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Review

A scoping review on the impact of rotational grazing in beef cattle systems on greenhouse gas emissions, soil health, plant diversity, and plant productivity parameters

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Abstract

Recently, the government of Canada has encouraged the use of rotational grazing (RG) within its Sustainable Agriculture Strategy to improve soil health and decrease greenhouse gas (GHG) emissions from the livestock sector. However, the effectiveness of RG in improving soil health and preventing climate change remains unclear. The objective was to summarize the evidence on the impact of RG on plant productivity, GHG emissions, soil health, and plant richness and diversity in cow–calf operations in Canada and similar climate regions. This scoping review followed PRISMA-ScR reporting guidelines. Studies could be randomized controlled trials, randomized block design, controlled trials, observational, or simulation studies. Retrieved studies were screened in two stages by two independent reviewers. After screening, 15 studies were considered relevant and included in the review, and 46 outcomes were extracted. Of these, 46.5% showed a positive impact of RG, while 53.5% reported RG having neutral or no impact. There was a consistent body of evidence proving that RG benefits plant productivity. However, the evidence showing benefits on soil health and GHG emissions varied depending on the outcomes assessed. There was minimal evidence of impact on plant diversity. Rotational grazing has benefited soil surface properties, water dynamics, and nutrient availability.

Key words: adaptive multi-paddock grazing (AMP), intensive grazing, controlled grazing, carbon sequestration, ecosystem services, sustainable productive systems

Introduction

The global population is projected to increase to 9.7 billion people by 2050; therefore, food production systems are intensifying to keep up with the high demand (AAFC 2023). Consequently, this intensification process may increase greenhouse gas (GHG) emissions and exacerbate climate change (Brulle et al. 2012; Scholtz et al. 2012; Brohe´ 2017; Sakamoto et al. 2020). Climate change may increase the frequency of wildfires, droughts, and floods by altering weather patterns, increasing temperatures, disrupting precipitation cycles, ultimately leading to more extreme weather events (National Research Council 2011; Wong 2016).

Grazing is crucial for supporting livestock production, as it provides cows with feed to maintain or increase weight and produce milk (Boval and Dixon 2012). However, grazing practices with higher inputs may lead to negative environmental outcomes (Eriksen et al. 2010). Recently, the Government of Canada has encouraged the use of rotational grazing (RG) as a mitigation practice to reduce GHG emissions from the agriculture sector (AAFC 2023). The theoretical benefits of RG include improving soil health and reducing GHG emissions (Soussana and Lemaire 2013; Rutledge et al. 2015; AAFC 2023) by boosting grassland carbon (C) sequestration (Stanley 2017). This initiative is based on the fact that agriculture and livestock production produce 10% of the total Canadian GHG emissions, and ruminants are the main contributors (ECCC 2024*a*) where cow–calf operations contribute the highest CH_4 emissions compared to all other beef cattle categories (Statistics Canada 2024; ECCC 2024*b*). Furthermore, the relationship between GHG emissions and soil health is complex. The soil's top layers store the largest amount of organic C found in the earth, double the amount of C present in the atmosphere (Sándor et al. 2020). Therefore, slightly increasing the amount of C stored in soils can reduce the atmospheric GHG levels (Scharlemann et al. 2014). However, to date, the effectiveness of this practice in reducing GHG emissions in cow–calf operations in the Canadian context is still unknown.

Rotational grazing involves the movement of cattle between pastures or paddocks, to reduce the grazing selectivity of animals and allow strategic rest periods for paddocks to improve forage quantity and nutritive value (Voisin 1988; Briske et al. 2008, 2011*b*; Sanderman et al. 2015; Savory and Butterfield 2016). The stocking density (SD) used for RG varies among production systems and depends directly on the availability of forage and residency period (Voisin 1988). However, the technical aspects of this practice are relevant and may impact its effectiveness in reducing GHG emissions. For example, heavy intensive grazing has been found to decrease soil quality (Lai and Kumar 2020), and excessive trampling may lead to soil compaction, which causes soil pores to compress, leading to decreased water infiltration and eventually reducing plant vigour (Bilotta et al. 2007). Hence, the positive impact of RG depends on variables including climatic region, soil properties, and stocking density, among others (Klumpp et al. 2011; Mudge et al. 2011; Rutledge et al. 2015; Cusack et al. 2021). Therefore, evidence of the impact of RG in cow–calf operations plant productivity, GHG emissions, soil health, plant richness and diversity parameters is crucial to determine whether the Government's initiative may decrease GHG emissions. Research synthesis is key for comprehensively gathering and evaluating all available evidence on a specific topic (O'Connor and Sargeant 2015). Scoping reviews are literature reviews with a systematic search that ensures all relevant studies are included. They identify the available evidence on a topic (Munn et al. 2018). Building evidence of RG effectiveness is relevant, given that the implementation of this practice requires an investment in infrastructure compared to continuous grazing (CG) (Wang et al. 2018). Because of this, a scoping review was conducted to summarize RG's impact on supporting soil health, productivity, plant diversity, and mitigating GHG emissions. Rotational grazing was expected to increase plant richness and diversity and productivity, reduce GHG emissions, and improve soil health compared to other grazing systems. To the best of our knowledge, no other review has attempted to summarize this evidence to support this initiative and potentially guide financial mechanisms to reward these practices.

Materials and methods

Protocol and registration

This review followed the PRISMA-ScR reporting guidelines for scoping reviews (Tricco et al. 2018). A protocol was developed and published in the University of Calgary Digital Repository PRISM (https://prism.ucalgary.ca). Modifications were made to this published version; the last version is shown in Supplementary Material 1.

Eligibility criteria

The eligibility criteria for selecting studies included in this review were based on the PICOSL framework, which involves relevant aspects of Population (P), Intervention (I), Comparator (C), Outcomes (O), Study design (S), and Location (L) (O'Connor and Sargeant 2015).

Population

The population of interest was *Bos taurus* beef cow–calf pairs or pregnant heifers. Studies that presented findings on other productive groups, dairy breeds, and subspecies, including *Bos indicus* or hybrids (e.g., Zebu, Nellore, Brahman, Braford, and Brangus), were excluded.

Interventions and comparators

The intervention assessed was RG. This included different intensification levels: extensive RG (≤0.65 AUM/ha), moderate RG (0.65–1.5 AUM/ha), intensive RG (>1.5 AUM/ha), and adaptive multi-paddock grazing (AMP, intensive RG with extended rest periods). Included studies were required to have a concurrent comparison group (e.g., CG, conventional, mowing, and non-grazed treatments). Continuous grazing refers to uninterrupted grazing with variable stocking rates. Conventional grazing refers to CG.

