

Review

Response of Grazing Land Soil Health to Management Strategies: A Summary Review

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Abstract: Grazing land ecosystem services including food provision and climate regulation are greatly influenced by soil health. This paper provides a condensed review of studies on the response of three important soil properties related to soil health to grazing land management: water infiltration, carbon (C) sequestration, and nitrogen use efficiency (NUE). Impacts of management strategies that are often used in grazing lands are discussed in this review including vegetation composition, grazing methods, and other factors such as fertilizer use and climatic conditions. In general, proper grazing management such as continuous moderate grazing and rotational/deferred-rotational grazing with low or moderate stocking rates tends to benefit all three soil properties. Water infiltration can usually be increased with full vegetation cover, increased soil C, and aggregate stability, or be decreased with greater soil bulk density. Adoption of highly productive plant species with faster turnover rates can promote soil C sequestration by increasing C input. However, excessive C removal from ecosystems due to overgrazing or improper soil fertilization management results in higher C loss, which can have detrimental effects on soil C sequestration. Proper stocking rate and a balanced manure/fertilizer management was found to be critical for enhancing NUE. Grazing land management sometimes simultaneously influence the three soil properties. Techniques that can increase soil C such as introduction of high productive plant species can often promote water infiltration and soil nitrogen (N). Some other practices such as adoption of N fertilizer may enhance C sequestration while being detrimental to NUE. An integrated management plan for a specific location or farm should be considered carefully to improve soil health as well as ecosystem production. This review provides farmers and policy makers the current state of general knowledge on how health-related soil processes are affected by grazing land management.

Keywords: carbon sequestration; water infiltration; nitrogen use efficiency; grazing land management

1. Introduction

Grazing lands comprise 3.6 billion ha globally and various management strategies are adopted on these lands to meet the demand for greater productivity and climate resilience [1]. Ecosystem functions such as forage production, nutrient cycling, carbon (C) accumulation, root processes [2–4], and the ecosystem sustainability [5] can be enhanced if a good grazing land management plan is adopted. Grazing management practices can also impact soil properties (e.g., [6]), which play an important role in determining ecosystem productivity and sustainability [7,8]. As a result, adopting improved management for building soil health, which is defined as the sustainable ability of soil to function as a vital living ecosystem that can continuously support plants, animals, and humans [9] is critical. Specifically, three important components of soil health including soil water infiltration, C sequestration,

and nitrogen use efficiency (NUE) present water, carbon, and nutrient dynamics and are strongly influenced by the grazing management practices.

Soil water infiltration, which regulates the ecosystem water cycle and indicates the soil's resistance to erosion, can be influenced by grazing land management (e.g., [10]). When management leads to a decrease in water infiltration, it can cause increased runoff and soil erosion, which are detrimental to ecosystem functions such as livestock productivity [11]. Thus, understanding and improving soil water infiltration is particularly important especially in dry lands [12], which accounts for about 40% of the global land area [13,14]. Past studies investigating the response of soil water infiltration to grazing land management strategies are very few and are often conducted in specific farms or rangelands, which are not representative to the entire grazing lands in the world.

Soil C regulates nutrient and water supply, soil erosion, and soil physical and chemical properties [15] and can also be strongly influenced by grazing land management (e.g., [16]). Under different management, soil C sequestration can be influenced by changes in both C inputs and outputs. In grazing lands, soil C accumulation accounts for ~90% of the total ecosystem C [17]. Therefore, a slight change in soil C in grazing lands can have a large impact on the global C cycling. Considering the benefits of soil C sequestration on ecosystem functions such as sustaining productivity and mitigating climate change, knowledge on better ways to manage grazing lands is highly needed. However, contradictory results on the response of soil C to similar grazing land management are often reported.

Nitrogen use efficiency is the ability of plants to use available nitrogen (N), which determines the yield per unit of N input and can be affected by grazing land management such as plant species (e.g., [18]), fertilizer management (e.g., [19]), and grazing activities (e.g., [20]). Improper management such as overuse of synthetic fertilizers can increase the cost of production as well as N loss from the ecosystem, which leads to water contamination and greenhouse gas emissions. Thus, improving NUE on grazing lands is essential for both economic and environmental benefits.

Considering the need for achieving the overall impacts of grazing land management towards improved soil health, we reviewed existing refereed manuscripts investigating the changes in infiltration, C sequestration, and NUE by different grazing land management strategies including the vegetation structures (e.g., different grass species, legume incorporation, conversion of forest to pastures, afforestation), grazing methods (e.g., grazing exclusion, grazing intensity, rotational grazing), and other land management approaches (e.g., fertilization, irrigation, prescribed fire) in tandem with climatic and soil factors (Table 1). The goal is to provide the readers a quick and condensed review of the grazing management strategies to improve the sustainability of grazing lands.

Table 1. Grazing land management options influencing the three soil properties surveyed in this review.

	Grazing Management	Vegetation Composition	Other Factors
Infiltration	Grazed vs. enclosure Intensity (heavy vs. moderate vs. light grazed) Frequency (continuous vs. rotational grazed)	Trees/shrubs vs. bunchgrasses vs. sodgrasses Grass vs. forbs Conversion from woodlands to pastures	Management duration Topography Burning Animal type
Carbon Sequestration	Grazed vs. enclosure Intensity (heavy vs. moderate vs. light grazed) Frequency (continuous vs. rotational grazed)	Legume incorporation Conversion from cultivated lands to pastures Crop-pasture rotation Pasture establishment after deforestation	Fertilization Irrigation Burning Management duration Soil type Climate
Nitrogen Use Efficiency	Grazed vs. ungrazed intensity (heavy vs. moderate vs. light grazed)	Crop vs. pasture Legume incorporation C4 vs. C3 grass	Fertilization

2. Methods

The literature was retrieved in 2017 by searching the Google Scholar using the following search words: “grazing lands/grasslands management,” “soil health,” “soil water infiltration,” “soil C sequestration,” and “nutrient/ N use efficiency.” No restrictions were imposed for article selections on study locations or the year of publication to prepare this review as long as the articles were written in the English language and focused on grazing land management effects on the three soil properties considered in this review. The reference list of articles used to derive the statements and conclusions in the present review are shown in Appendix A. If there is more than one article with similar conclusions, one or two of the latest ones were cited in the text as example references. The majority of these studies are peer-reviewed articles and books. Study sites reported in the articles were mapped and shown in Appendix B (Figure A1 for soil water, Figure A2 for soil C, and Figure A3 for NUE). If referred articles showed data from a specific country, the coordinates of the corresponding country capital were included in the maps. For comparative analysis of water infiltration, we only selected articles in which the water infiltration rate was given in cm hr^{-1} or can be converted to cm hr^{-1} (Table 2). The infiltration rate in Table 2 is shown as the percentage of difference between the two management options, which was calculated as:

$$\text{Percentage of infiltration rate difference (\%)} = (\text{Management 1 infiltration rate} - \text{Management 2 infiltration rate}) / \text{Management 2 infiltration rate} \times 100\% \quad (1)$$

Articles describing soil C was selected if the data were in Mg C ha^{-1} or can be converted to Mg C ha^{-1} (Table 3). The C sequestration rate after management changes shown in the Table 3 was calculated as:

$$\text{C sequestration rate (Mg C ha}^{-1} \text{ yr}^{-1}) = (\text{Management 1 C content} - \text{Management 2 C content}) / \text{years of management}$$

Different parameters associated with NUE were selected from the literature including NUE (%), N balance (kg N ha^{-1}), N uptake (kg N ha^{-1}), inorganic N (mg N ha^{-1}), and the mineralization rate ($\text{mg N kg}^{-1} \text{ d}^{-1}$) (Table 4). The difference of each parameter between two types of management in Table 4 was calculated as:

$$\text{Difference in parameters} = \text{Management 1} - \text{Management 2}$$

3. Soil Water Infiltration

Soil water infiltration refers to the rate of rainfall or the irrigation water that enters the soil. To sustain soil water infiltration, vegetation cover is critical since it protects soil from high intensity rainfall [21] and improves soil aggregation and other physical properties [22]. Compacted soils negatively influence soil water infiltration rates due to the decreased amount and size of surface pore space [23]. Thus, water infiltration is negatively affected if the vegetation cover is considerably decreased due to intensive grazing [24,25] and/or the soil bulk density is increased by animal trampling [26].

