Journal of Environmental Management 347 (2023) 119146

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Grazing management for soil carbon in Australia: A review

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ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Soil organic carbon
Biomass
Production
Livestock
Grazing intensity
Grazing strategy
Sequestration
Carbon neutral

ABSTRACT

The livestock industry accounts for a considerable proportion of agricultural greenhouse gas emissions, and in response, the Australian red meat industry has committed to an aspirational target of net-zero emissions by 2030. Increasing soil carbon storage in grazing lands has been identified as one method to help achieve this, while also potentially improving production and provision of other ecosystem services. This review examined the effects of grazing management on soil carbon and factors that drive soil carbon sequestration in Australia. A systematic literature search and meta-analysis was used to compare effects of stocking intensity (stocking rate or utilisation) and stocking method (i.e, continuous, rotational or seasonal grazing systems) on soil organic carbon, pasture herbage mass, plant growth and ground cover. Impacts on below ground biomass, soil nitrogen and soil structure are also discussed.

Overall, no significant impact of stocking intensity or method on soil carbon sequestration in Australia was found, although lower stocking intensity and incorporating periods of rest into grazing systems (rotational grazing) had positive effects on herbage mass and ground cover compared with higher stocking intensity or continuous grazing. Minimal impact of grazing management on pasture growth rate and below-ground biomass has been reported in Australia. However, these factors improved with grazing intensity or rotational grazing in some circumstances.

While there is a lack of evidence in Australia that grazing management directly increases soil carbon, this meta-analysis indicated that grazing management practices have potential to benefit the drivers of soil carbon sequestration by increasing above and below-ground plant production, maintaining a higher residual biomass, and promoting productive perennial pasture species. Specific recommendations for future research and management are provided in the paper.

1. Introduction

Livestock production occurs on approximately 30% of global land and contributes to a significant proportion of agricultural output from developed (40%) and developing (20%) countries (Steinfeld et al., 2006; FAO, 2018). Globally, livestock contribute to around 34% of the food

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https://doi.org/10.1016/j.jenvman.2023.119146
Received 28 June 2023; Received in revised form 23 August 2023; Accepted 22 September 2023

protein supply and directly support the livelihoods of 1.3 B people (FAO, 2018). However, population growth, changing diets, higher incomes, climate change and urbanisation are increasing the demand for livestock products and pressure on agricultural landscapes and biodiversity (The World Bank, 2009; Wellesley et al., 2015; Harrison et al., 2021).

In the absence of land use change, the livestock sector is agriculture's largest producer of greenhouse gas (GHG) emissions (Smith et al., 2014; Harrison et al., 2021). The livestock sector emits an estimated 7.1 GT of carbon dioxide equivalents (CO_2e) each year (14.5% of total human-induced GHG emissions) (Gerber et al., 2013). In Australia, 71% of agricultural emissions are from methane emitted from livestock (DCCEEW, 2020). In response, the Australian red meat industry has committed to an aspirational target of net-zero emissions by 2030 (CN30, MLA, 2021). Achieving CN30 requires, in part, the identification and implementation of grazing management approaches that reduce emissions and/or sequester carbon in soil and vegetation, while demonstrating environmental stewardship, increasing profitability and maintaining social licence to operate (Harrison et al., 2021; Henry et al., 2023).

Carbon stored in the top metre of soil represents the largest store of terrestrial organic carbon and is around three times that stored in vegetation and two times that in the atmosphere (Sándor et al. 2020; Farina et al. 2021). Agricultural soils are an important stock of carbon, and in Australia 12.76 Gt of organic carbon is estimated to be stored in the 0–30 cm soil layer (Viscarra Rossel et al., 2014). In effect, small changes in the amount of carbon stored in soil could have a significant impact on atmospheric carbon levels (Scharlemann et al., 2014; Viscarra Rossel et al., 2014).

Pasture management (pasture species, soil nutrition and grazing management) influences above and below-ground contributions of organic matter (OM) to soil, and hence soil organic carbon (SOC) accumulation (Jastrow et al., 2007). The potential benefits of grazing management on SOC accumulation in pasture systems are associated with promoting deep-rooted perennial plants (Fisher et al., 1994), increasing plant and root growth (Johnston, 1961), promoting nitrogen (N) input from legumes, encouraging root turnover (Chen et al., 2015) and litter return to the soil surface (Fig. 1). In addition, reducing soil disturbance, compaction and erosion (by maintaining groundcover) can increase the retention of OM in soils (Sanjari et al., 2008, 2009; Palacio et al., 2014; Galdino et al., 2016). Understanding relationships between grazing management and the key drivers of SOC sequestration is important to increase sequestration and to avoid further losses of SOC in grazing lands (Derner and Schuman, 2007). This is particularly important in Australia, where more than half of the land mass is subject to livestock grazing and from which livestock commodities make a significant contribution to the agricultural economy (Snow et al., 2021).

International reviews have reported negative impacts of moderate to high stocking intensity on SOC stocks, but not at light stocking intensities (Byrnes et al., 2018; Jiang et al., 2020) when compared to grazing exclusion. Effects of stocking method (frequency, timing or duration of grazing) have received less attention. However, a global meta-analysis found an increase in SOC stocks under rotational grazing compared with continuous grazing (Byrnes et al., 2018). Similarly, a review by Conant et al., 2017) reported increased SOC with 'improved grazing', along with other management practices including improving soil fertility, irrigation, and sowing legume and grass species. The category of improved grazing in this study was broad, including lowering stocking rates, various forms of rotational or seasonal grazing or removing livestock entirely. Overseas, adaptive multi-paddock (AMP) grazing has been shown to increase soil carbon (Stanley et al., 2018;