Outcomes

Plant productivity, GHG emissions, soil health, and plant richness and diversity were among the outcomes of interest. Figure 2 shows a causal diagram (Müller et al. 2007; Proesmans et al. 2022; Amin et al. 2023; Navarro-Perea et al. 2023).

Study design and report characteristics

Randomized and non-randomized controlled trials and block designs, observational studies, and simulation studies were included. Studies had to be published in a peer-reviewed journal or thesis and be written in English.

Location

Included studies had to be conducted in Canada or any other region with a similar climate. The criteria used to define a similar climate were based on the Köppen-Geiger classification (Kottek et al. 2006). Only geographic locations with climates classified as Bsk (cold semi-arid climate), Cfb (temperate oceanic climate), Dfb (warm-summer humid continental climate), Dfc (subarctic climate), were considered similar to Canadian climates (Kottek et al. 2006).

Information sources

The electronic databases used were CAB Abstracts (Ebsco platform), Environment Complete (Ebsco platform), BIOSIS previews (Web of Science platform), Web of Science Core Collection—Science Citation Index and Emerging Sources Citation Index (Web of Science platform), and ProQuest dissertations.

Search strategy

The search strategy was developed by a librarian (HG). Keywords and controlled vocabulary terms related to RG and beef cattle were used to retrieve relevant studies from databases. The search was conducted on the same day across all databases (29 March 2023). Google Scholar was used to ensure that all relevant studies were found. Details concerning the search strategy are shown in Supplementary Material

2. The search results were imported into Covidence (Veritas Health Innovation, Melbourne, Australia).

Screening and study selection

Two independent reviewers and co-authors of this manuscript screened studies in two stages (LS and MT). During the first stage, titles and abstracts were screened, and full texts were screened in the second stage. Signalling questions described in the protocol were used to conduct the screening process based on the pre-defined inclusion and exclusion criteria. During these stages, reviewers voted on the relevance of the study for this review. Conflict between reviewers was resolved by discussion. If necessary, a third reviewer (GL) participated in the discussion. Details concerning the signalling questions and inclusion and exclusion criteria are shown in the protocol (Supplementary Material 1).

Data collection synthesis

The data was extracted using pre-tested Microsoft Excel tables (Microsoft Corporation, Redmond, WA). Studies were anonymized at this stage by identifying them with an individual number. In cases where a study reported more than one outcome of interest and had statistically assessed the relationship with the RG, these were split into practice assessments (PAs). Table 1 reports the general characteristics of the studies included in the review, and in Table 2, the outcomes of interest isolated within each study. These were identified with an alphanumeric code based on the study number. Results were considered statistically significant if ($P \leq 0.05$). The evidence was synthesized into a narrative structure. The results were organized by outcomes of interest with at least one PA with statistically significant effects or associations and outcomes without any PAs with statistically significant effects or associations.

Results

The initial search retrieved 5198 studies with 1418 duplicates removed by the software or manually. Three thousand and eighty studies underwent title and abstract screening and underwent the two-phase screening: the first stage was the title and abstract screening ($n = 3780$). During the second stage, full-text screening ($n = 611$), 15 studies were selected for the review (Fig. 1).

Out of the total, eight studies reported the impact of RG on soil health outcomes (33.33%), seven studies on plant productivity (29.16%), seven studies on GHG emissions (including soil fluxes) (29.16%), and two studies on plant diversity (8.33%). Nine studies reported more than one of these outcomes. Stocking rates used in the included studies by outcome are shown in Fig. 3.

Geographic location of included studies

Given the exclusion criteria regarding climate, most of the studies were conducted in Canada. Nine studies were located in Canada, and one in each of France, the Netherlands, Hungary, Belgium, the United States of America, and Germany.

Outcomes with a significant association with RG

Plant productivity: biomass, nutritive value, and length of grazing season

Rotational grazing was proven to benefit plant productivity (PAs 2a, 2b, 5a, 11a, 13a, 14a, and 14b; Table 2). Specific plant productivity outcomes assessed were total biomass, standing biomass, above-ground biomass, peak grassland biomass, potential utilizable forage, forb biomass, forage nutritive value, and impact on the length of the grazing season. Seven out of 10 PAs found beneficial associations regardless of the specific outcome assessed, while two PA reported a neutral impact of RG and another found a negative impact compared to the control group (PAs 1a, 1b, 2a, 2b, 3a, 5a, 11a, 13a, 14a, and 14b; Table 2). For example, RG treatments produced 2–5 times more total biomass than CG ones (PA 11a). Also, intensive RG was associated with higher forage nutritive value compared to CG and non-grazed treatments (PA 2b). Besides this, RG was shown to impact the length of the grazing season, given ranches that used intensive RG (AMP) could start grazing earlier than those that used conventional grazing (PA 14a and 14b).

Soil health: soil surface properties, water dynamics, and nutrient availability

Rotational grazing was found to improve soil health by enhancing soil surface properties (litter cover, litter depth, and bare soil), water dynamics (water infiltration, volumetric water content, water-filled pore space), and nutrient availability (water-extractable C and N, N mineralization). All 7 PAs found a positive impact of RG on soil health parameters (PAs 2c, 2d, 7a, 7b, 9a, 10a, and 11b; Table 2). For example, intensive RG was demonstrated to improve soil surface properties, increasing vegetation cover, litter depth, and litter mass and reducing the amount of bare ground compared to CG treatments (PAs 2c, 7a, and 10a).

Net carbon and green house gas balance

Rotational grazing was shown to not affect GHG emissions, by being neutral. These emissions included total farm emissions, net GHG balance, soil CO_2 fluxes (rates of CO_2 movement), and Net Ecosystem Carbon Balance (NECB) (net amount of CO_2 absorbed or released, indicating whether it is a carbon (C) source or sink) (Chapin et al. 2006). Five of the ten PAs found that RG reduced GHG emissions, while the remaining five found a neutral impact (PAs 1c, 3b, 3c, 3d, 3e, 4a, 4e, 5b, 6a, and 9b; Table 2). For example, the PA that assessed the relationship between RG and NECB found that RG treatments acted as carbon sinks (PA 3e) compared to the comparison groups (mowing).

Plant richness and diversity

Rotational grazing was shown to increase plant richness and diversity. All PAs found that RG benefitted vegetation di-

Table 1. Characteristics of studies included in a scoping review on the impact of rotational grazing on GHG emissions, soil health, plant diversity, and plant productivity parameters.