Because of the negative effect of grazing on infiltration rates (e.g., [25]), more recent studies have found that using long-term exclosures can be an effective management strategy to improve hydrological cycling, which can increase water infiltration by 11% to 132% (Table 2). Since mismanagement of grazing lands (e.g., overgrazing and undesirable vegetation) can result in soil compaction and water run-off, a balanced livestock management on grazing lands are critical in providing food provisioning to animals while sustaining/improving soil water infiltration and conservation.

Table 2. Water infiltration rate as affected by grazing land management practices.

Management	Infiltration Rate (%) §	Location	Precipitation (mm)	Temperature (°C)	Soil Type	References
Exclosure vs. Grazed	11 to 132	Texas, USA	572	9 to 30	Clay	[27]
		New Mexico, USA	384	−6.7 to 18.9	Fine loam	[28]
		Arizona, USA	350	N/A	N/A	[29]
		Queensland, Australia	452 to 828	19 to 24	Loamy sand to clay loam	[30]
		Eastern Cape, South Africa	373	8 to 21	Silt loam	[31]
Light vs. Heavy Grazed	0 to 119	Colorado, USA	305	N/A	Sandy loam	[32]
		Texas, USA	609	N/A	Silty clay	[33]
		Addis Ababa, Ethiopia	650	N/A	Clay	[34]
		Oklahoma, USA	900	N/A	Loam, silt loam	[35]
Moderate vs. Heavy Grazed	0 to 116	Texas, USA	428 to 556	N/A	Silty clay	[21]
		Colorado, USA	305	N/A	Sandy loam	[32]
		Texas, USA	609	N/A	Silty clay	[33]
		Addis Ababa, Ethiopia	650	N/A	Clay	[34]
		Oklahoma, USA	900	N/A	Loam, silt loam	[35]
		Texas, USA	156 to 1054	N/A	Silty clay	[36]
Rotation vs. Continuous Grazed	−20 to 136	Texas, USA	572	9 to 30	Clay	[27]
		New Mexico, USA	384	−6.7 to 18.9	Fine loam	[28]
		Texas, USA	680	4 to 29	Clay, clay loam	[37]
Tree vs. Bunchgrass	18 to 30	Texas, USA	624	N/A	Clay	[38]
		Texas, USA	156 to 1054	N/A	Silty clay	[39]
Bunchgrass vs. Sodgrass	12 to 93	Texas, USA	428 to 556	N/A	Silty clay	[21]
		Texas, USA	680	4 to 29	Clay, clay loam	[37]
		Texas, USA	624	N/A	Clay	[38]
		Texas, USA	156 to 1054	N/A	Silty clay	[39]
Silvopasture vs. Forest	−38	Oregon, USA	N/A	N/A	Silty clay	[40]

§ The range of difference of first management from second management (e.g., infiltration rate in exclosure is 11% to 132% higher than that in grazed areas). N/A means the information is not available from the article.

3.1. Grazing Intensity and Frequency

Overgrazing is one of the most common mismanagement of the grazing lands. Besides the negative impacts in terms of soil compaction and loss of vegetation cover, overgrazing may also influence the botanical composition, changing it from long-lived perennials to annuals and forbs resulting in lower productivity [41], and higher land degradation [42]. Thus, adopting appropriate grazing methods can be an effective way to improve soil water infiltration while maintaining livestock productivity. Water infiltration rates can be decreased with higher stocking rates (e.g., [43]) especially with heavy-weight cattle [34]. In contrast, the water infiltration rate under light or moderate grazing can be as high as 119% greater than that under heavy grazing (Table 2). However, the benefits of decreased stocking rates on water infiltration may only be experienced in soils with higher clay and silt contents because soils with higher sand content are generally not vulnerable to compaction from trampling [34].

Besides adjusting grazing intensity, managing grazing frequency such as rotational grazing can also benefit hydrological properties relative to overgrazing by lowering runoff [44], increasing ground cover [45], and increasing water infiltration [46] to decrease soil erosion and nutrient losses [47]. Specifically, multipaddock grazing [46] and deferred-rotational grazing [27,38] systems were found to benefit water infiltration in some studies. However, the benefit of rotational grazing on infiltration may be offset by higher grazing intensity [35]. The infiltration rates under rotational grazing can be 20% lower to 136% higher than continuous grazing (Table 2). This wide variability of the rotational grazing effect on water infiltration in the literature is mainly attributed to the different stocking rates

used in each ecosystem. In the study [27], the rotational grazing system had 136% greater infiltration rates than continuous grazed systems despite having similar animal types, study region, vegetation composition, and equal stocking rates (~5 ha/AU). However, it should be noted that, in this study, the continuously-grazed system was heavily stocked for 27 years while the rotational grazing system was rotationally grazed for only seven years after 20 years of continuous grazing under a moderate stocking rate (16.2 ha/AU). The study [27,28] showed that rotational grazing at a heavy stocking rate can have a lower infiltration rate than continuous grazing at a moderate rate. Other factors such as lower precipitation or a higher stocking rate in the sampling area due to the unevenly distributed livestock movements in the rotational grazed area can result in a lower infiltration rate than continuous grazing [28]. These results indicate that management approaches encompassing both proper grazing intensity and frequency are important for improving soil water infiltration and that the grazing methods need to be adjusted according to the specific ecosystem conditions such as climate.

The response of hydrologic processes to grazing methods is influenced by other factors such as management duration [29], topography [34], fire [25], and animal types [12], which are important to consider when determining the grazing intensity and frequency for a specific farm for better water management. For instance, a study on Arizona grasslands observed that grazing exclusion for 54 years had a greater infiltration rate than no-grazing for 25 or 10 years [29]. A study conducted on Ethiopian highlands [34] revealed that proper management such as decreasing the grazing intensity or improving plant cover largely alleviates an adverse effect of grazing in steep than flat lands. Prescribed early fire tended to decrease water infiltration [25] and larger size animals can decrease the water infiltration rate more than smaller size animals such as rabbits and kangaroos [12]. Despite this complexity, the majority of earlier studies have demonstrated that heavy grazing has a detrimental impact on soil water infiltration while light and moderate grazing can be beneficial. Rotational grazing has the potential to improve water infiltration even though this benefit can be nullified if it is associated with heavy grazing.

3.2. Vegetation Composition

The vegetation type controls water infiltration rates by influencing soil properties [36]. Water infiltration rates are usually the highest under trees and shrubs (15.1–20 cm hr⁻¹), which is followed by bunchgrasses (8.4–17 cm hr⁻¹) and the lowest under sodgrasses (6–13 cm hr⁻¹) (Table 2). It was also shown that the infiltration rate is higher under grass cover than under annual forbs because grass has lower decomposition rates, which may protect the soil from raindrop for a longer time [48]. When both shrub canopy and grass pastures were studied, the grazing effects on water infiltration were not detected [38]. However, the vegetation's impacts are influenced by grazing intensity if only grass pastures are studied. For example, bunchgrass pastures could have lower infiltration rates than sodgrass pastures under heavy grazing conditions [21]. Furthermore, the vegetation cover is the key factor determining water infiltration. One study in Cardigan, Australia found that, if the conversion from native woodlands to managed pastures can increase vegetation cover, it can decrease the runoff by 30% [49]. Thus, grass species selection in grazing pastures for greater soil water infiltration should also be considered while making a decision on grazing intensities and frequencies.

