are of the same order of magnitude as many land-use-related emission/removal factors applied in CO_2 emissions and removal reporting for Iceland to the UN-FCCC and the Kyoto Protocol (Keller et al., 2019). These results indicate that following cessation of grazing on previous grazing grounds, there is a considerable reduction in SOC.

The NEE measurements in our study only include daytime measurements during the growing season and do not represent any seasonal budget over growing season or the whole year. The difference in daytime NEE between IG and EG sites on the one hand and NG sites on the other, is 0.31 and 0.18 g CO_2 m^{-2} h^{-1} respectively. The NEE measurements can be stated to represent the daytime uptake of the growing season. If we assume only 12 h of daytime for 100 days, the difference in NEE over that period is 3.72 and 2.16 t CO_2 ha^{-1} or 1.01 and 0.58 t C ha^{-1} for the IG and EG sites on the one hand and NG sites on the other respectively. From these calculations, grazing seems to nearly double carbon sequestration per unit area, which can explain the higher SOC in our grazed sites. Other studies have found that grazing slows down the turnover rate of the microbial biomass and thereby increases the longevity of soil C (Olsen et al., 2011), maintaining or increasing stored carbon (Kang et al., 2013) and increasing the capacity of the grazing land to serve as sink for atmospheric CO_2 (Ziter & MacDougall, 2013).

5 | CONCLUSIONS

This study was planned as a pilot study, focusing on the effect of grazing on carbon flux and carbon storage and the relationship between SOC and NEE. Although this is a pilot study with limited data collection, it gives an interesting picture to study further. It reveals the importance of a known timeline for previous land use/grazing on the study sites and of a continuum of land use, reflected in the soil. Further, it reveals the importance of sampling the whole soil profile for SOC. This variation explains to some degree why carbon sequestration measures from different studies can be difficult to compare and explains why many meta-analyses do not come to the same conclusion.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data are available from the authors upon request.

ORCID

Anna Gudrun Thorhallsdottir https://orcid.org/0000-0002-3735-3876

Jon Gudmundsson https://orcid.org/0000-0002-1703-8916

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