Study	Reference	Country and year of the study	Koppen climate classification	Study design	Population	Comparator	Case definitions	Outcome level
1	McGinn et al. 2014	Canada, 2010–2012	Dfb	Unclear design, longitudinal observational study with repeated measures	Aberdeen Angus heifers	Extensive RG with different SD (0.1 or 0.2 animals/ha)		Treatment/ paddock
2	Oates et al. 2011	United States, 2006–2007	Dfb	RBD	Cow–calf pairs	Intensive RG (108 AUM) versus CG (112 AUM), mowing and non-grazing	Mowing: harvesting treatment twice per growing season. Nutrients were replenished through the application of phosphate fertilizer. Forage was mechanically harvested and removed. External GHG emissions from hay fed to cattle were included, covering production, transportation, and feeding.	Treatment/ paddock
3	Koncz et al. 2017	Hungary, 2011–2013	Dfb	CT. Randomization unclear	Cow–calf and heifers, Hungarian Grey Cattle	Extensive RG (SD 0.64 LSU) versus mowing	Mowed site was established near the grazed site (250 m apart) and was mowed once per year (at 6 cm height). 1 livestock unit = 381 kg. Nutrients were not replenished. Forage was harvested and removed. External GHG emissions from hay fed to cattle were included, covering production, transportation, and feeding.	Treatment/ paddock
4	Ma et al. 2021	Canada, 2017–2019	Dfb	Case-control	Cow–calf pairs	AMP grazing versus conventional grazing (with similar SR).	AMP is an intensive RG system with a short duration at a high stock density, followed by long rest periods. AUM = 454 kg cow, with or without a calf per hectare.	Farm level
5	Gourlez de la Motte et al. 2018	Belgium, 2015	Cfb	CT. Randomization unclear	Cow–calf pairs	Intensive RG (SD 19.3 LU/ha) versus CG (3.5 LU/Ha)	LU= 600 kg adult dairy cow producing 3000 kg of milk annually, without extra feed.	Treatment/ paddock

Table 1. (*continued*).

Study	Reference	Country and year of the study	Koppen climate classification	Study design	Population	Comparator	Case definitions	Outcome level
6	Hoeft et al. 2012	Germany, 2006–2009	Cfb	Factorial experiment with a block design	Cow–calf german simmental	RG grass sward versus RG diverse sward. Both with similar SD (2000–3000 kg/ha).	Grass Sward sward dominated by grasses. Diverse Sward untreated control, diverse mix of plants.	Treatment/paddock
7	Döbert et al. 2021	Canada, 2017–2018	Dfb	Cross-sectional	Cow–calf pairs	AMP versus conventional grazing	Adaptive grazing is an intensive RG system with short-duration and multi-paddock grazing. AP ranches were paired with nearby conventional grazing.	Farm level
8	Hoogsteen et al. 2020	Netherlands, 2011–2014	Cfb	Simulation of a RBD	Cow–calf pairs	Intensive RG, CG,	Lenient strip grazing is an intensive RG in which cows graze with high-standing biomass (2.5–3.0 Mg DM/ha). All treatments were simulated using mowing, with periodic fertilization. Forage was harvested and removed. External GHG emissions from hay fed to cattle were included, covering production, transportation, and feeding.	Treatment/ paddock
9	Thomas et al. 2017	Canada, 2010–2014	BSk	CT. Randomization unclear	Cow–calf pairs	Extensive RG (SR 0.6 AUM/ha) and non-grazed areas	Soil textures: Orthic Brown Chernozem (sandy loam texture). Rego Brown Chernozem (loamy sand texture)	Per soil texture and treatment/paddock
10	Pyle et al. 2019	Canada, 2012–2013	Cfb	Cross-sectional	Beef cattle	RG, non-grazed areas, CG		Treatment/ paddock
11	Miller et al. 2018	Canada, 2011–2015	Dfb	Cross-sectional	Beef Cattle	Intensive N-RG (SR 3.8 AUM/ha) versus CG (SR 0.3–0.5 AUM/ha)	N-RG treatment: non-grazed for 11 years, and then RG for 3 years	Treatment/year
12	De Bruijn et al. 2006	Canada, 2000–2003	Dfb	RCT	Beef cattle	1) CG, 2) Low intensity-high frequency RG, 3) high intensity-low frequency RG	2) 4–6-week rest period. Herbage grazed to a height of 15 cm in 2–3 days.	Farm level

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Table 1. (*concluded*).

Study	Reference	Country and year of the study	Koppen climate classification	Study design	Population	Comparator	Case definitions	Outcome level
13	Picon-Cochard et al. 2021	France, 2014–2015	Dfb	RCT	Cow–calf pairs	Difference in SD RG (6 to 13.8 SD) and none treatment	The two cattle treatments corresponded to two levels of herbage utilisation by grazing and had on average, a residual plant height of 15.2 cm ± 0.5 (mean ± SE) for Ca− and 7.7 cm ± 0.2 for Ca+ at the end of each grazing rotation	Treatment
14	Bork et al. 2021	Canada, 2018–2019	Dfb, Dfc, BSk	Case-control	Beef cattle	AMP and conventional with similar SR	AMP = highly flexible, multi paddock grazing to facilitate short grazing periods and long recovery spells during the growing season. And neighboring ranches (n-AMP) for comparison (conventional grazing)	Farm level
15	Olson et al. 2011	Canada, 2007–2010	Dfa	Longitudinal observational study	Cow–calf pairs	CG	Compared same ranches, from CG to RG	Farm level

Note: RCT = randomized controlled trial; RBD = randomized block design; CT = controlled trial; AUM = animal unit month; RG = rotational grazing; CG = continuous grazing; AMP = adaptative multi-paddock grazing; SR = stocking rate; Bsk = cold semi-arid climate; Cfb = temperate oceanic climate; Dfb = warm-summer humid continental climate; Dfc = subarctic climate.