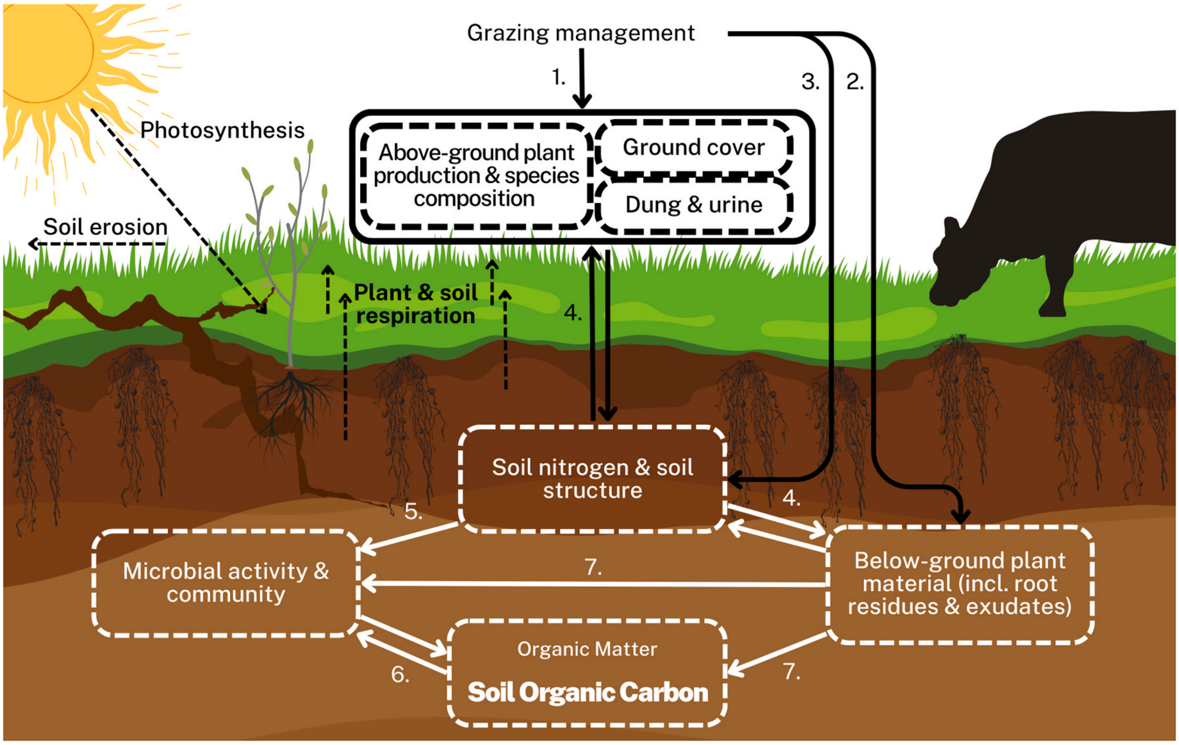

Fig. 1. Key drivers and processes of soil organic carbon accumulation in grazing systems. **1.** Intensity, frequency, timing and duration of stocking impacts above-ground biomass, plant growth rate and species composition (incl. Legumes, C_3/C_4 grasses, annual/perennial), as well as dung and urine (carbon and nitrogen) contribution to soil and ground cover. **2.** Grazing changes carbon allocation to roots and root growth rate **3.** Management of grazing impacts soil structure, infiltration and potential erodibility. Dung, urine, root carbon allocation and legume composition affect soil nitrogen. **4.** Nitrogen increases above-ground plant and root production, and legumes and their symbionts fix atmospheric N. Soil structure impacts above and below ground plant production. **5.** Soil compaction and loss of ground cover reduces soil porosity and infiltration and increases soil temperature fluctuations, leading to changes in microbial activity and communities. N availability impacts stability of OM in soil and soil respiration. **6.** Microbes and microbial detritus are a component of soil organic matter with various stability. **7.** Root residues and exudates are significant drivers of microbial activity, and contribute directly to soil OM.

Mosier et al., 2021; Apfelbaum et al., 2022). These findings indicate potential for grazing management to increase SOC in Australia.

While there has been a significant focus on international reviews (Conant et al., 2017; Abdalla et al., 2018; Byrnes et al., 2018; di Virgilio et al., 2019; Jiang et al., 2020), there has not been a focus on interpreting how the processes associated with SOC accumulation are controlled for livestock production systems under Australian conditions. This is important as rainfall patterns in Australia, particularly in the tropical north, are amongst the most variable in the world (Dey et al., 2021), and fertility of Australian soils is relatively low (Charley and Cowling, 1968; Eldridge et al., 2018). Sequestering SOC under conditions of low soil fertility, high temperatures and highly variable rainfall patterns may not have the same potential as environments with more reliable rainfall patterns (Eldridge et al., 2018; Meyer et al., 2018). This review aimed to examine the effect of grazing management (stocking intensity and stocking method - frequency, timing, duration) on SOC and key drivers of SOC in Australian pasture and grazing systems.

2. Methods

2.1. Literature search

A systematic literature search was conducted using the Web of Science platform to retrieve Australian studies that examined the impact of grazing management (e.g., stocking intensity, stocking method) using domesticated livestock on SOC, herbage mass (total standing herbage mass at time of sampling), plant growth rate (change in herbage mass over specific period), below-ground biomass and total ground cover. Additional articles were identified by searching reference lists of previous relevant reviews, articles referenced in the returned articles, and personal libraries. See Appendix Afor detail on methodology of the literature search. In total, 178 articles were retained for inclusion in the meta-analysis.

2.2. Data preparation

For each paper, information on grazing treatment (stocking intensity and method) including the mean, sample size and standard deviation for each treatment and control was extracted, along with co-variate data including climate, vegetation, rest and grazing time, and management cues. In studies comparing stocking intensity, grazing treatments were classified as low, medium or high based on the study information and authors' assessment. The lower stocking intensity treatment was considered the control. In studies comparing stocking method, grazing treatments were classified as either continuously grazed, low (stock rotated through <5 paddocks), moderate (5–10 paddocks) or high (>10 paddocks) intensity rotational grazing, or seasonal (where stock grazed or were removed from an area at a specific time in the year). The continuous grazing treatment was considered the control for these contrasts.

2.3. Statistical analysis

Effect sizes were calculated using the natural logarithm (ln) of the response ratio (RR), representing the proportional change between treatment means (Hedges et al., 1999).

$$lnRR = \ln\left(\frac{X_T}{X_C}\right) \tag{1}$$

Where X_T represents the mean of the treatment and X_C represents the mean of the control.

A significant proportion of studies (up to 85%) did not provide a measure of error to enable the calculation or imputation of standard deviation, therefore variance was calculated using replicate number assuming a coefficient of variation of 1.

$$v_i = \frac{1}{n_T} + \frac{1}{n_C} \tag{2}$$

Where n_T represents the number of replicates (including study sites and years) of the treatment and n_C represents the number of replicates of the control.

Dependence of sampling errors through shared controls was considered by dividing the number of replicates for the control by the number of contrasts within an article that share a control (Higgins et al., 2019; Bishop and Nakagawa, 2021). Dependence of sampling errors through multiple effect sizes per treatment was calculated with a variance co-variance matrix (Bishop and Nakagawa, 2021) using the make_VCV_matrix function in MetaAid package (Noble, 2019) in R (R Core Team, 2022).

Random and mixed-effects models were used to identify significance of treatment effects and other explanatory variables. Comparisons of stocking intensity and method were analysed separately. Response ratios were analysed using the rma. mv function in metafor (Viechtbauer and Viechtbauer, 2015). A unique identifier for each study (where one study was published across multiple papers), reference, grazing contrast, year within study, and depth of sampling (soil carbon only) were initially included as random effects, and the optimum null model (random effects only) to determine overall effects of stocking intensity or method was determined by comparing AICs for each variable. Moderator variables including comparison type (low v moderate, low v high or moderate v high stocking intensity), rainfall, climate and vegetation were tested separately in all models and compared with the null (random effect) model. In addition, management cues (based on pasture availability/phase or time) and number of rest days per year were tested in models comparing stocking method. Due to the low number of studies, and lack of information presented in some studies, results of models with management cues and vegetation type are not presented. Model selection was performed using the maximum likelihood (ML) estimator, and restricted maximum likelihood (REML) was used to generate values reported in this paper. Significance of null models and of moderator variables were determined using the *P* values (<0.05), and the lnRR estimates and confidence intervals of 95% were converted into the percentage change for interpretation.

Sensitivity analysis was performed using sample number (which included the number of cores, quadrats or animals measured) instead of replicate number to calculate the variance using an unweighted analysis. Full results of all additional models are provided inTables A.3 – A.7.

Publication bias was tested using funnel plots and Egger's regression test (Egger et al., 1997), and Skewness (Lin and Chu, 2020). Results of this test are summarised in Table A.8. The ggplot2 package (Wickham et al., 2016) was used to visualise results of the overall meta-analyses, and orchaRd (Nakagawa et al., 2021) used to create orchard plots of different grazing treatment comparisons. On these graphs, values to the left of 0 indicate greater values under the lower stocking intensity treatment or continuously grazed treatment.