4. Soil C Sequestration

Grazing lands can offset about 20% of the annual CO₂ emitted from land use changes [1]. Therefore, these lands play an important role in mitigating greenhouse gas emission. Soil C sequestration in grazing lands is controlled by above-ground and below-ground plant composition and inputs, C lost from animal consumption, soil characteristics, C distribution in labile and stable pools, and litter and root deposition and decomposition rates [50–59]. Management strategies such as adjusting stocking rates to regulate the vegetation utilization rate [16] and adoption of improved grass species or conversion from agricultural lands or woodlands to grasslands would increase C input and potentially promote soil C accumulation [3,60]. However, since soil C decomposition rates can also be

influenced by management, the response of both C input and loss should be evaluated to assess the overall effect of grazing land management on C sequestration.

Based on published studies, the C sequestration rate under improved grazing managements can be from 0 to 4.2 Mg C ha⁻¹ yr⁻¹ (Table 3). Earlier reviews on soil C responses to grazing land managements were regional-specific. For example, References [2,3] mainly focused on countries such as Australia, the United Kingdom, New Zealand, Canada, Brazil, and the United States, which encompasses only 26% of the world's grazing land area. Some other reviews such as Reference [61] considered only one country. However, geographic location was not a factor in selecting articles for the current review.

Table 3. Soil carbon (C) sequestration as affected by grazing land management practices.

Management	C Sequestration (Mg C ha ⁻¹ yr ⁻¹)	Location	Precipitation (mm)	Temperature (°C)	Soil Type	Reference
Exclosure vs. Grazed	−1.5 to 4.2	Wyoming, USA	384	N/A	Sandy loam	[52]
		Wyoming & Colorado, USA	366	N/A	Sandy loam	[54]
		Alberta, Canada	310 to 500	N/A	Sand to clay loam	[62]
		Colorado, USA	325	N/A	Fine sandy loam	[63]
		Inner Mongolia, China	366	5.1 to 7.7	Sandy	[64]
		Lanzhou, China	382	6.7	Sandy loam	[65]
		Wyoming, USA	200 to 210	N/A	Sandy loam to clay loam	[66]
		Queensland, Australia	150 to 500	>36 in summer, <6 in winter	Loam, clay, sand	[67]
		Nagqu Prefecture, China	410 to 480	−1.2 to −0.6	Loam to clay	[68]
		Sichuan, China	749	−36 to 26	Silt loam	[69]
		New South Wales, Australia	582	4 to 18	Sandy clay	[70]
		Borana rangeland, Ethiopia	436	19 to 26	Sandy clay loam	[71]
Borana rangelands, Ethiopia	238 to 896	17 to 28	Sandy clay loam	[72]		
Light vs. Heavy Grazed	−0.22 to 2.2	Wyoming, USA	384	N/A	Sandy loam	[52]
		Wyoming & Colorado, USA	366	N/A	Sandy loam	[54]
		Sichuan, China	752	−10 to 11	Loam to clay	[73]
		Wyoming, USA	425	N/A	Fine loam	[74]
		Inner Mongolia, China	280	3.4	Loamy sand	[75]
Moderate vs. Heavy Grazed	−1.4 to 1.8	North Dakota, USA	N/A	N/A	Silt loam	[51]
		Sichuan, China	752	−10 to 11	Loam to clay	[73]
		Inner Mongolia, China	280	3.4	Loamy sand	[75]
		North America (Review)	N/A	N/A	N/A	[76]
		North Dakota, USA	414	−11 to 21	Silt loam	[77]
Pasture & Legume Incorporation vs. Crop	0.3 to 1.6	Australia, the United Kingdom, New Zealand, Canada, Brazil, and the United State (Review)	N/A	N/A	N/A	[2]
		South Dakota, USA	380	13	Loam, fine sandy loam	[78]
		Goiás, Brazil	280 to 1500	23	Clay	[79]

The range of the C sequestration rate of first management from second management (e.g., exclosures result in −1.5 Mg C ha⁻¹ yr⁻¹ to 4.2 Mg C ha⁻¹ yr⁻¹ soil C compared to grazed areas). N/A means the information is not available from the article.

4.1. Grazing Intensity and Frequency

Grazing may decrease soil C input through animal consumption of forages and promotion of C emissions [80]. Grazing activities may decrease soil porosity and increase bulk density [69,81] to limit gas exchange, which can be detrimental to plant production and then negatively affect C accumulation. Hence, a viable strategy for promoting soil C sequestration is grazing exclusion especially for areas under long-term over-grazing history [72,82]. In a study conducted in the Qinghai–Tibetan Plateau, it showed that grazing decreased 33% soil organic C (SOC) at the top 10 cm when compared to grazing enclosure for five years [69]. However, based on past studies, grazing exclusion may not always result in soil C sequestration [83] because this practice is often associated with an invasion of forbs or weeds with the shallow root system [52,84]. Sometimes grazing adds carbon to the soil by improving plant productivity [85], stimulating tillering [86], promoting compensatory photosynthesis after defoliation [87], and increasing litter incorporation through trampling [58]. The stimulated plant production through grazing can contribute to greater C input, which results in low soil C sequestration under a grazing exclusion [70,88]. In addition, grazing can change the vegetation composition through animal diet selection [89], shoot and root C allocation (e.g., [54]), or microbial activities [90], which will influence both the C input quantity and quality and decomposition rates in different ways. As a result, soil C stocks can respond positively or negatively to grazing methods. Past studies showed that grazing increased [70], decreased [69], or did not affect [66] soil C stocks when compared to un-grazed or grazing exclusion strategies (Table 3). Thus, the grazing exclusion strategy can benefit soil C sequestration in areas under long-term overgrazing [82] while the effect may not be positive in other locations.

Due to this complexity, adoption of proper grazing methods such as the appropriate grazing intensity and frequency is the key to enhance soil C sequestration while sustaining ecosystem productivity. If the stocking rates were low in the grazed areas, they may have a similar amount of soil C as exclusions [66,71]. Several studies indicated that slight or moderate grazing intensity can usually increase aboveground and belowground biomass or plant biodiversity [91–93] or improve soil properties and root dynamics [94], which can promote C sequestration (e.g., [76]). Differently, heavy grazing often decreases soil C accumulation due to a lower infiltration rate and higher erosion or soil compaction, which can limit plant production [25,95,96]. The adoption of light and moderate grazing can sequester as high as 2.2 Mg C ha⁻¹ yr⁻¹ more C compared to heavy grazing (Table 3).

Some studies, however, reported increased soil C content under heavy grazing due to the shift in plant composition such as changing to C4 grass, which can allocate more below-ground carbon [54]. Thus, it is also possible that the light grazing can lose SOC at a rate of 0.22 Mg C ha⁻¹ yr⁻¹ when compared to heavy grazing (Table 3). Despite this, moderate grazing, in general, showed promise for long-term accumulation of soil C due to the favorable effect on biodiversity and plant structure [97].

In contrast to the grazing intensity, rotational grazing can promote C sequestration [98] by increasing plant productivity through a recovery period [99]. For example, grazing increased SOC stocks by 30% at 0 to 30 cm than grazing exclusions in a study conducted in New South Wales, which may be due to the promoted root turnover and forage production under grazing because there was 4 to 6 weeks of rest over late spring/summer and late summer/autumn to allow seed set and recruitment. However, some studies reported a decreased effect [100] or no effect of rotational grazing on soil C sequestration [98] due to the interactive effect of other factors such as vegetation composition, climate conditions, fertilizer application, and soil type. Thus, grazing intensity should be adjusted to sustain or improve soil C sequestration when the rotational grazing method is used.

4.2. Vegetation Composition

Adoption of a highly productive plant species with faster turnover rates usually results in higher soil C stocks. For instance, legume incorporation in pasture lands can increase SOC since the legume can promote N fixation to increase aboveground biomass and soil C input [78,101,102]. Including C4 grass in C3 grasslands under a warm and humid climate can enhance C sequestration because

C4 grass can be more productive under this climate condition and benefit the net ecosystem carbon exchange [103]. Conversion from cultivated lands to pastures [2] or crop-pasture rotations [79] can often exhibit a positive effect on SOC accumulation because of the higher forage litter input.