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Table 2. Summary of findings table with statistically significant effects or associations of rotational grazing

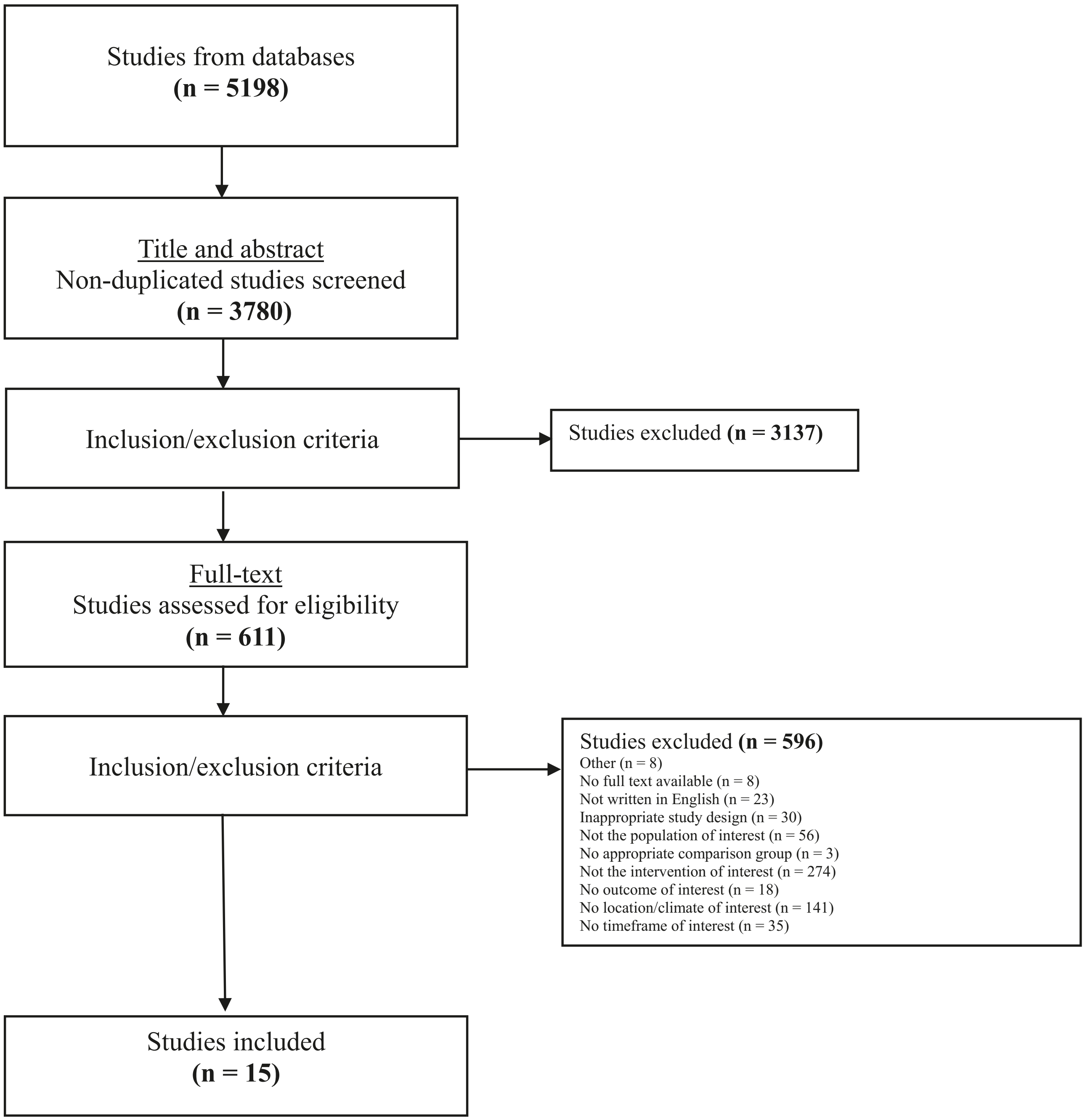
Practice Assessment Number	Outcome	Intervention	Comparator	Impact/effect	Comments
Plant productivity					
Biomass					
2a	Potential utilizable forage (PUF)	Intensive RG	CG, mowing and non-grazed areas	Effect ($P < 0.05$). Higher PUF in RG treatment.	PUF was estimated using the total biomass production (refused and unutilised biomass accounted).
3a	Standing biomass	Extensive RG	Mowing	Effect ($P < 0.05$). Mowed had higher biomass than extensive RG.	
5a	Biomass	Intensive RG	CG	Effect. RG showed slightly better biomass production.	No *P* values.
11a	Total biomass	Intensive N-RG	CG	Impact. In all 5 years, the N-RG treatment increased total biomass by 2–5 times compared to the CG treatment.	
13a	Annual above-ground biomass production (ANPP)	Low/moderate RG, inten-sive/moderate RG	Difference in SD RG, and non-grazed	Effect ($P < 0.05$). Both cattle treatments had higher ANPP than the non-grazed. Ca+ had the highest ANPP.	
DMI and standing biomass					
1a	Standing biomass and DMI	Extensive RG	RG with different SD (both extensive)	Positive weak correlation between standing biomass (pre-grazing sampling) and DMI ($R^2 = 0.3$).	
Forage nutritive value					
1b	Forage nutritive value	Extensive RG	RG with different SD (both extensive)	Unclear effect between both RG treatments.	No *P* values
2b	Forage nutritive value	Intensive RG	CG, harvest and non-grazing areas	Effect ($P < 0.05$). RG treatment had the highest forage nutritive value during summer and fall.	RG and harvest treatment had similar forage nutritive value during summer 2007.
Season length					
14a	Total grazing season length	AMP	Conventional grazing	Effect ($P \leq 0.05$). AMP had longer season length.	$P < 0.0001$
14b	Early season grazing period	AMP	Conventional grazing	Effect ($P \leq 0.05$). AMP had earlier grazing season.	Early season = 31 July or sooner
Soil health					
Soil surface properties					
2c	Vegetation cover	Intensive RG	CG, mowing and non-grazing areas	Effect ($P = 0.002$). CG had higher bare ground than others.	
10a	Soil surface properties (litter cover, litter depth, and bare soil)	RG	Non-grazed, CG	Effect ($P < 0.05$). Less cover and bare ground twice as high under CG compared to RG.	No impact ($P > 0.05$) between RG and non-grazed.
7a	Litter mass	AMP RG	Conventional grazing	Higher in RG ranches. Mean of 303.2 g/m^2 litter mass.	The higher the litter mass, the higher the infiltration rate in AP ranches. Conventional grazing mean litter mass = 248.8 g/m^2
Soil water dynamics					
7b	Water infiltration	AMP RG	Conventional grazing	Impact. Higher infiltration rates on RG ranches. Infiltration at AP mean 105 mm/h.	Infiltration of conventional grazing mean of 74 mm/h.
9a	Water-filled pore space (WFPS)	Extensive RG	Non-grazed areas	Effect ($P < 0.05$) greater in RG loamy sand soil texture. Average increase of 10% compared to rested areas.	