3. Impacts of grazing management on soil organic carbon

Of the studies that examined the effect of grazing management on SOC, 13 studies reported the effect of stocking intensity and 19 compared stocking strategies (Table 1). Studies were located across Australia in multiple climate zones and soil types (Fig. 2). The meta-analysis of these Australian studies found no significant effect of stocking intensity (−1.3%, CI -11.2 – 9.7%) or method(4.4%, CI -6.8 – 17.0) on SOC (Fig. 3), and there was no significant interaction with rainfall, climatic region, or rest time ($P > 0.05$, see Table A.3 for detail on model results).

Overall, most studies reported no significant difference in SOC between grazing management treatments. Of the studies that reported an effect of stocking intensity, most reported negative effects of increasing

Table 1
Summary of Australian studies examining impact of grazing management on soil carbon.

Reference	Location	Average Annual Rainfall (mm)	Grazing treatment/s	Soil Carbon*	Depth (cm)	Length of treatment (years)
Alemseged et al. (2011)	Cobar Peneplain, NSW	<500	Light/rotational grazing	0.81%	0–10	>10
			Set stocking	0.71%		
Allen et al. (2013)	Rangelands, QLD	256–1138	Rotational grazing	0.84% 29.04 t/ha	0–30	10
			Cell Grazing	1.02% 34.72 t/ha		
			Continuous grazing	0.56% 17.86 t/ha		
Badgery et al. (2014)	Central West Slopes and Plains, NSW	300–650	Increasing intensity of rotational grazing	28.7–40.4 t/ha	0–30	Various
Bray et al. (2014)	Northern QLD (Charters Tower Region)	640	Moderate stocking rate	20.17 t/ha †	0–30	16
			Heavy stocking rate	18.85 t/ha †		
Cattle and Southorn (2010)	Central Tablelands, NSW	919	High intensity -short duration grazing	2.90%	0–10	3
			Set stocking	2.80%		
Chan et al. (2010)	Central & Southern NSW, North-East VIC	600–800	Continuous/loose rotational grazing	38.5 t/ha	0–30	>10
			Rotational/cell grazing	39.2 t/ha		
Cowie et al. (2013)	Northern Tablelands, NSW	792	Rotational grazing	46.8 t/ha	0–30	>5
			Continuous grazing	40.1 t/ha		>10
Eldridge et al. (2015)	Cobar Peneplain, NSW	250	Low grazing intensity (*shrub*)	1.04%	0–5	1+
			Moderate grazing intensity (*shrub*)	0.86%		
			High grazing intensity (*shrub*)	0.89%		
			Low grazing intensity (*open*)	0.92%		
			Moderate grazing intensity (*open*)	0.93%		
			High grazing intensity (*open*)	0.77%		
Holt (1997)	Northern QLD (Charters Tower Region)	650	Heavy grazing (*Cardigan*)	0.70%	0–7.5	6
			Light grazing (*Cardigan*)	0.70%		
		535	Light grazing (*Hillgrove*)	1.90%	0–7.5	8
			Heavy grazing (*Hillgrove*)	1.80%		
Limpert et al. (2021)	Wimmera Region, VIC	400–600	Continuous grazing	3.80%	0–10	1
			Short duration (crash) grazing	3.50%		
Lodge and King (2006)	North-west slopes, NSW (Barraba)	694	Continuous low intensity	14.75 mg/g of soil	0–5	4
			Continuous high intensity	14.25 mg/g of soil		
			2 paddock rotation low intensity	15.06 mg/g of soil		
			4 paddock rotation low intensity	17.16 mg/g of soil		

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Table 1 (*continued*)

Reference	Location	Average Annual Rainfall (mm)	Grazing treatment/s	Soil Carbon*	Depth (cm)	Length of treatment (years)
	North-west slopes, NSW (Manilla)	654	Continuous low intensity	18.34 mg/g of soil	0–5	4
			Continuous high intensity	18.22 mg/g of soil		
			2 paddock rotation low intensity	16.91 mg/g of soil		
			4 paddock rotation low intensity	19.74 mg/g of soil		
	North-west slopes, NSW (Nundle)	834	Continuous low intensity	28.42 mg/g of soil	0–5	4
			Continuous high intensity	29.56 mg/g of soil		
			Spring/Autumn rest high intensity	29.9 mg/g of soil		
Lodge et al. (2003a)	North-West Slopes, NSW (Barraba)	694	Continuous low intensity	0.396 mg/g of soil.year ‡ 3.56 mg/g of soil.year δ	0–5	0–4
			Continuous high intensity	0.372 mg/g of soil.year ‡ 3.57 mg/g of soil.year δ		
			2 paddock rotation low intensity	0.440 mg/g of soil.year ‡ 3.68 mg/g of soil.year δ		
			4 paddock rotation low intensity	0.502 mg/g of soil.year ‡ 4.02 mg/g of soil.year δ		
Lodge et al. (2003b)	North-West Slopes, NSW (Manilla)	654	Continuous low intensity	0.483 mg/g of soil.year ‡ 4.09 mg/g of soil.year δ	0–5	0–4
			Continuous high intensity	0.476 mg/g of soil.year ‡ 3.89 mg/g of soil.year δ		
			2 paddock rotation low intensity	0.511 mg/g of soil.year ‡ 4.17 mg/g of soil.year δ		
			4 paddock rotation low intensity	0.583 mg/g of soil.year ‡ 4.62 mg/g of soil.year δ		
Lodge et al. (2006)	North-West Slopes, NSW	654	Light grazing 1998 (pre-switch)	761 μg/g	0–5	8
			Strategic heavy grazing 1998 (pre switch)	680 μg/g		
McDonald et al. (2018)	Western NSW (Bourke Region)	307	Moderate intensity rotation (*patch*)	0.53%	0–5	5
			Set-stocking/continuous (*patch*)	0.51%		
			Moderate intensity rotation (*interpatch*)	0.34%		
			Set-stocking/continuous (*interpatch*)	0.35%		
Northup et al. (1999)	Northern QLD (Charters Tower Region)	527	Light grazing (Initially excellent condition)	1.04%	0–7.5	4
			Heavy grazing (Initially excellent condition)	0.83%		
Orgill et al. (2017)	Western NSW (Brewarrina region)	392	Continuous grazing (*claypan*)	13.54 t/ha	0–30	10
			Rotational grazing (*claypan*)	13.65 t/ha		
			Continuous grazing (*no claypan*)	13.97 t/ha		
			Rotational grazing (*no claypan*)	12.85 t/ha		
Orgill et al. (2018)	South eastern NSW (Berridale region)	582	Tactical (set-stock with biannual rest)	33.7 t/ha	0–40**	4

(*continued on next page*)

Table 1 (*continued*)