The conversion of the forest to pasture was also found to increase C sequestration in soils by 0–41% [104–107] due to the redistribution of more C from aboveground biomass to the soil. Effects of the pasture establishment after clearing the forest of soil C can be influenced by grazing intensity, which can be decreased by 0% to 26% if the pastures are under higher stocking rates [108] while it can be increased under low stocking rates [109]. The plant species adopted after afforestation determines the response of soil C. It was found that planting pines in pastures can decrease soil C [110–113] while planting a broadleaf tree can benefit soil C sequestration in native pastures [104].

4.3. Fertilization, Irrigation, Burning, and Other Factors

Applying fertilizer on grazing land can improve plant production because nutrients are needed to meet the plant growth demand [114]. At the same time, litter and root production and turnover can be increased to promote soil C sequestration [50,60,61,115]. Conversely, ecosystems under limited soil nutrients can decrease C sequestration due to the competition between plant and soil microbes [116–118]. It was also demonstrated that use of organic fertilizers can lead to a higher C sequestration rate than inorganic fertilizers (0.82 vs. $0.54 \text{ Mg C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) [3] because of the increase C input from organic fertilizers. However, organically fertilized systems often have low NUE due to poor management [119]. It was reported that fertilizer inputs decrease soil C in ecosystems with higher initial soil C such as New Zealand dairy farms [120]. A prudent fertilizer management with appropriate selection of the fertilizer type and rate is critical to improve C sequestration.

Together with the fertilizer application, irrigation can also improve soil C [121,122]. It should be noted that the benefit of irrigation on soil C may only be realized in dry areas [50]. Conversely, excess water may decrease soil C accumulation [50] because of higher soil respiration [123] or lower C input (root biomass) to soil [124,125]. Moreover, the response of soil C to irrigation sometimes may only be observed under long-term management [122,126].

Soil C sequestration can be influenced by fire since it can change the plant species composition [127], affect nutrient loss [128,129], and promote C transformation to more stable compounds [130,131]. It was shown that prescribed fire in tandem with light grazing can have little negative or even potentially positive effect on soil C content due to the faster regeneration of improved quality grasses and eventual turning over of such plant inputs to soil C [113].

In reality, grazing land management normally encompasses multiple and inter-related management strategies. For example, the impacts of vegetation on C sequestration may be influenced by grazing intensity [132]. In addition, although higher stocking rates are not desirable, combining it with fertilization may promote C accumulation [133]. Therefore, it is important to consider all management options collectively to evaluate the soil C response.

A multitude of other factors such as the duration of management [72], soil type [134], and climate [94] can alone or interactively influence how soil C accumulation respond to grazing management. For example, the soil C change can be a slow process [135] or it can be increased within a few years after imposing the management and reaching an equilibrium [136]. According to Reference [122], irrigation, legume incorporation, grassland establishment, and earthworm introduction enhance C sequestration within 10 years while a longer-time scale of 20 to 40 years is needed to detect changes in soil C from management such as plant species conversion, fertilizer application, or grazing. It was revealed that clay soils under high precipitation and heavy grazing can be more vulnerable to soil erosion [137] and soil C loss compared to sandy soils [138]. In addition, similar to irrigation, excessive rainfall (>3000 mm) may increase soil erosion and decrease soil C [104] which could be more serious under grazing [56]. Thus, these factors should be considered when developing the best grazing land management strategies for long-term soil C sequestration.

5. Nitrogen Use Efficiency

Nitrogen use efficiency often refers to the proportion of the N exports from the ecosystem of N imports to the ecosystem [139]. The global NUE is low in animal production systems (~10%) [140] because a large amount of N is lost through emissions and leaching [141]. Based on past studies, the NUE of feed ranges from 16% to 36%, manure/fertilizer ranges from 16% to 77%, and the entire dairy farm ranges from 8% to 64% [141]. These broader ranges indicate that there is a great potential to improve NUE and it is critical to promote the plant's ability to utilize nutrients or to increase nutrient availability for production. In earlier studies, the N surplus (difference between N inputs and outputs) was also often used to evaluate the N loss [142,143], which can provide similar information as the directly measured NUE. Beyond that, some other measurements, as indicated in Table 4, are also used to evaluate NUE.

Table 4. Nutrient use efficiency as affected by grazing land management practices.

Management	Measurement Parameter ‡		Location	Precipitation (mm)	Temperature (°C)	References
No/low vs. High fertilizer	NUE (%)	0.8 to 26	Hamilton, New Zealand	1200	N/A	[144]
			Legume/grass pastures (Review)	N/A	N/A	[145]
			Inner Mongolia, China	346	−22 to 19	[146]
			Ireland (Review)	N/A	N/A	[147]
No fertilizer vs. Fertilizer	N balance (kg N ha ^{−1})	−25.1	Ireland (Review)	N/A	N/A	[147]
	N uptake (kg N ha ^{−1})	49	New South Wales, Australia	609 to 750	N/A	[20]
Non-grazed vs. Grazed	Inorganic N (mg N kg ^{−1})	−0.3 to 1.9	Sichuan, China	−10 to 11	690	[148]
	Mineralization rate (mg N kg ^{−1} d ^{−1})	−0.4 to 0.12				
Light vs. Heavy Grazed	NUE (%) ‡	6.2	Legume/grass pastures (Review)	N/A	N/A	[145]
Moderate vs. Heavy Grazed	Inorganic N (mg N kg ^{−1})	2.2	Sichuan, China	−10 to 11	690	[148]
	mineralization rate (mg N kg ^{−1} d ^{−1})	1.6				
Clover/Grass vs. Mixed pasture	NUE (%)	−3.5	Legume/grass Pastures (Review)	N/A	N/A	[145]

‡ The amount is the difference between the first management and the second management (e.g., the difference in NUE between light and heavy grazed areas is 6.2%).

To improve the NUE in grazing lands, strategies such as lowering the stocking rate on overgrazed farms, promoting plant production, managing animal manure efficiently, providing N feed based on animals' needs, decreasing synthetic N application, using low-protein high-energy feed, or introducing legumes are recommended [140,144].

5.1. Grazing Intensity

Grazing can benefit soil N cycling by facilitating litter decomposition, increasing N availability (e.g., [90]), promoting N mineralization in excreta, decreasing N immobilization [120], or enhancing soil microbial activities [149]. The N dynamics were shown to be promoted under grazing with greater N accumulation at 0–30 cm soil depth [52]. Livestock integration on row production systems can also benefit N dynamics by enhancing N mineralization and plant assimilation [120] or affecting crop development to realize greater production [20]. However, heavy grazing may be detrimental to N cycling since it can cause a loss of more nitrate N due to the higher urinary N [150] and may decrease the soil N mineralization rate [148]. Nevertheless, moderate grazing was found to benefit N cycling. A study in Sichuan, China detected that the non-grazed area had 1.9 mg N kg^{−1} more inorganic N

than a heavy grazed area while it was 0.3 mg N kg^{-1} lower than the moderately grazed area [148] (Table 4). The similar trend was also found in the N mineralization rate in this study.

5.2. Vegetation Composition

Vegetation species can influence N cycling through different N fixation abilities or root activities. It was reported that plant species, which exhibit higher N utilization by animals and higher N uptake from soil will increase NUE [145]. Including legumes in grasslands can increase the N yield [151] and improve efficiency of the conversion of forage into animal products due to the enhanced nutritive value and voluntary intake [152]. It was also found that clover-ryegrass mixtures exhibit higher NUE compared to pure clover or ryegrass pastures [153] and deep-rooted perennial species showed increased NUE due to increased resiliency to weather fluctuations [145]. It was demonstrated that C4 grasses show higher NUE since they release N slowly belowground due to lower litter quality compared to C3 grasses [154].