Table 2. (*concluded*).

Practice Assessment Number	Outcome	Intervention	Comparator	Impact/effect	Comments
11b	Volumetric water content	Intensive N-RG	CG	Impact. The N-RG increased the volumetric water content of the surface soil by 7%–10% in 3 out of the 5 years.	
N mineralization					
2d	Net nitrogen mineralization	Intensive RG	CG, mowing and non grazing areas	Effect ($P = 0.02$). CG and RG had higher net nitrogen mineralization than non-grazed treatments.	
GHG emissions					
GHG emissions					
1c	Total GHG balance	Extensive RG	RG with different SD (both extensive)	Unclear effect between both RG treatments.	0.1 animals/ha: −9 kg CO_2e/ha/year (source). 0.2 animals/ha: −338 kg CO_2e/ha/year (source).
3c	Net greenhouse gas balance (Net GHG)	Extensive RG	Mowing	Effect ($P < 0.05$). The RG acted as a net sink for GHGs.	The mowed treatment acted as a net source.
3d	Net GHG at a farm scale	Extensive RG	Mowing	Combining the whole farm (t1 + t2 + t3), the farm was GHG neutral, with no effect ($P > 0.05$) overall 3 years.	Net sink in moisture years and net source in dry years.
4a	Soil GHG fluxes	AMP	Conventional grazing	No impact ($P > 0.05$). GHG fluxes did not differ.	
Soil CO_2 fluxes and NECB (includes respiration and photosynthesis)					
3b	CO_2 fluxes	Extensive RG	Mowing	Effect. RG acted as a C-sink	Mowing treatment abrupt changes in biomass and photosynthetic capacity
4e	CO_2 fluxes	AMP	Conventional grazing	No Impact ($P > 0.05$). Both treatments CO_2 sources.	Impact between the CO_2 fluxes and the stocking rates, soil moisture, and interaction ($P < 0.05$).
9b	CO_2 fluxes	Extensive RG	Non-grazed areas	The impact depends on the soil texture. Non-grazed had 24% greater CO_2 fluxes in sandy loam texture than RG. No effect in the loamy sand.	
3e	Net ecosystem carbon balance (NECB)	Extensive RG	Mowing	Effect. RG treatment proved to be a net C sink.	Mowed treatment was found to be a net source for NECB. Paired *t* test, $P = 0.01$, $n = 3$.
5b	NECB	Intensive RG	CG	Effect. NECB pattern (throughout the year) between RG and CG.	No *P* values. RG has a higher uptake of CO_2 than CG, and a higher peak too.
6a	Net ecosystem exchange (NEE)	Intensive RG	CG	No effect.	No *P* values.
Biodiversity					
15a	Vegetation diversity	Compare the same ranch before and after implementing RG	CG	Vegetation diversity increased along several paddocks, with the greatest increases in the first post-RG year.	Plant community favoured by wet weather conditions.
Weed control—biocontrol					
12a	Weed biological control- Canada thistle [Cirsium arvense (L.) Scop]	(1) Low intensity-high frequency RG (2) high intensity-low frequency RG	CG	Effect ($P \leq 0.05$). high intensity-low frequency RG reduced the Canadian thistle.	High intensity-low frequency RG reduced weed density, biomass, and flowering, and resulted in greater weed suppression over a 2- to 3-year period.

Note: RG = rotational grazing; CG = continuous grazing; AMP = adaptative multi-paddock grazing; SR = stocking rate; SD = stocking density

Fig. 1. Prisma flowchart of the scoping review.



versity and weed control (PAs 12a, 15a; Table 2). Rotational grazing was also shown to control invasive weeds such as Canada thistle (*Cirsium arvense* (*L.*) *Scop*) (PA, 12a).

Outcomes with no statistically significant associations with RG detected

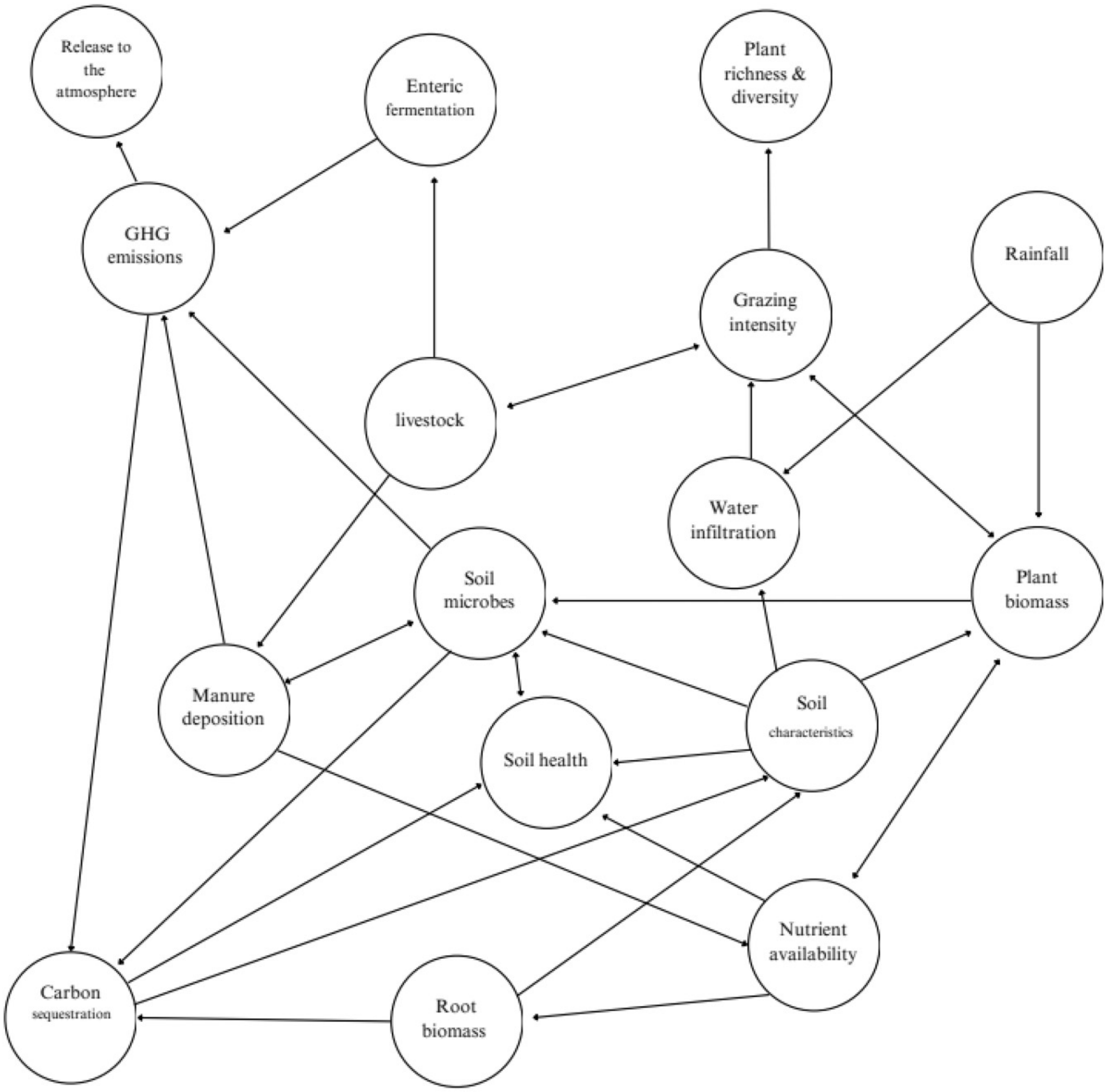
Soil health: soil organic carbon, soil organic matter, density, and root biomass