Reference	Location	Average Annual Rainfall (mm)	Grazing treatment/s	Soil Carbon*	Depth (cm)	Length of treatment (years)
			Cell Grazing	38.4 t/ha		
Orgill et al. (2014)	South-eastern NSW (Boorowa Region)	610	Continuous grazing on introduced pasture Rotational grazing on introduced pasture Continuous grazing on native pasture Rotational grazing on native pasture	57.7 t/ha 48 t/ha 53.6 t/ha 49.4 t/ha	0–70**	15
Pringle et al. (2014)	North-Western QLD (Julia Creek region)	429	10% pasture utilisation 20% pasture utilisation 30% pasture utilisation 50% pasture utilisation 80% pasture utilisation	21.78 t/ha 21.65 t/ha 21.43 t/ha 21.09 t/ha 20.58 t/ha	0–50	16
Pringle et al. (2011)	Northern QLD (Charters Tower Region)	617	Light stocking rate Heavy stocking rate	Carbon data not presented for grazing treatments	0–50	12
Proffitt et al. (1995)	Eastern wheatbelt, WA (Merredin region)	307	Low stocking rate (*traditional tillage*) High stocking rate (*traditional tillage*) Low stocking rate (*minimum tillage* + *gypsum*) High stocking rate (*minimum tillage* + *gypsum*)	0.92% 0.91% 1.16% 1.12%	0–5	1
Sanderman et al. (2015)	Upper and Mid-North region, SA	440	Continuous grazing Rotational grazing	26.3 t/ha 24.4 t/ha	0–10	>7
Sanjari et al. (2008)	South Eastern QLD (Stanthorpe region)	645	Continuous grazing Time-controlled grazing	26.63 t/ha 27.99 t/ha	0–10	5
Sato et al. (2019)	Southern NSW		Continuous grazing Long-conversion rotational grazing Short-conversion rotational grazing Strategic grazing	Carbon data not presented for grazing treatments	0–5	>10 10 5 2
Schatz et al. (2020)	Northern NT (Douglas-Daly Region)	1209	Continuous, variable stocking rates in dry season Continuous, consistent stocking rates in dry season Continuous, variable stocking rates in wet season Continuous, consistent stocking rates in wet season	16.01 t/ha 16.81 t/ha 16.38 t/ha 16.87 t/ha	0–30	9

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Table 1 (*continued*)

Reference	Location	Average Annual Rainfall (mm)	Grazing treatment/s	Soil Carbon*	Depth (cm)	Length of treatment (years)
			Intensive rotational grazing during the dry season	16.92 t/ha		
			Intensive rotational grazing during the wet season	17.35 t/ha		
Segoli et al. (2015)	Northern QLD (Charters Towers region)	636	Moderate stocking rate	0.85%	0–10	16
			High stocking rate	0.88%		
Valentine et al. (2009)	South-east SA (Flaxley region)	767	2.5 cows/ha (*dryland*)	3.90%	0–10	4
			2.9 cows/ha (*dryland*)	3.70%		
			3.3 cows/ha (*dryland*)	4.30%		
			3.6 cows/ha (*dryland*)	4.00%		
			4.1 cows/ha (*dryland*)	3.83%		
			4.1 cows/ha (*irrigated*)	4.53%		
			5.2 cows/ha (*irrigated*)	4.42%		
			6.3 cows/ha (*irrigated*)	4.46%		
			7.4 cows/ha (*irrigated*)	4.55%		
Waters et al. (2017)	Western NSW (Brewarrina region)	392	Continuous grazing (*claypan*)	0.36%	0–30***	>8
			Rotational grazing (*claypan*)	0.39%		
			Continuous grazing (*no claypan*)	0.41%		
			Rotational grazing (*no claypan*)	0.37%		
Young et al. (2016)	Southern New England Tablelands, NSW (Walcha region)	900–1200	Low stocking rates	130 t/ha	0–50	HSR >20
			High stocking rates	128 t/ha		

* Where multiple years are presented in study, the data from the last year are presented here. SOC concentration was either measured by dry combustion or wet chemistry (Heanes or Walkley and Black) depending on the study, and to our knowledge the figure reported relates to the organic carbon of the <2 mm soil.

** Total of all depths.

*** Mean of different depths.

† Carbon value reported in t CO_2e/1000 ha converted into t/ha for comparability here using the formula (t CO_2e/1000ha x ((1/3.6667)/1000)).

‡ microbial carbon.

δ labile carbon.

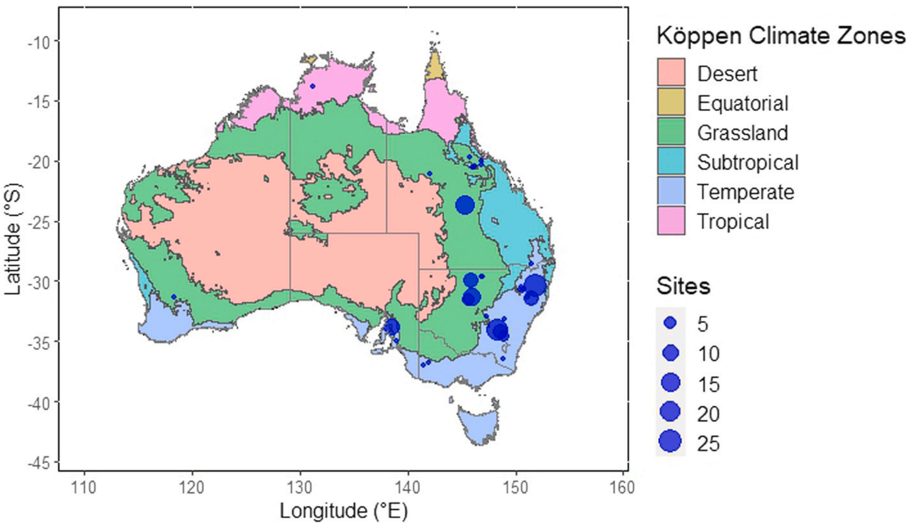

Fig. 2. Location of studies included in review of grazing management impact on soil carbon in Australia, with number of sites sampled and major climate classes based on a modified Koppen classification system (BOM, 2023).

stocking intensity on SOC (Lodge et al., 2006; Allen et al., 2013; Bray et al., 2014). Of the studies that reported a difference in SOC with stocking method, Lodge et al. (2003a, 2003b) reported that continuously grazed treatments had lower soil health scores (including carbon) relative to rotationally grazed treatments (significance not assessed). In contrast, Allen et al. (2013) reported a small negative effect of rotational grazing compared to continuous grazing and Orgill et al. (2014) reported higher SOC stocks at 0–0.7 m under continuous grazing than rotational grazing. However, in this study results were confounded by fertiliser management and no difference was found at 0–0.3 m.

Possible explanations for lack of a significant response in SOC to grazing management in Australia include context-specific responses and influence of climate, soil type, baseline SOC, pasture composition, type of management and soil sampling methodology. Soil, rainfall and pasture type are expected to impact the response of soil carbon to grazing management (McSherry and Ritchie, 2013). Furthermore, climatic variability, such as drought or above average rainfall years, can have a significant influence on plant production (Ibrahim et al., 2018) and thus the rate of SOC sequestration or loss (Derner and Schuman, 2007) and potentially mask changes observed through grazing management. Rainfall variability in Australia is 23% greater than elsewhere in the world (Love, 2005), and this variabilty may also explain a lack of significant response. In our review, grazing practices were grouped into broad classifications (e.g., low, medium, high intensity of grazing) and we were unable to examine impacts of all aspects of management associated with best practice. Teague and Barnes (2017) recommend rotational systems be managed adaptively (AMP grazing), to handle complexity and heterogeneity, over sufficient spatial scale and time frames to achieve and measure change. However, few studies strictly adhere to these principles. Limitations of grazing studies are well recognised, such as confounding of stocking rate between grazing treatments (Briske et al., 2008; McDonald et al., 2019), publication bias (e.g. Hawkins et al., 2017), small spatial scales and short timeframes, rigid management approaches not representative of flexible grazing regimes (Briske et al., 2008; Teague et al., 2013) and relatively few studies have been undertaken utilising grazing systems with large numbers of paddocks (McDonald et al., 2019). Low numbers of studies and often lack of detail reported in studies limited our ability to understand more specific context or management-related responses and explore nuances of the impacts of different grazing management systems in more detail.