5.3. Fertilization

A synthetic N fertilizer is often applied on grazing lands to increase plant productivity. However, a major part of the N input is lost to the environment. Higher N fertilizer application increases $\text{NH}_3\text{-N}$ loss and N% in animal urine [155], which could result in decreased NUE ranging from 0.8% to 26% compared to un-fertilized or lower fertilized grazing lands (Table 4). As in the case of other management, the fertilizer's effect may be influenced by other factors such as the stocking rate and climate [147].

Manure management and application are also critical to increase NUE especially for smallholder farms [156]. It was shown that the NUE in African crop–livestock integrated systems with limited resources for manure handling is between 6% and 99% and, for manure storage, it is between 30% and 87% [157], which indicates great potential to increase whole farm NUE through manure management.

5.4. Fire

Fire can decrease the quantity of above ground biomass while it may benefit the N dynamics by promoting N fixation because of the increased temperature [158]. Burning can result in more available light, less litter cover, and higher N immobilization in roots [159,160]. However, the benefit of fire on NUE usually only happens when fires are short-term since long occurring fires will decrease the litter quality, which will decrease soil organic N and available N [158].

6. Interplay between Soil Moisture, C, and Nutrient Dynamics

In some cases, grazing land management practices simultaneously influence soil moisture, C, and nutrient dynamics [26]. It was suggested that one of the important factors controlling the water infiltration rate is soil organic matter since it can enhance the soil resistance to the raindrop impact [21,25]. Thus, the water infiltration rate can be enhanced if the soil organic matter is increased by changing grazing intensities [28]. A study in north Texas tall grass prairie indicated that adoption of moderate grazing can not only increase SOC but also soil aggregate stability and fungal/bacterial ratio, which ultimately benefit the hydrologic process, nutrient availability, and retention [22]. Water infiltration is also closely related to NUE as the lower infiltration usually results in greater runoff, which will increase soil erosion and nutrient losses [46]. Improper management such as overgrazing and prescribed early fire can be detrimental to nutrient availability, aggregate structure, and the infiltration rate [25].

Soil C and N often exhibit a similar response to grazing management. For example, both soil C and N increase under a proper grazing intensity or frequency compared to overgrazing [161,162]. Even under intensive grazing, soil C and N can be increased with the incorporation of highly productive C4 grass and with N fertilization [163]. A study in resource-poor Africa grazing lands also suggested that both SOC and NUE can be improved under manure application and management [157].

Conversely, some management such as irrigation in non-arable areas may promote nutrient leaching and decomposition of soil organic matter and decrease the root biomass, which will result in lower soil C and N [164]. Sometimes adoption of specific management may lead to a diverse response of different soil properties. Synthetic N fertilizer application, for instance, can improve C sequestration in many cases [3] due to the improved forage productivity and C input while it often diminishes the NUE in grazing lands (Table 4).

7. Research Gaps

Despite the importance of water, C and N dynamics on soil health, the impact of grazing land management on water infiltration, and NUE were much less studied than C sequestration. The number of literature we found on soil C sequestration was three times more than that for water infiltration and NUE (~120 vs. 40). Studies on soil water infiltration responding to different grazing land management is geographically limited and the temporal effect is also not well understood. Although a lot of studies focused on soil C sequestration, there are still many uncertainties such as the mechanisms of soil C cycling, the climate effects, the response of deeper soils, the dynamics of soil inorganic C, and region-specific management strategies. Many studies on NUE were conducted on dairy farms. However, how to better manage these farms to limit N loss is still unclear. Moreover, other grazing lands besides dairy farms should also be investigated. In addition, the use of new approaches based on microbial analysis and modeling on NUE studies are rare.

8. Conclusions

Grazing land management strategies such as the change of vegetation composition, grazing intensity and duration, fertilizer use, irrigation, and fire can affect soil processes pertaining to healthy soil. Adoption of plant species with higher productivity and light or moderate grazing are desirable strategies to improve overall soil health. However, grazing land management often encompasses multiple practices, which can interactively influence soil health positively or negatively. Furthermore, factors such as grazing duration, climate, and soil type can also influence the impacts of grazing land management on soil properties. This review points to the need for more studies to establish regional-specific best grazing land management practices that support long-term soil health.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Papers associated with the effects of grazing land management on soil water infiltration.

Author name	Journal/Book name	Year, volume, page#	Note
Abdel-Magid et al.	Journal of Range Management	1987, 307-309	
Bharati et al.	Agroforestry systems	2002, 56 (3), 249-257	
Blackburn	Water Resources Research	1975, 11 (6), 929-937	
Castellano & Valone	Journal of Arid Environments	2007, 71 (1), 97-108	
Coughenour	Journal of Range Management	1991, 44 (6), 530-542	
Dadkhah & Gifford	Journal of the American Water Resources Association	1980, 16 (6), 979-986	
Daniel et al.	Transactions of the ASAE	2002, 45 (6), 1911	
Eldridge et al.	Ecological Applications	2016, 26 (4), 1273-1283	G
Fraser & Stone	The Rangeland Journal	2016, 38 (3), 245-259	
Gamougoun et al.	Journal of Range Management	1984, 538-541	
Gilley et al.	Applied engineering in agriculture	1996, 12 (6), 681-684	
GR McCalla et al.	Journal of Range Management	1984, 265-269	
Greenwood & McKenzie	Australian Journal of Experimental Agriculture	2001, 41 (8), 1231-1250	
Haan et al.	Rangeland Ecology & Management	2006, 59 (6), 607-615	G
Hillel	Book Introduction to environmental soil physics	2003	Book
Linnartz et al.	Journal of Forestry	1966, 64 (4), 239-243	
McGinty et al.	Journal of Range Management	1979, 33-37	
McIvor et al.	Australian Journal of Experimental Agriculture	1995, 35 (1), 55-65	
Moyo et al.	African Journal of Range & Forage Science	1998, 15 (1-2), 16-22	
Mwendera & Saleem	Soil Use and Management	1997, 13 (1), 29-35	G
Naeth & Chanasyk	Journal of Range Management	1995, 528-534	
Park et al.	Journal of Soil and Water Conservation	2017, 72 (2), 102-121	G
Pluhar et al.	Journal of Range Management	1987, 240-243	
Proffitt et al.	Australian Journal of Agricultural Research	1993, 44 (2), 317-331	
Rauzi & Smith	Journal of Range Management	1973, 126-129	
Rietkerk et al.	Plant Ecology	2000, 148 (2), 207-224	
Russell et al.	Journal of Range Management	2001, 184-190	
Sanjari et al.	Soil Research	2010, 47 (8), 796-808	
Savadogo et al.	Agriculture, Ecosystems & Environment	2007, 118 (1-4), 80-92	G
Takar et al.	Journal of Range Management	1990, 486-490	
Teague et al.	Agriculture, Ecosystems & Environment	2011, 141 (3-4), 310-322	
Thurow et al.	Journal of Range Management	1986, 505-509	
Thurow et al.	Journal of Range Management	1988, 296-302	
Van Haveren	Journal of Range Management	1983, 586-588	
Vandandorj et al.	Ecohydrology	2017, 10 (4), e1831	G
Warren et al.	Journal of Range Management	1986, 486-491	
Warren et al.	Journal of Range Management	1986, 500-504	
Weltz & Wood	Journal of Range Management	1986, 365-368	
West et al.	Rangeland Ecology & Management	2016, 69 (1), 20-27	
Wood & Blackburn	Journal of Range Management	1981, 331-335	
Yisehak et al.	Journal of arid environments	2013, 98, 70-78	

Notes: Articles related to several ecosystem functions including water infiltration are marked as "G" and books are marked as "Book" in the "Note" column.

Table A2. Papers associated with the effects of grazing land managements on soil carbon sequestration.

