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Effects of grazing management on spatio-temporal heterogeneity of soil carbon and greenhouse gas emissions of grasslands and rangelands: monitoring, modelling and upscaling

Junye Wang[1*], Yumei Li[1,2], Edward W. Bork[3], Goetz M. Richter[4], Hyung-Il Eum[5], Changchun Chen[6], Syed Hamid Hussain Shah[1], Symon Mezbahuddin[7,8]

[1]Faculty of Science and Technology, Athabasca University, 1 University Drive, Athabasca, Alberta T9S 3A3, Canada

[2]College of Earth Science, University of the Chinese Academy of Sciences, 19A Yuquan Rd, Shijingshan District, Beijing 100049, P.R. China

[3]Department of Agricultural, Food and Nutritional Science, University of Alberta, 410 Agriculture/Forestry Centre, Edmonton, AB T6G 2H1, Canada

[4]Department of Sustainable Agriculture Sciences, Rothamsted Research, Harpenden, AL5 2JQ, United Kingdom

[5]Alberta Environment and Parks (AEP), Environmental Monitoring and Science Division, Calgary, AB, Canada

[6]School of Geography & Remote Sensing, Nanjing University of Information Science and Technology, Nanjing 210044, P.R. China

[7]Environmental Stewardship Branch, Alberta Agriculture and Forestry, Edmonton, AB, Canada

[8]Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada

* Corresponding author. Email address: junye.wang@athabascau.ca (Junye Wang)

Abstract

The sustainability of grazing lands lies in the nexus of human consumption behavior, livestock productivity, and environmental sustainability. Due to fast growing global food demands, many grazing lands have suffered from overgrazing, leading to soil degradation, air and water pollution, and biodiversity losses. Multidisciplinary efforts are required to understand how grazing lands can be better monitored, assessed and managed to attain predictable outcomes of optimal benefit to society. This paper synthesizes our understanding based on previous work done on impacts of grazing on ecosystem goods and services, identifies current knowledge gaps, and formulates a plan forward. We review the impacts of two contrasting grazing systems, continuous and multi-paddock rotational grazing, on soil carbon (C), nutrient cycling and greenhouse gas emissions (GHGs). We then extend our review to explore challenges of incorporating spatial heterogeneity and temporal variability into monitoring and modelling C and nutrient cycling in grazing lands. We revisit two process-based models (i.e., DNDC and DayCent) and two watershed models (i.e., SWAT and VIC) widely used to simulate C, nutrient and water cycles of these lands. Finally we identify research directions for improving the knowledge base which is essential to conserve grazing lands and maintain their ecosystem goods and services.

Keywords: grazed grassland, rangelands, grazing management, soil carbon, nutrient cycles

1. Introduction

Grazing lands include grasslands, rangelands, and pasture lands (hereafter called ‘grazing lands’) that provide many goods and ecosystem services, including forage, livestock, soil carbon storage, biodiversity, and recreational opportunities, among others. Grazing lands cover about 30% of the total global land use area and comprise 70% of the total land used for agriculture (Latham et al., 2014; Oertel et al., 2016). The livestock sector is responsible for 18% of global greenhouse gas emissions (CO_2 equivalent) and account for 65% of anthropogenic nitrous oxide (N_2O) emissions (IPCC 2007). On the other hand, soil carbon stocks in grazing lands contain about 10% of all terrestrial biomass and hold 20–30% of the global pool of soil organic carbon (SOC) (Scurlock and Hall, 1998; Anderson, 1991). Due to rapidly increasing global food demands, particularly for red meats, many grazing lands have suffered from overgrazing, leading to soil degradation, air and water pollution, and biodiversity losses. Ensuring the long-term sustainability of grazing lands requires management be adjusted to simultaneously balance livestock productivity for sustaining human food and nutritional demands. Therefore, it is necessary, , to reduce soil degradation (i.e., SOC, erosion, and pollutants) and environmental impacts (i.e., greenhouse gas emissions and water pollution).