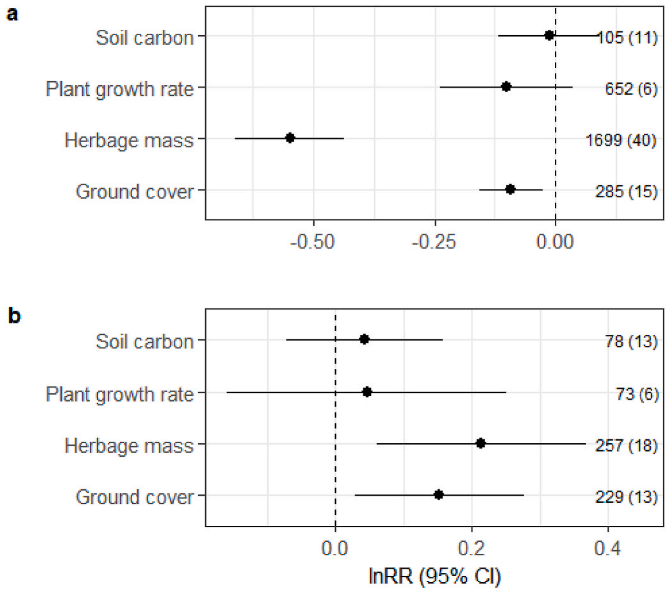

Fig. 3. Results of overall (null) models in meta-analysis comparing (a) low versus high stocking intensity, and (b) continuous versus non-continuous grazing. Points represent the mean values, and black lines represent the 95% confidence intervals. Variables with confidence intervals crossing the dashed line indicate a non-significant response of grazing management on that variable. Points to the left of the dashed line indicate the variable is greater under the control. The number of data points (contrasts) contributing to the analysis of each variable and unique studies included in the analysis is presented for each comparison.

Detection of significant changes in SOC can be challenging as change relative to existing soil carbon stocks is often slow over time, small in size, and spatially variable across multiple scales (Conant and Paustian, 2002). This is further complicated in that grazing systems often have high background levels of SOC compared with cropping systems (Conant et al., 2017). A comprehensive and sophisticated sampling plan is required to detect smaller changes in the stock of organic carbon in soil that could be attributed to grazing management (Henry et al., 2023). Limitations such as sampling depth, measurement of bulk density, duration of a grazing treatment prior to sampling, location and timing of sampling within a rotationally grazed system, and a lack of statistical power of sampling designs have also been identified as potential sources contributing to the variance in research studies (Allen et al., 2013; Robertson and Nash, 2013; Badgery et al., 2020).

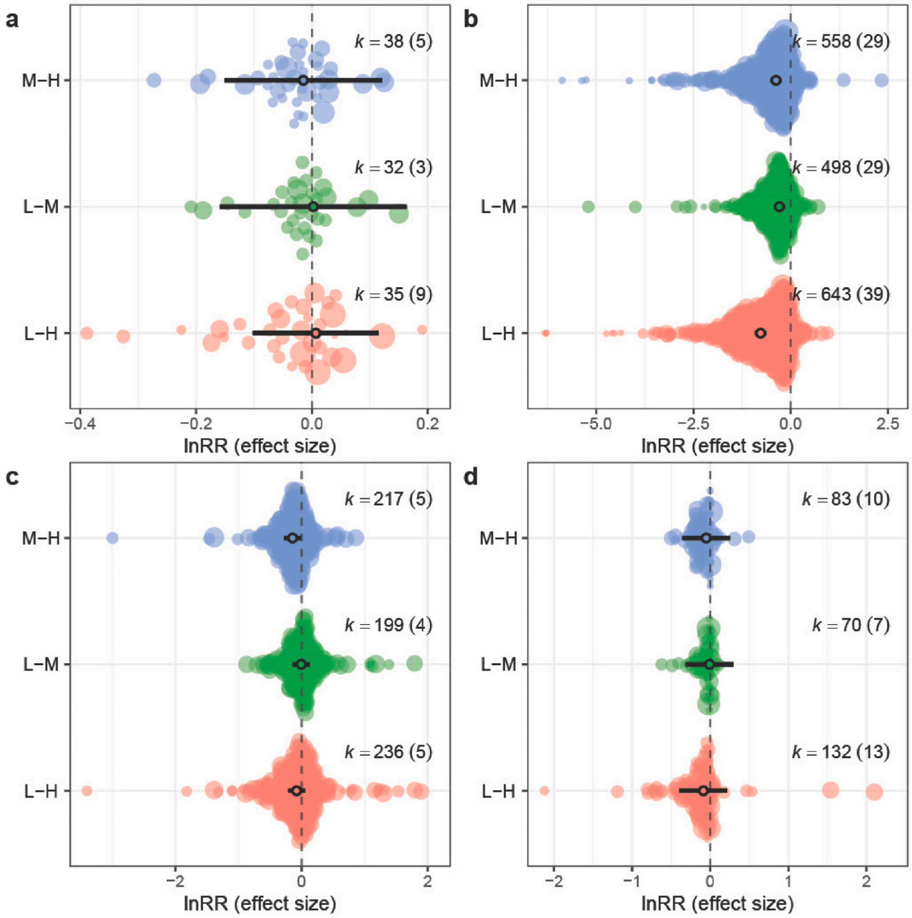

Fig. 4. Effects of stocking intensity on (a) soil organic carbon, (b) plant herbage mass, (c) plant growth rate, and (d) ground cover. L = low stocking rate, M = medium stocking rate, H = high stocking rate. Points represent the mean values, and thick black lines represent the 95% confidence intervals. Variables with confidence intervals crossing the dashed line indicate a non-significant response of grazing on that variable. Points to the left of the dashed line indicate the variable is greater under the lower stocking intensity compared. The number of data points (contrasts) and the number of unique studies contributing to the analysis of each variable is shown (k).

4. Impact of grazing management on above-ground plant production, composition and ground cover

The maximum amount of *in situ* OM supply to agricultural soil is mostly determined by net primary productivity (NPP) (Chapin et al., 2006). Grazing influences NPP directly through a reduction in photosynthetic tissue and indirectly through changes to pasture composition, nitrogen cycling and nutrient availability (Piñeiro et al., 2010). Increasing stocking intensity results in greater plant removal via consumption, and thus reduces OM inputs to soil which can decrease SOC (McSherry and Ritchie, 2013). Furthermore, as stocking intensity increases, leaf-area of plants is reduced and pasture production often decreases (e.g. Stockdale and King, 1980). This reduces carbon dioxide (CO_2) fixation from photosynthetic tissue and can limit belowground carbon inputs (Klumpp et al., 2009; Chen et al., 2015) and has implications for development of other plant traits (Falster et al., 2021). When grazing reduces NPP, pasture regeneration, or detrimentally changes pasture composition SOC stocks may decline (Chapman and Lemaire, 1993). However, where there is sufficient pasture growth to sustain stocking rates, there may be no difference in pasture mass, pasture composition, quality or intake between stocking rates (e.g. Ash and McIvor, 1998). Therefore, grazing management that leaves residual herbage mass at levels that doesn't cause a loss of desirable species is important for accumulation of SOC and sustaining production.