No evidence reported that RG impacted or benefitted other soil health parameters. Specifically, outcomes considered were soil organic matter (SOM), soil organic carbon (SOC), soil bulk density, and root biomass (annual below-ground biomass and root growth) (PAs 2e, 4b, 7c, 7e, 8a, 8b, 9c, 13b, and 13c; Table 3).

Soil green house gas fluxes

No evidence was found proving that RG impacted GHG fluxes. Specifically, outcomes assessed were soil CH_4 and N_2O fluxes (PAs 3f, 3 g, 4c, 4d, 8a, 9d; Table 3). Three PAs reported no association between RG and soil CH_4 fluxes and the comparison groups (e.g., conventional grazing, mowing, and resting) (PAs 3f, 4c, 9d). All RG treatments acted as soil CH_4 sinks (PAs 3f, 4c, 9d).

Fig. 2. Causal diagram for a scoping review on the impact of rotational grazing in beef cattle systems on greenhouse gas emissions, soil health, plant diversity, and plant productivity parameters. Figs created using Canva (Canva Pty Ltd., Sydney, Australia). Adapted from Müller et al. (2007), Proesmans et al. (2022), Amin et al. (2023), Navarro-Perea et al. (2023).

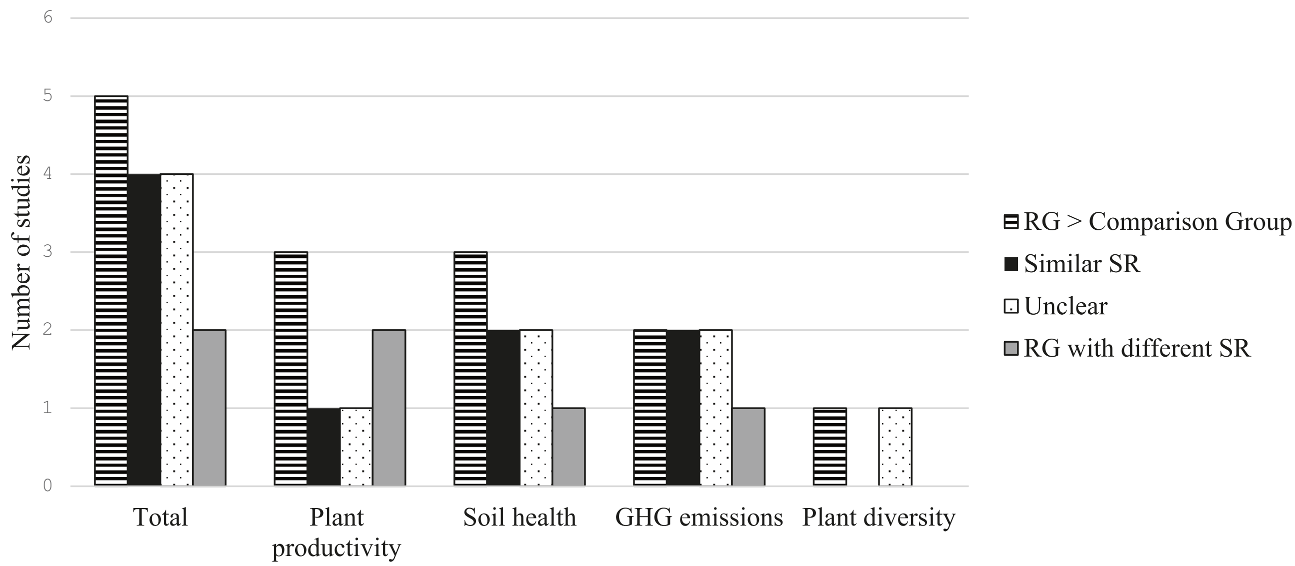


Discussion

This scoping review compiled the published scientific evidence of RCTs, RBD, CTs, observational, and simulation studies showing that RG benefits several outcomes in Canadian and other similar climate zones. Plant productivity, some soil health parameters, GHG balance, and plant richness and biodiversity were positively impacted by the practice. Specific outcomes were aboveground biomass, forage nutritive value, total range health score, soil surface properties (litter cover, litter depth, and bare soil), water dynamics, nutrient availability, net GHG balance, and NECB. However, no impact was found for some specific outcomes including soil health and GHG emissions, such as soil CH_4, N_2O fluxes, SOM, SOC, soil bulk density, root biomass, and microbial dynamics.

A consistent body of evidence showed that RG favours plant productivity, including above-ground biomass (Oates et al. 2011; McGinn et al. 2014; Koncz et al. 2017; Gourlez de la Motte et al. 2018; Miller et al. 2018; Bork et al. 2021; Picon-Cochard et al. 2021). This aligns with the findings of two different meta-analyses that reported that grazing practices with resting periods such as RG, increased biomass production (McDonald et al. 2019; Jordon et al. 2022). A potential explanation for why this practice increases plant productivity may be related to a specific aspect of RG, which involves rest periods during grazing. These periods are essential for plant recovery (Voisin 1988). Yet, the specific length of the resting periods depends on several aspects, including the stocking density during grazing. For example, paddocks that were grazed with higher stocking densities required longer recovery periods than those with moderate or low ones (Jordon et

Fig. 3. Stocking rates used in studies included in a scoping review on the impact of rotational grazing in beef cattle systems on greenhouse gas emissions, soil health, plant diversity, and plant productivity parameters. The figure was created using Microsoft Excel (Microsoft Corporation, Redmond, WA).



al. 2022). Therefore, the studies that assessed this outcome, and met the inclusion criteria to be included in this review probably used RG, considering optimum management of forage, stocking densities, and rest periods. Although, there was minimal evidence of the impact RG on plant diversity (De Bruijn and Bork 2006; Olson et al. 2011).