Author name	Journal name	Year, volume, page#	Note
Alemu et al.	Journal of Animal Science	2017, 95, 145-146	
Allard et al.	Agriculture, Ecosystems & Environment	2007, 121 (1-2), 47-58	
Ardö & Olsson	Journal of Arid Environments	2003, 54 (4), 633-651	
Asner et al.	Global Change Biology	2004, 10 (5), 844-862	
Aynekulu et al.	Geoderma	2017, 307 1-7	
Bagchi et al.	Agriculture, Ecosystems & Environment	2017, 239 199-206	G
Balogh et al.	Cereal Research Communications	2005, 33 (1), 149-152	
Bardgett & Wardle	Ecology	2003, 84 (9), 2258-2268	
Berthrong et al.	Ecological Applications	2009, 19 (8), 2228-2241	
Bikila et al.	Agriculture, Ecosystems & Environment	2016, 223 108-114	
Bowden et al.	Forest Ecology and Management	2004, 196 (1), 43-56	
Bremer et al.	Environmental Conservation	2016, 43 (4), 397-406	
Brewer	Influences of fuel moisture and repeated burning on black carbon production and loss in masticated fuels: An experimental combustion study.	2012	Thesis
Briggs et al.	AIBS Bulletin	2005, 55 (3), 243-254	G
Briske & Richards	Wildland plants: physiological ecology and developmental morphology	1995, 635-710	Book
Burke et al.	Biogeochemistry of managed grasslands in central north america	1997, 85-98	G, Book
Buytaert et al.	Catena	2007, 70 (2), 143-154	
Carvalho et al.	Soil and Tillage Research	2010, 110 (1), 175-186	N
Carvalho et al.	Agriculture, Ecosystems & Environment	2014, 183 167-175	
Chan et al.	Soil Research	2010, 48 (1), 7-15	
Chen et al.	Scientific reports	2015, 5 10892	
Chimner & Welker	Pastoralism: Research, Policy and Practice	2011, 1 (1), 20	
Conant et al.	Ecological Applications	2017, 27 (2), 662-668	
Conant & Paustian	Global Biogeochemical Cycles	2002, 16 (4),	
Conant et al.	Ecological Applications	2001, 11 (2), 343-355	
Conrad et al.	Agriculture, Ecosystems & Environment	2017, 248 38-47	
Cui et al.	Ecological Research	2005, 20 (5), 519-527	
de Figueiredo et al.	Journal of Cleaner Production	2017, 142 420-431	
De Rose	Earth Surface Processes and Landforms	2013, 38 (4), 356-371	
Derner et al.	Plant and Soil	1997, 191 (2), 147-156	
Detling et al.	Oecologia	1979, 41 (2), 127-134	
Doescher et al.	Journal of Range Management	1997, 285-289	
Don et al.	Global Change Biology	2011, 17 (4), 1658-1670	
Dormaar et al.	Journal of Range Management	1977, 195-198	
Dormaar et al.	Journal of Range Management	1997, 647-651	
Dyer & Bokhari	Ecology	1976, 57 (4), 762-772	
Eclesia et al.	Global Change Biology	2012, 18 (10), 3237-3251	
Elmore & Asner	Global Change Biology	2006, 12 (9), 1761-1772	
Fearnside & Barbosa	Forest Ecology and Management	1998, 108 (1-2), 147-166	
Feyisa et al.	Catena	2017, 159 9-19	
Follett & Reed	Rangeland Ecology & Management	2010, 63 (1), 4-15	
Fontaine et al.	Ecology letters	2004, 7 (4), 314-320	
Frank et al.	Journal of Range Management	1995, 470-474	
Frank et al.	Ecology	2002, 83 (3), 602-606	
Frank & McNaughton	Oecologia	1993, 96 (2), 157-161	
Franzluebbers & Stuedemann	Agriculture, Ecosystems & Environment	2009, 129 (1-3), 28-36	
Giardina et al.	Oecologia	2004, 139 (4), 545-550	
González-Pérez et al.	Environment international	2004, 30 (6), 855-870	G
Grünzweig et al.	Global Change Biology	2003, 9 (5), 791-799	
Guo & Gifford	Global Change Biology	2002, 8 (4), 345-360	
He et al.	Ecosphere	2011, 2 (1), 1-10	
Hewitt et al.	Soil Use and Management	2012, 28 (4), 508-516	
Hiernaux et al.	Journal of Arid Environments	1999, 41 (3), 231-245	G
Hik & Jefferies	The Journal of Ecology	1990, 180-195	G

Table A2. Cont.

Author name	Journal name	Year, volume, page#	Note
Houlbrooke et al.	Soil Use and Management	2008, 24 (4), 416-423	
Hunt & Phillips	Biogeosciences	2016, 13 (10), 2927	N
Ingram et al.	Soil Science Society of America Journal	2008, 72 (4), 939-948	
Jastrow et al.	Climatic Change	2007, 80 (1-2), 5-23	
Jobbágy & Jackson	Ecological Applications	2000, 10 (2), 423-436	
Jones & Donnelly	New Phytologist	2004, 164 (3), 423-439	
Kallenbach et al.	Nature communications	2016, 7 13630	
Kang et al.	Journal of Soils and Sediments	2013, 13 (6), 1012-1023	
Kauffman et al.	Oecologia	1995, 104 (4), 397-408	
Kelliher et al.	Agriculture, Ecosystems & Environment	2012, 148 29-36	
Kelliher et al.	New Zealand Journal of Agricultural Research	2015, 58 (1), 78-83	
Khan et al.	Journal of Environmental Quality	2007, 36 (6), 1821-1832	
Kirschbaum et al.	Forest Ecology and Management	2008, 255 (7), 2990-3000	
Kirschbaum et al.	Science of the Total Environment	2017, 577 61-72	
Knicker	Biogeochemistry	2007, 85 (1), 91-118	
Kuhry	Journal of Ecology	1994, 899-910	
Lal	Soil Conservation and Management in the Humid Tropics; Proceedings of the International Conference	1977	Conference
Lal	Annals of Arid Zone	2000, 39 (1), 1-10	G
Lal & Follett	Soil carbon sequestration and the greenhouse effect.	2009	Book
Li et al.	New Zealand Journal of Agricultural Research	2008, 51 (1), 45-52	
Liebig et al.	Agriculture, Ecosystems & Environment	2006, 115 (1-4), 270-276	
Liu et al.	PloS one	2012, 7 (5), e36434	
Ma et al.	Ecological Engineering	2016, 87 203-211	G
Maia et al.	Geoderma	2009, 149 (1-2), 84-91	
Manzoni et al.	Ecological Monographs	2010, 80 (1), 89-106	
Martinez & Zinck	Soil and Tillage Research	2004, 75 (1), 3-18	
McNally et al.	Plant and Soil	2015, 392 (1-2), 289-299	
McNaughton	The American Naturalist	1979, 113 (5), 691-703	G
McSherry & Ritchie	Global Change Biology	2013, 19 (5), 1347-1357	
Medina-Roldán et al.	Agriculture, Ecosystems & Environment	2012, 149 118-123	
Meersmans et al.	Global Change Biology	2009, 15 (11), 2739-2750	
Miller	Soils: An introduction to soils and plant growth.	1990	Book
Moinet et al.	Geoderma	2016, 274 68-78	
Moinet et al.	Science of the Total Environment	2017, 579 1715-1725	
Mortenson et al.	Environmental Management	2004, 33 (1), S475-S481	
Naeth et al.	Journal of Range Management	1991, 7-12	G
Navarrete et al.	Global Change Biology	2016, 22 (10), 3503-3517	G
Orgill et al.	Land Degradation & Development	2018, 29 (2), 274-283	
Parfitt & Ross	Soil Research	2011, 49 (6), 494-503	
Piñeiro et al.	Global Biogeochemical Cycles	2009, 23 (2)	
Pineiro et al.	Global Change Biology	2006, 12 (7), 1267-1284	G
Powers & Veldkamp	Biogeochemistry	2005, 72 (3), 315-336	
Reeder et al.	The potential of US grazing lands to sequester carbon and mitigate the greenhouse effect.	2001, 139-166	G, Book
Reeder & Schuman	Environmental pollution	2002, 116 (3), 457-463	G
Reeder et al.	Environmental Management	2004, 33 (4), 485-495	
Rong et al.	Agriculture, Ecosystems & Environment	2017, 237 194-202	G
Rufino et al.	Livestock Science	2007, 112 (3), 273-287	N
Sanderman et al.	PloS one	2015, 10 (8), e0136157	G
Sanjari et al.	Soil Research	2008, 46 (4), 348-358	
Schipper et al.	Soil Science Society of America Journal	2013, 77 (1), 246-256	
Schipper et al.	New Zealand Journal of Agricultural Research	2017, 60 (2), 93-118	
Schipper et al.	Agriculture, Ecosystems & Environment	2010, 139 (4), 611-617	
Schipper & Sparling	Biogeochemistry	2011, 104 (1-3), 49-58	
Schulz et al.	Forest Ecology and Management	2016, 367 62-70	
Schuman et al.	Ecological Applications	1999, 9 (1), 65-71	N
Stahl et al.	Regional environmental change	2016, 16 (7), 2059-2069	
Steffens et al.	Geoderma	2008, 143 (1-2), 63-72	
Stiles et al.	Science of the Total Environment	2017, 593 688-694	
Talore et al.	Journal of the Science of Food and Agriculture	2016, 96 (6), 1945-1952	

Table A2. Cont.