Overall, the meta-analysis estimated herbage mass was on average 42% (CI 35.2–48.4%) lower under the higher compared with lower stocking intensity treatments. Negative effects of higher stocking intensity were significant for all intensity comparisons (Fig. 4b), in all climate regions, and such negative effects increased as annual rainfall increased ($P < 0.05$, Table A.4). Overall, plant growth rate was not significantly different with differing stocking intensity (Fig. 3, $P = 0.148$). When comparing type of intensity, growth rate was 15.5% (CI 3.1–26.4%) greater under moderate stocking intensity compared with higher grazing intensities (Fig. 4c), although the number of studies examining growth rate was low (total n = 6).

Grazing frequency affects the replenishment of non-structural carbohydrates (water-soluble carbohydrates and starch reserves). If the grazing interval of individual plants is too short to accumulate adequate reserves, plant regrowth will be suppressed. If this continues for an extended period, plant dry matter reduces and persistence can decline (Parsons and Chapman, 2000; Slack et al., 2000; Fulkerson and Donaghy, 2001). Overall, herbage mass was 25% (CI 6.2–44.3%) greater under grazing systems that incorporated periods of rest than continuous grazing (Fig. 3). We found herbage mass was on average 40% (CI 10.9–76.7%) greater under high-intensity rotational grazing (>10 paddocks) than continuous grazing, but the difference for low or moderate intensity rotational or seasonal grazing was not significant ($P > 0.05$, Fig. 5b). Inclusion of other moderator variables revealed the impact of stocking method was only significant in temperate regions ($P = 0.003$), the difference increased with annual rainfall ($P < 0.001$) and with the number of rest days per year ($P < 0.001$). The effect of stocking method on plant growth rate was not significant ($P > 0.05$).

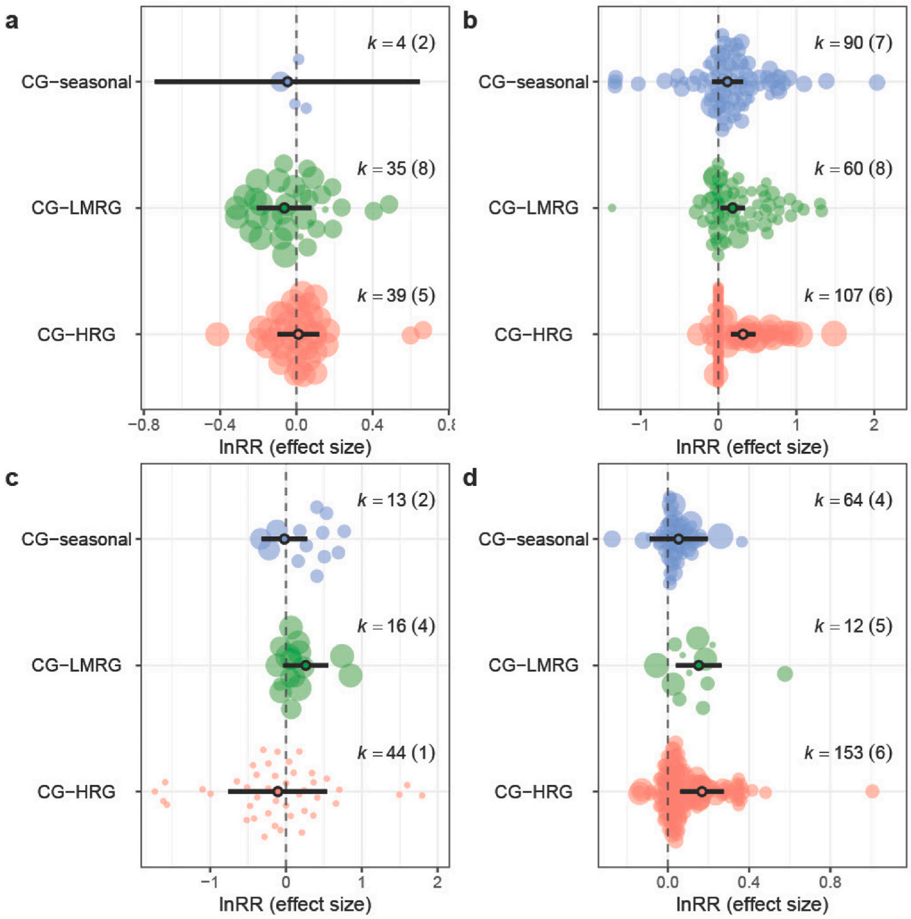

Fig. 5. Effect of stocking method on (a) soil organic carbon, (b) plant herbage mass, (c) plant growth rate, and (d) ground cover. CG = continuous grazing, LMRG = low/moderate intensity rotational grazing (<10 paddocks), HRG = high intensity rotational grazing (>10 paddocks), seasonal = seasonal grazing or resting strategies. Points represent the mean values, and thick black lines represent the 95% confidence intervals. Variables with confidence intervals crossing the dashed line indicate a non-significant response of grazing on that variable. Points to the left of the dashed line indicate the variable is greater under the continuous grazing treatment. The number of data points (contrasts) and the number of unique studies contributing to the analysis of each variable is shown (k).

While our meta-analysis did not reveal a significant impact of stocking method on pasture growth, the potential of high-intensity grazing over short durations and with long recovery periods to increase pasture production is highlighted by Badgery et al. (2017b) in the high rainfall (>600 mm rainfall per annum) a temperate zone of New South Wales (NSW). They found that intensive rotational grazing with a 20-paddock flexible system was able to increase pasture growth of a native pasture by 21% or 1.6 t DM ha^{-1} year^{-1} compared to continuous grazing, with most of the additional growth occurring in spring. In this study there was minimal change in pasture composition between systems. Few studies have examined the impact of stocking method on herbage mass or growth rate in drier (<500 mm) or subtropical environments in Australia.

High stocking intensity can also reduce the botanical composition of the pasture, reduce the survival of desirable pasture species (e.g., Moore, 1970; Freudenberger et al., 1999; Kemp et al., 2000; Ash et al., 2011; Orr and Phelps, 2013) and change the morphology of plants (Clark et al., 1982). Changes in plant botanical composition under grazing management is a key driver of changes in SOC, in particular management that increases the relative proportion or abundance of C_3 to C_4 species (Derner et al., 2006; Derner and Schuman, 2007; Porensky et al., 2016). C_4 grasses generally produce more biomass and have lower soil moisture requirements compared with C_3 grasses and therefore are likely to produce more biomass and persist longer during drought (Taylor et al., 2014; Bell et al. 2013). In Australia, Neal et al. (2013) examined SOC change for a wide range of forages and found that the C_4 forages, Kikuyu (*Cenchrus clandestinus*) and Paspalum (*Paspalum dilatatum*), were the only forages to increase SOC despite other C_3 forages having similar yields. There is often a shift in composition of perennial grasses with increased grazing pressure (Moore, 1970; Ash et al., 1997). This can alter the grassland productivity and the root dynamics, particularly if tap rooted broadleaf species increase. There is also evidence to suggest that increasing pasture diversity can increase SOC sequestration (e.g., Lange et al. 2015; Yang et al., 2019), although these relationships have not been examined in detail in Australia.