Rotational grazing was also shown to benefit soil health outcomes, such as soil surface properties including litter cover, litter depth, bare soil (Oates et al. 2011; Pyle et al. 2019; Döbert et al. 2021), and soil water dynamics (Thomas et al. 2017; Miller et al. 2018; Döbert et al. 2021). Similarly, this has been described in another review, where given optimum forage management, the RG treatment was superior to the CG one (Xu et al. 2018). Soil properties and water dynamics are outcomes that are related with each other. For example, soil surface properties help retain soil moisture and prevent water runoff and evaporation (Facelli and Pickett 1991; Deutsch et al. 2010). Therefore, water infiltration helps to maintain the hydraulic functions of grasslands and thus builds resilience against extreme conditions such as droughts (Döbert et al. 2021). However, there is some conflicting evidence concerning the optimum stocking density to boost the infiltration rate. This is because some studies have shown that high stocking densities and short residency periods are associated with higher infiltration (Savory and Parsons 1980; DeLonge and Basche 2018). However, excessive trampling could potentially lead to soil compaction and negatively affect infiltration rates (Weltz and Wood 1986; Nash et al. 2004; Bilotta et al. 2007). Overall, RG is known to have impacts on soil surface and water dynamics, which could potentially boost forage production (Deutsch et al. 2010). Therefore, the benefits of this practice depend on optimum management, and for it to be determined, more research is required in this area.

The evidence showing RG to have an impact on NECB, NEE, and net GHG balance was minimal (Hoeft et al. 2012; Koncz et al. 2017; Gourlez de la Motte et al. 2018). Extensive RG may have lower emissions (Net GHG balance) than mowing (or hay exporting). Net ecosystem carbon balance is defined as the net rate of carbon accumulation or loss from an ecosystem (Chapin et al. 2006), as it predicts the amount of C stored or lost in the ecosystem (Schulze et al. 2010). This is related to C sequestration. Systems are considered as C sinks when NECB values are negative and when C sources are positive. The net GHG balance is the net amount of CO_2, CH_4, and N_2O fluxes. The main factors influencing net GHG emissions are machinery, fossil fuels (e.g., fuels, production of fertilizers), plant and animal respiration, enteric fermentation from livestock, manure, crop residues, the oxidation of organic carbon in soils, and pedoclimatic conditions (Marland et al. 2003; Herrero et al. 2016; Koncz et al. 2017). No other review showed the beneficial impact of RG compared to CG on NECB or Net GHG balance. Yet, another study found similar results for Net GHG balance while comparing grazing and mowed sites (Soussana et al. 2010). The findings for NECB may be explained by the fact that RG is characterized by abrupt changes in standing biomass, which lead to enhanced photosynthetic activity during rest periods that maximize C uptake (Wohlfahrt et al. 2008; Rutledge et al. 2015) compared to CG. It may be expected that mowing treatments act as C sources (NECB) due to the hay removal compared to grazing treatments (Senapati et al. 2014). Due to the fact both outcomes heavily depend on precipitation, and given the current importance of GHG emissions, more studies, including RCTs, are needed to estimate the magnitude of the effect.

The evidence of RG showing positive impacts on forage nutritive value found in this review was minimal (Oates et al. 2011; McGinn et al. 2014). However, this has been described before (Pittarello et al. 2019). Forage nutritive value was defined as the concentration of total digestible nutrients, including digestible fibers, non-structural carbohydrates, pro-

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Table 3. Summary of findings table with no statistically significant effects or associations of rotational grazing (RG).

Practice assessment number	Outcome	Intervention	Comparison	Impact/effect	Comments
Soil health					
Soil organic carbon (SOC) and soil organic matter (SOM)					
4b	SOC	AMP	Conventional grazing	No effect ($P > 0.05$).	0–60 cm depth.
9c	SOC	Extensive RG	Non-grazed areas	Unclear impact.	Non-grazed areas had 34% higher SOC.
8a	SOM	Intensive RG	CG	No impact ($P > 0.05$) on SOM between treatments, soil layers, or soil types.	Three soil layers: 0–10 cm, 10–30 cm, and 30–60 cm. The soil types are loamy and sandy. SOM increased in most fertilized treatments (0–60 cm layer).
Soil bulk density					
7c	Stocking rates and soil bulk density	AMP RG	Conventional grazing	No impact. Effect only within CG ranches.	In conventional grazing ranches, the higher stocking density increases soil bulk density (compaction).
7e	Soil bulk density	Intensive RG	Conventional grazing	No impact.	The higher the bulk density, the lower the infiltration rate and greater compactation for both treatments.
Root biomass					
8b	Root biomass	Intensive RG	CG	No impact ($P > 0.05$) in any soil layers.	Soil layers 0–10 cm, 10–30 cm, and 30–60 cm.
13b	Root growth	Low/moderate RG, intensive/moderate RG	Difference in SD RG, and non-grazed	Effect ($P < 0.05$). The none treatment had lower root growth than the cattle treatments during spring.	In the abandonment treatment, the spring and autumn root growth peaks were delayed by approximately one month compared to the two cattle treatments.
13c	Annual below-ground biomass production (BNPP)	Low/moderate RG, intensive/moderate RG	Difference in SD RG, and non-grazed	Effect ($P < 0.05$). Both cattle treatments had higher BNPP than the none treatment.	
2e	Belowground net primary production (BNPP)	Intensive RG	CG, mowing, and non-grazing areas	Effect on BNPP ($P < 0.05$) in the none treatment, with higher BNPP. CG and RG treatments no effect ($P > 0.05$).	

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Table 3. (*concluded*).