Grazing management includes the variety of decision-making tools needed to involve alteration of the timing, frequency and intensity of grazing events, by altering the number of paddocks, animal density, and severity of defoliation, together with the length of subsequent rest (i.e., recovery) periods for optimizing livestock production and environmental sustainability (Jacobo et al., 2006). While high grazing stocking can increase livestock productivity in the short-term, high stocking and corresponding intensive livestock production practices with inadequate rest periods may increase GHG emissions and lead to nutrient losses and soil degradation (De Klein and Eckard, 2008). Despite many successful examples wherein grazing systems have been balanced with livestock productivity, the benefits of multi-paddock rotational grazing to plant and livestock production are still debated, particularly relative to continuous grazing (Briske et al., 2008; Teague et al., 2013; de Groot et al., 2009). For example, many studies found that even at low stocking rates, animal preferences lead to patch-selection, and in turn, localized overgrazing due to inadequate recovery of the palatable (i.e., selected) species (Teague et al., 2009; Broadbent et al., 2019; De Bruijin et al., 2010). While the use of high stocking rates could increase livestock productivity they may also initiate soil erosion and water pollution. Adjustments to grazing, which improve soil and water resources, particularly in nutrient and water limited environments (AAFRD, 2004), can increase pasture production and lead to sustainable livestock production (Orr et al., 2016). Although many comparisons of different grazing systems have been conducted, including multi-paddock systems, comparisons among them are complicated by uncertainty within the data from different disciplines and across divergent scales, and a lack of fundamental mechanistic studies identifying the causes of degradation (and comparative improvements) within grazing lands.

A major challenge for grazing managers has been identifying specific grazing systems capable of balancing pasture growth and animal intake, in part due to limitations of narrowly imposed experimental grazing research and resultant knowledge transfer between researchers and ranchers (Teague et al., 2009; Becker et al., 2017; Mann and Sherren, 2018). Much effort has been made to control grazing intensity (i.e., stocking rate, frequency and duration of defoliation), as well as the season, distribution of grazing and subsequent resting periods to optimize plant and livestock performance (Heitschmidt and Walker, 1996). However, livestock management and animal husbandry under multi-paddock grazing includes complex processes at the forage-animal interface, which along with stocking rate considerations, affect pasture productivity and sustainability. Ultimately, changes to the sustainability of grazing ecosystems may impact not only global food security, but also key environmental metrices, such as the ability of grazing lands to respond to changes in soil health. Therefore, the challenge to achieving sustainable grazing management (i.e., grazing systems and stocking levels) is to understand all interactions among animal intake, forage and vegetation responses, and soil and water dynamics, connecting below-ground to more easily measured above-ground processes (Scurlock and Hall, 1998). Most studies conducted by researchers do not reflect a broad understanding of the ranchers' perspectives regarding the efficacy of alternative grazing systems (Becker et al., 2017). As such, the outcome of these investigations may impair progress towards achieving sustainable grazing systems. Substantial scientific and technological breakthroughs within key knowledge gaps is necessary to enhance conservation of grazing lands. In practice, many of the past studies testing grazing systems might limit relevance to the large, landscape scale at which livestock production occurs, and their rigid treatment structure could omit the adaptive nature of management commonly found on grazing lands (Teague et al., 2013). Moreover, various research experiments are performed separately in isolation, and thereby lack the systematic connection necessary to reach a consensus of scaling-up strategies due to the inconsistent and very limited context data. As a result, these studies can not scale up to the scale at which most grazing land are utilized and lack the flexibility (i.e. adaptability) of grazing management, thereby leading to a deficiency in the tools/methods available for the assessment of grazing at different scales and locations.

Most studies of multi-paddock rotational grazing are done at small scale (Smith, 2007), whilst in the real world continuous grazing occurs at the much larger scale. Experimental conditions used in multi-paddock rotational grazing are, therefore, not be a fair representation of the practices. Petrosillo et al. (2010) pointed out that environmental vulnerability is multi-layered, multi-scale and complex, existing in both the objective physical, biological, and social realm, and the subjective realm of individual human perception. Two main knowledge gaps exist in research and the associated management practice of grazing systems: scaling-up from local to complex landscapes, and expanding mechanisms to understand the role of multi-disciplinary perspectives (e.g., ecological vs social). Many questions remain to be answered. For example, how can knowledge of grazing systems and new technologies, be effectively utilized to achieve sustainability of grazing ecosystems by scaling up information?