Author name	Journal name	Year, volume, page#	Note
Wang et al.	Agriculture, Ecosystems & Environment	2016, 232 290-301	
Wang & Houlton	Geophysical Research Letters	2009, 36 (24)	
Wei et al.	Journal of soil science and plant nutrition	2011, 11 (4), 27-39	
Witt et al.	Agriculture, Ecosystems & Environment	2011, 141 (1-2), 108-118	
Wright et al.	Soil Biology and Biochemistry	2004, 36 (11), 1809-1816	
Wu et al.	Journal of Environmental Quality	2008, 37 (2), 663-668	
Xiong et al.	Chinese geographical science	2014, 24 (4), 488-498	
Xiong et al.	Ecological Engineering	2016, 94 647-655	
Xu et al.	Plant and Soil	2016, 399 (1-2), 233-245	
Su et al.	Catena	2005, 59 (3), 267-278	

Notes: Articles related to several ecosystem functions including carbon sequestration are marked as “G” in the “Note” column. Articles related to both carbon sequestration and nitrogen use efficiency are marked as “N” in the “Note” column. Books, thesis and conference paper are marked as “Book”, “Thesis” and “Conference”, respectively, in the “Note” column.

Table A3. Papers selected associated with the effects of grazing land managements on nitrogen use efficiency.

Author name	Journal name	Year, volume, page#	Note
Ball & Ryden	Biological processes and soil fertility	1984, 23-33	Book
Barraclough et al.	Soil Use and Management	1992, 8 (2), 51-55	
Chapin III et al.	The American Naturalist	1986, 127 (1), 48-58	
Di & Cameron	New Zealand Journal of Agricultural Research	2004, 47 (3), 351-361	
Erismann et al.	Environmental pollution	2007, 150 (1), 140-149	
Field et al.	Proceedings of the New Zealand Grassland Association	1985, 209-214	Conference
Gong et al.	Plant and Soil	2011, 340 (1-2), 227-238	
Gourley et al.	Animal Production Science	2012, 52 (10), 929-944	
Hobbs et al.	Ecology	1991, 72 (4), 1374-1382	
Høgh-Jensen & Schjørring	Plant and Soil	1997, 197 (2), 187-199	
Janssen	Nutrient disequilibria in agroecosystems: Concepts and case studies	1999, 27-56	Book
Knapp & Seastedt	BioScience	1986, 36 (10), 662-668	
Lambert et al.	New Zealand Journal of Agricultural Research	1985, 28 (3), 371-379	
Ledgard et al.	The Journal of Agricultural Science	1999, 132 (2), 215-225	
Ledgard	Plant and Soil	2001, 228 (1), 43-59	
Lü et al.	Plant and Soil	2015, 387 (1-2), 69-79	
Monaghan et al.	New Zealand Journal of Agricultural Research	2007, 50 (2), 181-201	
Ojima et al.	Biogeochemistry	1994, 24 (2), 67-84	
Peoples et al.	Australian Journal of Agricultural Research	1998, 49 (3), 459-474	
Phillips et al.	New Phytologist	2013, 199 (1), 41-51	
Phillips et al.	Ecology letters	2011, 14 (2), 187-194	
Powell et al.	Environmental Science & Policy	2010, 13 (3), 217-228	
Roten et al.	Computers and Electronics in Agriculture	2017, 135 128-133	
Rufino et al.	Agriculture, Ecosystems & Environment	2006, 112 (4), 261-282	
Scholefield et al.	Journal of Soil Science	1993, 44 (4), 601-613	
Schröder et al.	European Journal of Agronomy	2003, 20 (1-2), 33-44	
Seastedt & Ramundo	Fire in North American tallgrass prairies.	1990, 99-117	Book
Smith	Ecology	1976, 57 (2), 324-331	
Tilman & Wedin	Ecology	1991, 72 (2), 685-700	
Trotter et al.	Crop and Pasture Science	2014, 65 (8), 817-827	
Van der Hoek	Nitrogen, the confer-ns	1998, 127-132	Book
Van Noordwijk	Nutrient cycles and nutrient budgets in global agro-ecosystems.	1999, 1-26	Book
VandeHaar & St-Pierre	Journal of dairy science	2006, 89 (4), 1280-1291	
Vitousek	The American Naturalist	1982, 119 (4), 553-572	
Wedin & Tilman	Oecologia	1990, 84 (4), 433-441	

Table A3. Cont.

Author name	Journal name	Year, volume, page#	Note
Wilkins et al.	Grass and Forage Science	2000, 55 (1), 69-76	
Wilkins et al.	Euphytica	1997, 98 (1-2), 109-119	
Yin et al.	Soil Biology and Biochemistry	2014, 78 213-221	

Notes: Books are marked as “Book” and conference papers are marked as “Conference” in the “Note” column.

Table A4. Papers selected associated with the effects of grazing land managements on other ecosystem functions.