Practice assessment number	Outcome	Intervention	Comparison	Impact/effect	Comments
GHG emissions					
Soil CH_4 fluxes					
3f	CH_4 fluxes	Extensive RG	Mowing	No effect.	Weak CH4 flux net sinks. (paired *t* test, $n = 19$, $P = 0.79$)
4c	CH_4 fluxes	AMP	Conventional grazing	No impact ($P > 0.05$).	Both treatments CH_4 sinks. Influenced by cultivation history, soil moisture and bulk density.
9d	CH_4 fluxes	Extensive RG	Non-grazed areas	No effect ($P > 0.05$) between treatments (rested versus grazed) and soil textures for CH_4 fluxes.	Both treatments CH_4 sinks.
Soil N_2O fluxes					
4d	N_2O fluxes	AMP	Conventional grazing	No impact ($P > 0.05$).	Both treatments are soil N_2O sources.
3g	N_2O fluxes	Extensive RG	Mowing	No effect treatments and years.	Soils acted as net sources for N_2O. (paired *t* test by occasions, $n = 17–19$, $P = 0.13–0.78$).
8a	N_2O emissions	RG grass sward versus RG diverse sward.	RG grass sward versus RG diverse sward.	No impact ($P > 0.05$).	

Note: RG = rotational grazing; CG = continuous grazing; AMP = adaptative multi-paddock grazing; SR = stocking rate; SD = stocking density tein, and lipids (Collins et al. 2017). Potential reasons why RG improves forage nutritive value involve two relevant aspects: soil nutrient availability and maintaining plants in a juvenile state. As reported in the results, RG boosts nutrient availability (Oates et al. 2011; Khatri-Chhetri et al. 2022) by increasing water-extractable C and N and N mineralization (Voisin 1988), acting similarly to a fertilization treatment. Furthermore, this practice maintains the plant in a juvenile vegetation state, with a high leaf-stem ratio, preventing the cell walls from thickening and lowering neutral detergent fibre concentrations (Nelson and Moser 2015). Hence, despite this review showing scarce evidence of forage nutritive value, this is a well-known benefit of RG, specifically in the longer term, once plant populations shift. No evidence was found proving the impact of RG on SOC or SOM (Alemu et al. 2017; Thomas et al. 2017; Hoogsteen et al. 2020; Ma et al. 2021). These results are in accordance with the findings of two meta-analyses (Abdalla et al. 2018; Lai and Kumar 2020). Soil organic carbon refers to the C component of SOM. These non-significant results may be related to several reasons. Firstly, SOC is known to increase with abundant rainfall (Lyseng et al. 2018). However, the studies included in this review were conducted in geographic locations with climates similar to Canadian ones, which are not characterized by abundant rain. Secondly, the timeframe needed to observe significant changes in SOC is extensive. For example, a study found differences in SOC over a 38-year field trial (Tian et al. 2022). Yet, the follow-up times of studies included in this review were a maximum of eight years, and hence, it is possible that this could also have contributed to the lack of changes in C dynamics.

Additionally, no evidence was found that RG improves root biomass compared to CG (Oates et al. 2011; Hoogsteen et al. 2020). However, the review found contradictory evidence regarding root biomass in comparison to non-grazing treatments (Oates et al. 2011; Picon-Cochard et al. 2021). These results align with another review, which states that root growth depends heavily on the study context (McDonald et al. 2023). Root development is essential given that increased root depth of plants enhances plant growth and yield. In theory, allowing pastures a rest period, as in RG, improves root development, facilitating a faster regrowth even with infrequent grazing (Voisin 1988). Therefore, in CG treatments, with no rest periods, pastures usually have smaller root systems and reduced leaf photosynthetic area (Voisin 1988). Our results differ from theoretical ones because of other contextual factors, such as the type of grass (Culman et al. 2010), stocking rate (Wilson et al. 2018), defoliation frequency (Moot et al. 2021), pedoclimatic conditions, and fertilization. From a plant productivity perspective, increasing root depth by 1 m may lead to an extra 1.63 tons/ha of sward dry matter in grazing trials (Jordon et al. 2022), and may also contribute to C sequestration (Marshall et al. 2016).

Stocking rates substantially impact the environmental parameters of grazing systems (Briske et al. 2011*a*). Ideally, SR should balance forage demand and availability to enhance pasture productivity and soil health while minimizing negative consequences (Briske et al. 2011*a*). For example, RG has been shown to extend the grazing season and improve early-season forage availability, but this effect was primarily observed under AMP systems (Bork et al. 2021). These findings should be interpreted with caution, as there is insufficient evidence on the impact of RG at lower stocking rates and management. The impact of grazing systems on grazing outcomes was likely driven by adjustments in grazing pressure and the optimal balance between animal demand and availability.

Limited literature exists on the impact of RG on C sequestration, root biomass, and plant richness and diversity in cow–calf operations. The limited sample size may introduce selection bias and limit the generalizability of these findings. Another limitation identified was that study 5 followed the inclusion criteria, although a dairy metric was used (Gourlez de la Motte et al. 2018). Moreover, study 11 presented potential confounding effects due to differences between riparian and non-riparian areas, which could influence the comparison between periodic and continuous grazing (Miller et al. 2018). The prolonged pre-trial non-grazing period may have impacted results, limiting the study's comparability.

Furthermore, the lack of consistency in interventions, for example, differences in RG SR, may have introduced intervention bias, making it difficult to compare results across studies. Therefore, to partially address this issue, studies were classified by their level of intensification.

While most studies included in the review utilized direct measurement techniques, such as chamber gas flux measurements and eddy covariance, most compared their results with IPCC guidelines. However, not all studies specified the global warming potential (GWP) values used to convert CH_4 or report CO_2 equivalents. The lack of transparency in reporting conversion methods and the different measurement techniques could have introduced inconsistencies when comparing results across studies. As GWP estimates for CH_4 have been updated over time based on improved scientific understanding, these variations in GWP factors may have influenced how emissions were quantified and reported, potentially affecting the comparability of results.

Conclusion

This review filled the knowledge gap concerning the evidence about RG on plant productivity, GHG emissions, soil health, plant richness, and diversity. Of the 43 PAs included, 46.5% showed a positive impact of RG, while 53.5% reported RG as neutral or no effect with the control group. However, the impact of RG depended on the specific outcome of interest. Since not all studies were RCTs, the magnitude of the findings from other study designs are considered less reliable. Aboveground biomass, forage nutritive value, soil surface properties, water dynamics, nutrient availability, reduced or neutral impact on GHG emissions, and NECB were reported to have positive associations with RG. The findings emphasize the need for future RCTs with consistent interventions and comparison groups across studies to determine whether RG benefits C sequestration, root biomass, and plant biodiversity within Canada and similar eco-regions, as the current literature remains limited in these parameters.

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Supplementary material

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