Groundcover contributes to SOC accumulation in the surface soil layer (0–0.05 m). Beyond this layer, it is not a major source of organic material in the profile (Bird et al., 2003, 2008; Rees et al., 2005a; Swanston et al., 2005; Fröberg et al., 2007). However, g round cover (both standing vegetation and litter) can influence the rate of decomposition of OM by regulating changes in soil temperature and moisture (Sharafatmandrad et al., 2010). Both the low density of OM, and its concentration in the surface soil make it susceptible to removal through soil erosion. By protecting the soil surface, ground cover can reduce the risk of OM loss via erosion (Facelli and Pickett, 1991). Grazing and trampling of plant material, degradation of soil structure and associated negative feedbacks on soil properties and plant production can reduce ground cover, with these effects expected to be more pronounced as stocking intensity increases (Tongway et al., 2003; Hill et al., 2004; McGregor, 2010; Ash et al., 2011; Hall et al., 2017).

As with herbage mass, our analysis showed ground cover was greater under low intensity grazing, and under systems incorporating rest.

Overall, ground cover was on average 8% (CI 2.7–14.5%) greater under lower compared with higher grazing intensities (Fig. 3). Specifically, the difference in ground cover between low and high stocking intensity was significant ($P = 0.020$, Fig. 4d), but not between low-moderate or moderate-high intensity comparisons. The difference in ground cover with stocking intensity was significant in subtropical climate regions ($P = 0.032$), and it became more apparent as annual rainfall increased ($P = 0.008$). Ground cover was estimated on average to be 16.5% (CI 3.0–31.7%) greater in systems incorporating rest, compared to continuously grazed systems (Fig. 3). This difference was significant in the comparison of low-moderate intensity rotation with continuous grazing ($P = 0.010$, Fig. 5d), and in semi-arid climates ($P < 0.001$). See Table A.6 for further detail on model outputs.

5. Impact of grazing management on below-ground biomass and root allocation

Apart from the soil surface where litter and soil are in contact, the majority of OM in the soil profile is derived from root material and soil microbes (Milchunas et al., 1985; Boone, 1994; Norby and Cotrufo, 1998; Puget and Drinkwater, 2001; Rasse et al., 2005; Jastrow et al., 2007). Where grazing increases root carbon allocation and encourages growth of fast and deep growing fibrous roots, this can have positive impacts on SOC accumulation (Derner et al., 2006; McSherry and Ritchie, 2013). When plants are carbon-limited after defoliation they initially use root and pseudostem reserves to recover their leaf canopy. If defoliation occurs again before reserves have been fully replenished, the plants will prioritise shoot growth over roots, which reduces their root: shoot ratio (Moot et al., 2021), and potentially reduces carbon inputs into the soil. Reduced root biomass and changes in plant community structure can result in a decrease in soil fungi, proliferation of Gram (+) bacteria and accelerated decomposition of particulate organic carbon, decreasing SOC stocks (Klumpp et al., 2009).

The measurement of below-ground biomass (roots) is more difficult than above-ground biomass and few studies have quantified the contribution of SOC from plant roots and the effect of species or management on this (Bolinder et al., 1997; Gill et al., 2002; Rasse et al., 2005). Of the three Australian studies returned through our literature search, Lodge and King (2006) found no significant effect of stocking rate or method (low intensity rotation/seasonal resting) on root mass in native pastures, but in sown pasture, the lower stocking rate pasture had greater root mass; Lodge and Murphy (2006) found few differences in roots between grazing treatments; and in semi-arid NSW, increasing intensity of stocking had a negative impact on root growth of perennial grass and saltbush species (Hodgkinson and Becking, 1977).

Overseas, studies show below-ground net productivity can be influenced by stocking rate and stocking method (Gao et al., 2008; Chen et al., 2015; Wilson et al., 2018). However, vast differences in grazing pressure have also been shown to have little impact on root biomass when monitored over multiple seasons (McNaughton et al., 1998). Further research is required to understand the effects of grazing management on below-ground net primary productivity in an Australian context. While it is generally assumed that perennial grasses contribute more OM to soil compared with annual grasses (Bolinder et al., 1997; Jarecki and Lal, 2003; Culman et al., 2010), no significant difference in root contributions to soil under annual and perennial pastures has been reported in the few Australian studies that have tested this assumption (Chan et al., 2010, 2011).

6. Impact of grazing management on soil nitrogen and soil structure

Many grassland systems are limited by nitrogen availability for part or all their growing period (Rawnsley et al. 2019; Bilotto et al. 2021). The accumulation of organic carbon (C) in soil is closely linked with soil nitrogen availability (Piñeiro et al., 2010; Pringle et al., 2014) with the nitrogen and carbon cycles coupled through processes of accumulation, deposition and storage (Asner et al., 1997). Nitrogen can increase plant productivity (Christie et al. 2014) and reduce soil respiration (carbon loss from soil) (Piñeiro et al., 2010) provided other major nutrients are not limiting (Coonan et al., 2020), thus having a positive effect on SOC accumulation. As grazing pressure increases, the C:N ratio in the soil generally decreases and available N increases. The latter occurs through a higher utilisation of aboveground biomass and lower C content of litter returned to the soil (Wedin, 1999). The challenge is to understand this trade-off in different environments, and to determine at what level of grazing utilisation and incorporation of rest is optimal for building soil OM.

Mineralisation of soil OM, derived from above and below-ground organic material, and atmospheric nitrogen fixation via legumes is an important source of nitrogen in unfertilised pasture systems (Pringle et al., 2014). Reductions in pasture growth or a reduction in the legume component (often preferentially grazed) of pasture as a result of grazing management can therefore create negative feedback loops for total N in these systems (Pringle et al., 2014).

Grazing can also impact soil N through dung, urine (N losses or redistribution) and increased root allocation (thus N retention). Intensive rotational grazing systems are promoted to improve uniformity of the distribution of dung and urine and avoid concentration around livestock camps (Sanjari et al., 2008; Mosier et al., 2021) and could assist in reducing N losses through denitrification. Cattle dung is approximately 10–40% C on a dry weight basis (Eghball et al., 1997; Bol et al., 2000) and cattle urine is approximately 1.5% C or 15,000 mg C/L (Lambie et al., 2012). Livestock excrement has been demonstrated to increase SOC in some parts of grazed fields (Franzluebbers et al., 2000). However, although dung and urine contain a considerable concentration of C, they rapidly decompose in soil (Underhay and Dickinson, 1978; Dickinson et al., 1981; Bol et al., 2000; Hatch et al., 2000). When considering the whole field, the 0–0.30 m soil layer, the rapid rate of excrement decomposition (Bol et al., 2000) and the lower input of OM from livestock excrement compared with plants (Rees et al., 2005a, 2005b), livestock excreta is only a minor source of soil OM.

Trampling by livestock can affect physical and chemical soil properties, including soil structure, water infiltration, soil moisture availability and nutrient cycling (Greenwood and McKenzie, 2001; Byrnes et al., 2018; Jiang et al., 2020). These impacts are generally greater in the soil surface layers and under higher grazing pressure (Greenwood and McKenzie, 2001). These factors in turn also affect root growth and plant productivity, creating a negative feedback cycle resulting in further degradation of soil and losses of carbon (Byrnes et al., 2018). Reduced porosity of soil due to compaction can also lead to changes in microbial communities and decrease microbial activity. Soil ecology is important in stabilising SOC, thereby reducing SOC loss and improving soil quality (Jastrow et al., 2007; Bhattacharyya et al., 2022).