Author name	Journal name	Year, volume, page#	Note
Al-Kaisi & Lowery	Soil health and intensification of agroecosystems	2017	Book
Ayres et al.	Functional Ecology	2007, 21 (2), 256-263	
Bagchi & Ritchie	Ecology letters	2010, 13 (8), 959-968	
Bardgett & Wardle	Aboveground-belowground linkages: Biotic interactions, ecosystem processes, and global change	2010	Book
Flack	The art and science of grazing: How grass farmers can create sustainable systems for healthy animals and farm ecosystems	2017, 7-10	Book
Belnap	Frontiers in Ecology and the Environment	2003, 1 (4), 181-189	
Bond & Keeley	Trends in ecology & evolution	2005, 20 (7), 387-394	
Buckley et al.	Nutrient cycling in agroecosystems	2016, 104 (1), 1-13	
Cherif & Loreau	Proc. R. Soc. B	2013, 280 (1754), 20122453	
Frank & Groffman	Ecology	1998, 79 (7), 2229-2241	
Frink et al.	Proceedings of the National Academy of Sciences	1999, 96 (4), 1175-1180	
Fuhlendorf et al.	Applied Vegetation Science	2001, 4 (2), 177-188	
Gao et al.	Research Journal of Agriculture and Biological Sciences	2007, 3 (6), 642-647	
Hamilton III & Frank	Ecology	2001, 82 (9), 2397-2402	
Han et al.	Agriculture, Ecosystems & Environment	2008, 125 (1-4), 21-32	
Hart	Plant Ecology	2001, 155 (1), 111-118	
Hobbs	The Journal of Wildlife Management	1996, 695-713	
Kersebaum et al.	Physics and Chemistry of the Earth, Parts A/B/C	2003, 28 (12-13), 537-545	
Keya	Agriculture, Ecosystems & Environment	1998, 69 (1), 55-67	
Knicker	Biogeochemistry	2007, 85 (1), 91-118	
Leriche et al.	Oecologia	2001, 129 (1), 114-124	
Manzano & N�avar	Journal of Arid Environments	2000, 44 (1), 1-17	
McDowell.	Environmental impacts of pasture-based farming	2008, 33-76	Book
Morris & Jensen	Journal of Ecology	1998, 86 (2), 229-242	
Mueller et al.	Ecological Applications	2017, 27 (5), 1435-1450	
Neff et al.	Ecological Applications	2005, 15 (1), 87-95	
Ning et al.	Rangifer	2004, 24 (4), 9-15	
Nolte et al.	Estuarine, Coastal and Shelf Science	2013, 135 296-305	
Oenema et al.	Nitrogen, the confer-ns	1998, 471-478	Book
Oesterheld et al.	Ecosystems of the world	1999, 287-306	
Olsen et al.	Soil Biology and Biochemistry	2011, 43 (3), 531-541	
Pandey & Singh	Canadian Journal of Botany	1992, 70 (9), 1885-1890	
Peoples et al.	Plant and Soil	1995, 174 (1-2), 3-28	
Pi�neiro et al.	Rangeland Ecology & Management	2010, 63 (1), 109-119	
Renzhong & Ripley	Journal of Arid Environments	1997, 36 (2), 307-318	
Rosser & Ross	New Zealand Journal of Agricultural Research	2011, 54 (1), 23-44	
Seagle et al.	Ecology	1992, 73 (3), 1105-1123	
Smith et al.	New Zealand Journal of Agricultural Research	2012, 55 (2), 105-117	
Sun et al.	Plant and Soil	2017, 416 (1-2), 515-525	
Thomas	Grass and Forage Science	1992, 47 (2), 133-142	
Vallentine	Grazing management	2000	Book
Virgona et al.	Australian Journal of Agricultural Research	2006, 57 (12), 1307-1319	
Wang et al.	Catena	2017, 158 141-147	
Waters et al.	The Rangeland Journal	2015, 37 (3), 297-307	
Wilson et al.	Journal of Soil and Water Conservation	2014, 69 (4), 330-342	
Xu et al.	Geoderma	2017, 293 73-81	
Zhu et al.	Journal of Arid Environments	2015, 114 41-48	

Notes: Books are marked as “Book” in the “Note” column.

Appendix B

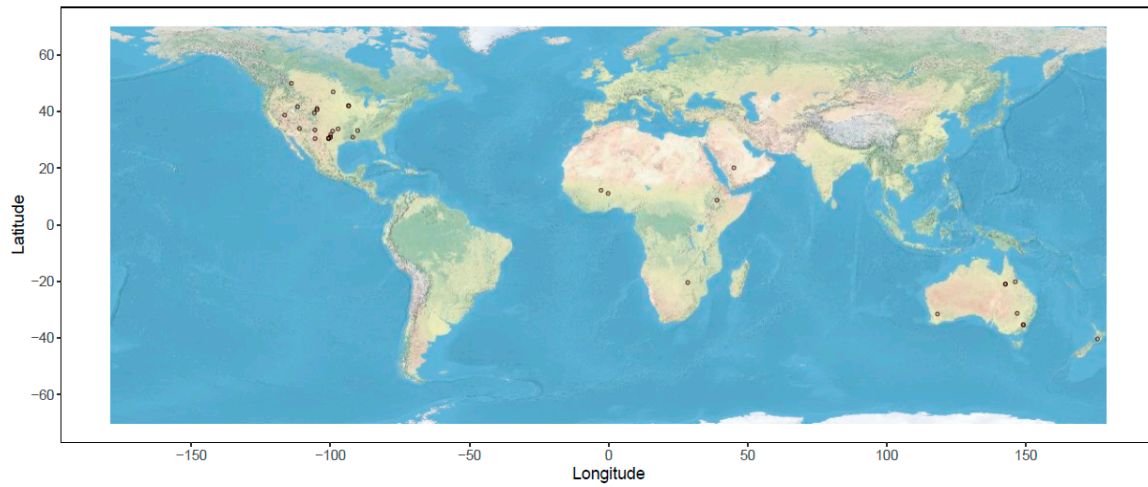


Figure A1. Locations of reviewed articles related to the effect of grazing land management on water infiltration.

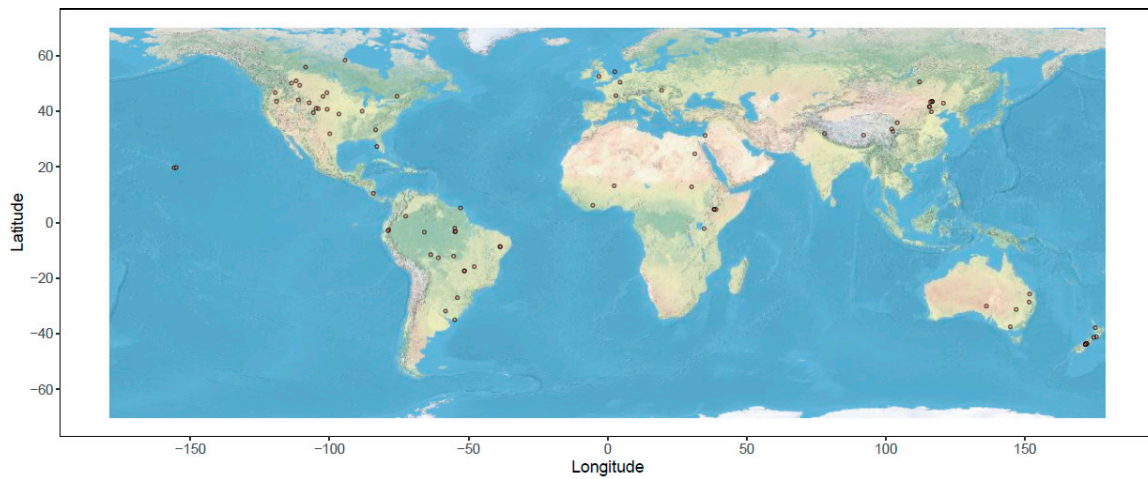


Figure A2. Locations of reviewed articles related to the effect of grazing land management on soil carbon sequestration.

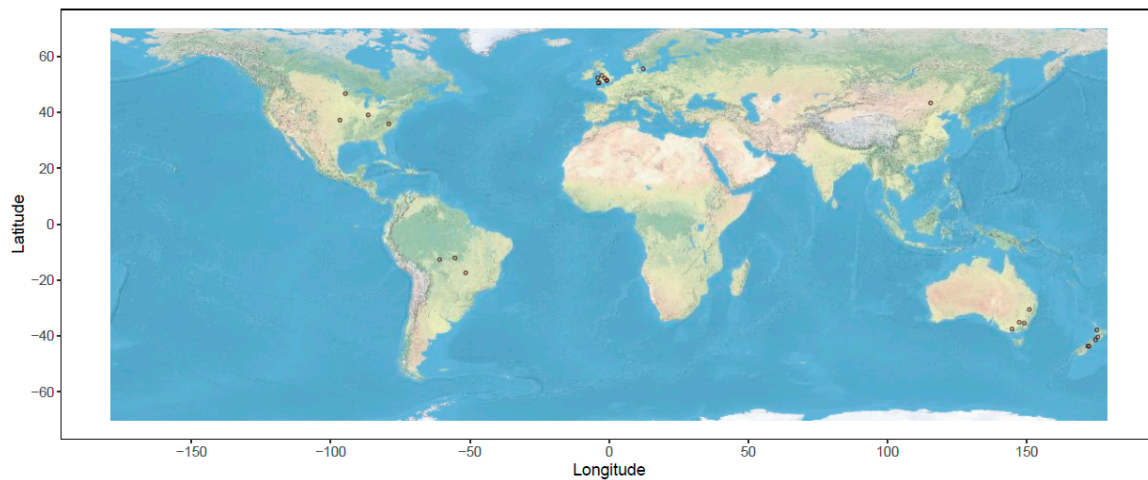


Figure A3. Locations of reviewed articles related to the effect of grazing land management on nitrogen use efficiency.

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