The primary goal of this paper is to review the processes of managed grazing systems to identify key knowledge and knowledge transfer gaps between scales and disciplinarity. The secondary goal is to explore a way to integrate evidence and information at different scales, sources and regions, including with that at which management occurs. Emphasis is on the connection among models, data scaling-up and sustainable management. Our intent is not to conduct an exhaustive review of all past literature on the topic. Rather, it is to synthesize information and identify knowledge gaps between the design of grazing systems and experimental data supporting their use and to bridge the knowledge gaps. This review is limited to the management of grazing livestock on areas managed under extensive management systems. This paper is organized as follows. First, we analyze the pros and cons of using different grazing systems, specifically continuous and multi-paddock grazing, in Section 2. In Section 3 we review experiments and field studies monitoring grazing lands exposed to different systems considering economic and environmental aspects of sustainability: productivity, nutrient runoff and soil erosion, as well as GHGs. In section 4, we review process-based models, and focus on two flagship models of agroecosystems: DNDC (Li et al., 1992) and DayCent (Parton et al., 1996; 1998). Thereafter, we review watershed modelling with an emphasis on SWAT (Neitsch et al., 2009) and the VIC models (Eum et al., 2016) in Section 5. Finally, in Section 6, we point out the current and future needs of grazing system research and management.

2. Management using grazing systems

Grazing systems can be broadly categorized into two types: continuous grazing and multi-paddock rotational grazing, depending on the length of time that animals remain on a given land area, known as the grazing period. The latter effectively determines whether vegetation is able to recover following a defoliation event (Thomas, 2009). Generally, sustainable grazing systems strive to balance animal growth/production through forage removal, with the inherent defoliation tolerance of the plant community and resident plant species. As these are competing ecological processes, it is impossible to maximize both forage removal and production (overcompensation withstanding), with associated impacts on vegetation composition and soils. This process is further complicated by the fact that grazing animals do not move and feed at random, but instead favor select areas, including those near water, available salt and mineral, together with easily accessible areas. Given this, grazing lands are never grazed uniformly within a designated time frame, and the spatial distribution of animal impact is rarely uniform. Grazing systems are paramount in aligning forage productivity to livestock production and the maintenance of desirable forage plant composition and productivity (Teague et al., 2009). Furthermore, design of sustainable grazing land management should account for natural ecosystem goods and services, such as biodiversity retention and habitat conservation, but also resources available, livestock stocking rates, and the availability of time and financial resources.

2.1. Continuous grazing

A continuous grazing system allows livestock to graze on a single pasture for an extended period of time, typically the entire grazing season. In temperate environments, this period often coincides with the full duration of the active growing season, and is therefore called 'season-long' grazing. Its main advantage is that livestock do not require high management attention, with little infrastructure needed (fencing, water development) and labor kept to a minimum (i.e., movement of animals). Continuous systems are usually used for a relatively large pasture base having relatively low productivity, and in which low numbers of livestock limit the justification for costly infrastructure. Continuous grazing also allows for maximum selectivity by animals throughout the growing season, thereby maximizing selection at all times, which in turn increase the relative quality of dietary intake and can favor individual animal gains (Forbes, 2007; Gardener, 1980). This same factor however, results in continuous grazing being associated with little control over the timing, distribution and intensity of grazing. Even at low stocking rates, patch-selective overgrazing can occur (Teague et al., 2009). Repeated use of palatable plant species within these patches causes them to decline in abundance, and even be lost from the forage sward, a process that can occur under even moderate stocking rates. Moreover, extensively distributed use by grazing animals over a large pasture leads to highly heterogeneous utilization, and this usually results in lower livestock productivity (per unit area) due to the lack of use of much of the forage resource. While continuous grazing helps maintain animal performance during periods of slow forage growth (by maintaining selectivity), a low stocking rate is required to ensure adequate forage quantity and quality.

Degradation of grazing lands and biodiversity loss are common under continuous grazing because the damage during overgrazing exceeds pasture recovery (Müller et al. 2007). However, it should be noted that this degradation may be limited to only a small fraction of the overall grazing area, depending on the degree of selectivity exhibited by livestock and the associated stocking levels.