Hoof action of livestock is suggested to break hard setting soil crusts, thus facilitating nutrient cycling, microbial activity, and carbon sequestration, but this has not been adequately tested and needs careful attention where biological crusts are dominant (Hawkins, 2017). This phenomenon also varies between land types and may be less relevant in Australia where there were no native hard-hoofed animals prior to colonisation (Garnett et al., 2017).

7. Co-benefits of managing grazing for SOC accumulation

SOC is linked with provisioning, regulating and supporting ecosystem services (Adhikari and Hartemink, 2016). In particular, soil OM can increase soil stability (and associated positive functional changes including increased soil porosity, aeration and water infiltration & retention) by promoting the formation of soil aggregates, which has subsequent benefits for reducing soil erosion, soil degradation, and improving productivity of soil (Masciandaro et al., 2018). Furthermore, soil OM is associated with increased soil biodiversity, nutrient cycling and soil fertility, primary productivity and economic benefits associated with increased pasture and livestock production (Pringle et al., 2011; Meyer et al., 2015; Waters et al., 2017; Masciandaro et al., 2018; Orgill et al., 2018). Increasing soil OM can also have considerable influence on regulating atmospheric CO_2 levels, and thus an important role in climate regulation and may provide land-managers access to carbon markets.

The review identified reducing stocking intensity, and incorporating periods of strategic rest into grazing systems as potentially benefitting key drivers of SOC accumulation, including above-ground biomass, perennial and N-fixing species, above and below-ground NPP, ground cover and soil structure. Incorporation of rest periods, which require some form of animal rotation, has been identified as a practice which supports long-term pasture productivity and sustainability (Hunt et al., 2014) and can increase production per hectare (Waller and Sale, 2001; Graham et al., 2003; Badgery et al., 2017a; McDonald et al., 2019). However, other studies have shown that when stocking rate is accounted for, there is limited support for any effect of intensive rotational grazing systems on animal performance (Briske et al., 2008; Norman et al., 2010; Schatz et al., 2020) or profitability (Broadfoot et al. 2017; Amidy et al. 2017). Reducing stocking rate can increase production per head (Jones and Sandland, 1974), but is also associated with a reduction in farm profitability (Amidy et al., 2017). Impacts of stocking rate and method on biodiversity in Australia are less clear and context-specific. Benefits for the conservation of threatened species or other desired species may be achieved when the timing of grazing and grazing pressure is targeted to the life-cycle of the desired species and to discourage less desirable species (e.g. Lodge et al., 1999).

8. Potential role of improved grazing to increase soil carbon to meet CN30

While we have not demonstrated soil carbon sequestration from improved grazing strategies, what would be needed to offset livestock emissions? Livestock GHG emissions from a 1200 ha grazing property used for wool production and carrying 7–9 DSE/ha in Victoria, Australia were estimated to be 2520 t CO_2e/year (Browne et al., 2014). This would require 2.1 t CO_2e or 0.57 t C/ha/year to be stored in the soil to fully offset the livestock emissions. While this rate of sequestration is in the range of what is achievable under optimal conditions and management, more intensive systems would generally have higher emissions and require greater sequestration (Doran-Browne et al., 2017). Additionally, there are several constraining factors that contribute to rare occurrence of optimal conditions for soil carbon sequestration.

Over time, soil carbon sequestration reaches an equilibrium level based on site conditions and management (Godde et al., 2020; Smith et al., 2014), which has implications on spatial and temporal potential for optimal soil C sequestration. 1) In areas with already high levels of SOC methods to increase SOC further are limited; 2) in areas with low to moderate carbon, over time the sequestration associated with management will slow as the new equilibrium is reached; and 3) management implemented to increase SOC needs to continue in perpetuity to maintain the new equilibrium SOC amount. Other changes in conditions, including climate change, also impact on the potential to sequester soil carbon (Meyer et al., 2018), and soil carbon sequestration is prone to substantial seasonal fluctuations (Badgery et al., 2020). Compounding this is the difficulty in monitoring the potentially small changes over large diverse areas (Robertson and Nash, 2013). The uncertainty involved leads to accounting deductions, further reducing the carbon reduction that can be claimed.

It is also important to consider off-site impacts associated with displaced production if a reduction in production is required to increase SOC. These off-site impacts tend to outweigh the local effects for grazing management by a factor of 6–8 (Balmford et al., 2018). For these reasons, management of grazing strategy alone is considered a high-risk option to offset emissions in the Australian livestock industries and will have a limited role either in time or in area of application. This supports the suggestion of Herrero et al. (2016) that sequestration of SOC in grazing systems be considered a co-benefit of improved productivity and ecosystem services, but not the primary objective of management.

9. Conclusions and research recommendations

Despite limited direct evidence of the impact of grazing management on SOC under Australian conditions, there is evidence stocking intensity and method can positively affect the key drivers of carbon sequestration, including above and below-ground biomass, plant growth rate, groundcover, soil structure and soil nitrogen. In managing the grazing system to improve these key drivers the conditions for sequestering carbon are enhanced. The results highlight the context-specific nature of grazing management impacts and the complexity of landscapes, grazing systems, and farmer decision making. Further research is warranted to better understand the environments and management approaches that are conducive to greater carbon sequestration in Australian soils. Plant growth rate, below-ground plant production and root dynamics are recognised as key drivers of carbon sequestration in grazing systems. However, there is little research in Australia that has explored the impact of grazing management on these factors, and it is recommended future research focuses on the response of these drivers to grazing management and includes these as explanatory variables in soil carbon research. Furthermore, grazing systems are complex, and integrated with other landscape specific practices (e.g. addressing soil constraints) that increase inputs of organic material into soil and influence stability of organic carbon in soil, research incorporating the impact of these additional management practices may be informative. As technology develops, sampling costs decrease and methodologies for sampling improve, changes in SOC under contrasting grazing management may become more apparent. However, due to temporal and spatial limitations for improved grazing strategies to store soil carbon or to monitor change in soil carbon with confidence, it is unlikely to be a cornerstone strategy for the Australian Livestock Industry to mitigate livestock emissions.

Funding

This work was supported by Meat and Livestock Australia [grant number B.CCH.2121] and the Australian Wool Innovation (Project Number OF-00614).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sarah McDonald, Warwick Badgery, Simon Clarendon, Susan Orgill, Katrina Sinclair, Rachelle Meyer, Dominique Bowen Butchart, Richard Eckard, David Rowlings, Peter Grace, Natalie Doran-Browne, Ainslie Macdonald, Michael Wellington, Anibal Nahuel Pachas, Martin Amidy, Rowan Eisner, Matthew Harrison reports financial support was provided by Meat and Livestock Australia. Matthew Harrison reports financial support was provided by Australian Wool Innovation.

Data availability

Data will be made available on request.

Acknowledgements

The Authors are thankful for the assistance of Yohannes Alemseged and Ian Toole for assistance in the initial literature search, Mick Rose for providing helpful advice and guidance regarding methodology of the meta-analysis and Lachy Ingram, Aaron Simmons and the anonymous reviewers for reviewing drafts of this paper and providing helpful comments and advice.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119146.

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