High stocking levels are likely to increase the negative effects of continuous grazing, because the area exposed to heavy, repeated re-use over time throughout the growing season will expand. Aside from the benefits of limited fencing and low daily management, this approach is most effective where forage availability is plentiful and the stocking rate is low, as required in steppe environments and arid grasslands. Furthermore, another benefit to continuous grazing is the limited presence of fences, which allows wild animal movement to be maintained. Grazing lands subject to continuous grazing systems can provide natural functions and generally remain well-adapted to both water and temperature stress (Borken & Matzner, 2009). This includes maintaining high carbon-use efficiencies (Maseyk et al., 2008) and soil organic carbon (SOC) storage (Lal, 2004; Yang et al., 2019), reduced land use impacts, and biodiversity benefits.

2.2 Multi-paddock rotational grazing

A multi-paddock grazing system is designed to control the timing, frequency and intensity of grazing by altering the length of the grazing period (Stanley et al., 2018; Teague et al., 2009). Using this system, grazing lands are separated into small patches or paddocks, and livestock are only allowed to access to relatively small parts of a pasture for a relatively short period. Thereafter, livestock are moved (rotated) through additional paddocks in sequence to ensure that desirable forage plants experience tolerable leaf area loss and have adequate time for recovery before being re-grazed (Da Trindade et al., 2012). Since adequate rest periods are an essential tool for managing grazing land productivity, recovery is determined by many factors, such as the inherent grazing tolerance of the plant species, plant phenology and rate of growth given the season, length of prior rest, weather and moisture availability, soil conditions including management factors, such as, fertility, irrigation for arid lands. . Ideally, multi-paddock grazing adjusts animal movement from each paddock to allow a length of plant recovery time adequate to ensure plant vigor and productivity given factors such as plant species and growing conditions.

The benefits of multi-paddock rotational grazing on livestock production have been realized (McDonald et al.,2018). By using high animals densities in small areas, multi-paddock grazing allows for more uniform forage offtake and subsequent manure/urine distribution, thereby cycling nutrients to the soil more effectively and preventing the redistribution of nutrients from grazed areas to loafing/bedding areas. When utilized properly, multi-paddock grazing may maintain plant vigor at higher levels throughout the landscape, thereby maintaining or increasing forage productivity, and under ideal conditions, future stocking rates. Multi-paddock grazing can help improve livestock productivity, measured as meat or milk production per hectacre, and overall net returns to the operator. However, the optimal recovery time under rotational grazing also depends on the season or time of year, which in turn, determines conditions such as day length and temperature. Grazing system sustainability depends on the length of the grazing period because grazing lands need an adequate recover interval prior to re-grazing. McDonald et al. (2018) indicated that sustainable grazing strategies incorporating periods of planned rest can improve the functionality and productivity of agricultural landscapes compared to continuous grazing.

However, multi-paddock grazing is not necessarily superior to continuous grazing (McDonald et al., 2018; Briske et al., 2013). As a form of management-intensive grazing, multi-paddock grazing requires detailed knowledge of plant ecophysiology and plant community ecology. Additionally, the use of high stocking densities can create greater risk to vegetation and soils if even small increases in grazing periods occur over and above optimal intervals. In dry or arid grazing lands, plant growth rates can be so slow that the need to have short grazing intervals is less important. Instead, pasture recovery will require a longer rest period in dry summers and arid rangelands. Moreover, these same conditions (aridity, low productivity) are not conducive to the use of small pastures due to the lack of drinking water, and low productivity, which would greatly increase costs per unit animal production. In contrast, multi-paddock grazing may be most effective in wetter and warmer seasons. Determining the number of days of rest required is, unfortunately, not a simple calculation. Understanding these factors and implementing the optimal grazing system is key to effective grazing management. However, this requires more knowledge and experience of forage plants, grazing intensity and pasture-animal interactions through watching and evaluating how pastures grow and recover. Furthermore, multi-paddock grazing requires more fence to be constructed, greater time requirements to move cattle, and reliable access to water and shade within each smaller paddock, leading to greater costs per unit area, and therefore unit animal production.

2.3 Paddock Design for optimal grazing management

The ideal layout of pastures to facilitate rotational grazing depends on the local landscape, vegetation, and soil conditions, together with the availability of drinking water. Here we focus on managed multi-paddock grazing lands because this approach may enhance the vigor of preferred plants, improve profitability and associated quality of life (Becker et al., 2017). Optimizing the grazing system can make a farm more productive and profitable. A multi-paddock grazing system is rotational to allow the more uniform seasonal forage productivity and increased stocking rates through a balance among utilization rate, animal consumption, forage yield and stocking rate (Fig. 1). Therefore, multi-paddock grazing management is essential to control livestock distribution in time and space, as well as allow adequate pasture recovery to maintain or improve the grazing resource.

Four basic parameters of paddock design include: 1) a balance between forage yield and livestock stocking rates, 2) attaining a uniform distribution of forage removal across each paddock, 3) an adaptable rest period during the interval between successive grazing period to ensure recovery and maintain pasture growth, and 4) matching the type of livestock with the composition and supply of forage. However, this summary is oversimplified because in multi-paddock rotational grazing, while selectivity is reduced, it is not eliminated, and therefore grazing animals still demonstrate a preference for certain species. Muller et al. (2007) showed that grazing management requires an adaptive framework to deal with this complexity, and which are mainly driven by unpredictable and stochastic rainfall. Therefore, the frequency and timing of livestock movement is very important and demands constant monitoring.

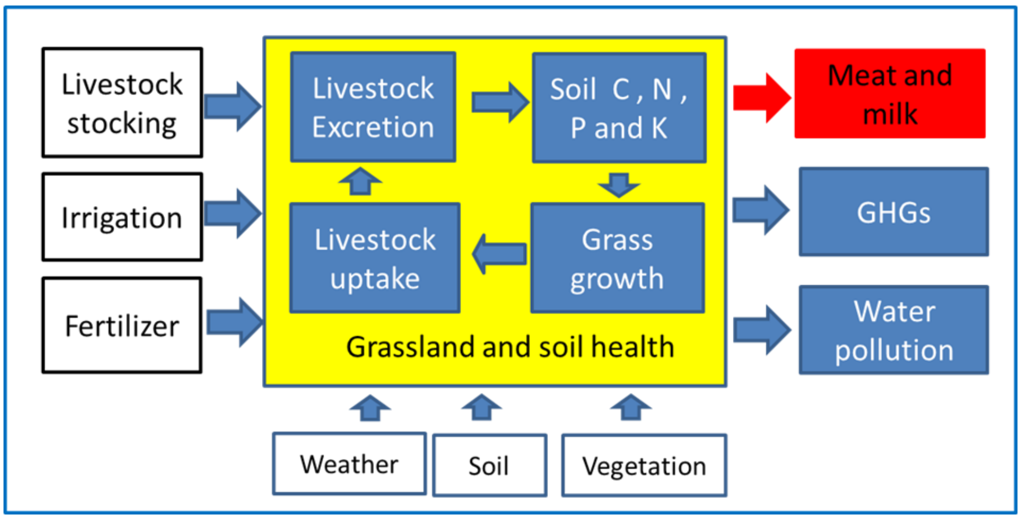

Fig. 1 A schematic of grassland system and nutrient cycle

Understanding the phases of annual forage growth, the corresponding instantaneous rates of growth, and the timing of the growth period for each forage species, are critical to facilitating management decisions, desinging adequate grazing and recovery periods. The overall conditions of a forage stand affect the number of animals that a pasture can support and the length of grazing, further modified by climate, fertilization, irrigation, and seasonality. Records of animal intake and pasture productivity are essential for maintaining pasture quality and optimal paddock designs. However, this increases labor cost to maintain the system since pastures will need to be checked more frequently. Furthermore, livestock are typically moved more frequently when plant growth is more rapid, and depends on frequent assessment of vegetation development and adaptation to use.

3. **Effects of grazing intensity on SOC, GHG emissions and other indicators**

Current studies focused primarily on collecting data to learn as much as possible about management actions (i.e., treatments) imposed at individual sites. However, there are many inconsistences among studies, including: 1) nuanced differences in grazing treatments, contrasting methods during soil sampling and chemical analyses, and variation in statistical analyses used to compile data over the long-term, leading to different formats, accuracies, units and structures of long-term data, and ultimately to inconsistent interpretation of results (Singer and Munns, 2006), 2) varied vegetation and soil responses to grazing along specific abiotic gradients due to ecological complexity (Wang and Wesche, 2016), and 3) profound differences among the temporal and spatial scales assessed. Overall, most data lack long-term temporal, spatial or methodological generality, obscuring the grazing impact mechanisms that determine ecosystem responses in grazing lands to new environments, or novel 'non-analogue' future conditions (Abdalla et al., 2018). The main aim of the evidence review is to identify knowledge gaps, overcome inconsistencies to eventually derive mitigation objectives.

3.1 Experimental setup, field sampling and indicators

Many field experiments compared effects of contrasting grazing practices on soil health, water infiltration, soil carbon stock, greenhouse gas emissions, nutrient runoff and soil erosion and grass cover (Wang et al., 2014; 2016). Controlled grazing experiments were commonly designed to use a gradient of grazing intensities, varying from ungrazed to very heavy grazing (Biondini et al. 1998; Patton et al. 2007) for a comprehensive analysis of grazing system responses to grazing. They found that belowground carbon stocks were higher than aboveground carbon in all management regimes. Badgery et al. (2017) performed a grazing system experiment to determine effects of the intensity of grazing management, varying from continuous grazing to flexible 4- and 20-paddock rotational systems, on the profitability and sustainability of a sheep production system.

Their results showed large variations in feed availability and quality over summer among years and flexible management were therefore suggested to utilize the greater feed supply in better seasons.

Wang and Wesche (2016) compared two groups of grassland indicators: vegetation (plant species richness, vegetation cover, aboveground biomass, belowground biomass and root/shoot ratio) and soil (pH, bulk density, SOC, total N, total P and available P) at sites with gradient grazing intensity. Most performance indicators declined with high stocking rates, while soil pH, bulk density and belowground biomass increased linearly with grazing intensity. Elevation and weather conditions had an impact on aboveground biomass and SOC while grazing effects on belowground biomass were affected by temperature. Savian et al. (2018) reported that multi-paddock rotational stocking at pre- and post-grazing sward target heights of 25 and 5 cm and 18 and 11 cm, respectively. They found a rotatinuous stockinghad a high potential to mitigate methane emissions by sheep. Jones et al. (2005) found that soil respiration from plots receiving manure was up to 1.6 times larger than CO_2 release from control plots and up to 1.7 times larger compared to inorganic treatments ($p<0.05$).

3.2 Carbon Input-Outputs: Vegetation diversity, productivity and quality

A large body of experimental evidence (Biondini et al. 1998; Patton et al. 2007) showed the impact of grazing management on biodiversity, SOC and GHG emission, nutrient run-off and leaching, and forage productivity . Lyseng et al. (2018) examined long-term grazing impacts on vegetation diversity, composition, and exotic species presence across an aridity gradient in northern temperate grasslands, and found that long-term grazing increased plant diversity, particularly the contribution of introduced vegetation, compared to the removal of grazing. Hewins et al. (2018) found that while climate had the largest impact on soil organic carbon concentration, grazing increased C concentration in more mesic grazing lands of Alberta, Canada. Flanagan et al. (2015) estimated ecosystem photosynthesis and net primary production from remote sensing measurements in a northern Great Plains grassland. Although substantial advances have been made in these areas, many gaps in our knowledge remain. Schönbach et al. (2009; 2011) performed five-years of trials with seven grazing intensities to assess ecosystem functioning in the Sino-German experimental sites, and estimated grazing-intensity effects on yielding performance, herbage quality and aboveground net primary production (ANPP). Herbage mass decreased linearly as the stocking rate increased. Herbage crude protein content was highest at high stocking rates, while lignin was lowest. The ANPP of production units was negatively affected by grazing stocking rates Gourlez de la Motte et al. (2018) monitored the net ecosystem exchange (NEE) and CO_2 fluxes using eddy covariance in two adjacent pastures located in southern Belgium during a complete grazing season. Their results showed that NEE fluxes were greatly affected by the grazing approach. Wang et al. (2016) used airborne imaging spectrometry to estimate the spatial pattern of productivity and biodiversity for two sites of contrasting productivity in a southern Alberta prairie ecosystem. Their reults showed that more diverse sites generally had greater productivity, supporting the hypothesis of a positive relationship between production and biodiversity for this site.

3.3. SOC and N Cycle as a Function of Grazing Intensity

Teague et al. (2016) indicated that grass cover under proper management is highly effective in reducing soil erosion and in increasing SOC stocks. A meta-analysis by Zhou et al. (2017) showed that livestock grazing activities potentially alter ecosystem carbon (C) and nitrogen (N) cycles in grassland ecosystems. Sustainable grazing leads to ecologically healthy, resilient agroecosystems and simultaneously reduces large quantities of anthropogenic GHG emissions. Badiou et al. (2011) studied GHGs and soil carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Li et al. (2012) studied SOM and carbon and nitrogen in grazing land. SOC and N stocks on a rough fescue grassland were not affected by grazing while soil bulk densities (0–30cm) were higher. Phosphorus (P) stocks (15–30 cm) were lower under grazing than ungrazing. Labile SOM responds to grazing at different slope positions is heterogeneous. Slope position plays an important role in regulating the response of labile soil organic matter to grazing (Zhang et al., 2018). In the bottom position, SOC, Total N, active C, NH_4^+-N, soil protein and water extractable N contents were higher under light grazing than under Heavy or Very Heavy grazing while in the top position, no significant differences were found among the three grazing treatments. Gao et al. (2018) investigated soil trace gas fluxes from grasslands in the foothills of the Rocky Mountains, Alberta. The grazed grassland soils increased 37 to 51% of CO_2 compared to ungrazed soils. The N_2O emissions under heavy and very heavy grazing were 122 to 179% greater than ungrazed in the wet season. There were no effects of grazing on N_2O emissions in the normal precipitation season. Bikila et al. (2016) compared grazing during the dry season with grazing enclosed for 20 years and burned grazing lands after fired for more than five years in Borana rangelands, Ethiopia. Their results showed that belowground carbon stocks were higher than the aboveground carbon stocks in all management systems. Tree and shrub carbon and soil organic carbon stocks were higher ($P < 0.01$) in rangelands enclosed for 20 years than other rangeland management systems, whereas grass carbon stocks was higher ($P < 0.05$) in fired rangelands.

McSherry and Ritchie (2013) conducted a multifactorial meta-analysis of grazing influences on SOC stocks on 47 independent experimental contrasts from 17 studies. They found that increasing grazing intensity increased SOC by 6-7% on C_4-dominated and C_4-C_3 mixed grasslands, but decreased SOC by an average 18% in C_3-dominated grasslands. Zhou et al. (2017) performed a comprehensive meta-analysis of 115 published studies to examine the responses of 19 indicators related to belowground C and N cycling to livestock grazing in global grasslands. They found that grazing intensity significantly altered belowground C and N cycling. Low grazing intensity contributed to soil C and N sequestration while moderate and high grazing intensity increased C and N losses. Their results showed that moderate and intensive grazing significantly decreased belowground C and N pools, with the largest decreases in microbial biomass C and N. Pools of C and N were also affected by soil depth, livestock type and climatic conditions. Therefore, grazing lands may act as a net sink of emitted GHGs by sequestrating carbon, and thus having a high potential to offset a substantial portion of GHG global mean forcing through the use of optimal grazing management (McSherry and Ritchie, 2013; Singer and Munns, 2006; Abdalla et al., 2018; Willians et al., 2007; Wilson et al., 2018).

Although enormous data have been collected on an exceptionally large number of variables, including soil properties (SOC, N, soil moisture, density, clay fraction) and management (grazing intensity, and fertilization), our understanding of underlying processes and quantification of environmental impacts and the underlying processes regulating soil C and N remains piecemeal. McSherry and Ritchie (2013) suggested that grazers in different regions may need to be uniquely managed to mitigate GHGs because . the effects of grazing on SOC stocks and GHGs are highly variable. Impacts of grazing on SOC stocks are in part because SOC stock and GHGs rely heavily on climate/weather conditions, soils, vegetation type, and grazing intensity at a variety of scales (McSherry and Ritchie, 2013; Belknap et al., 2005; Teague et al., 2011). Agro-climatic regions are particularly important for determining the vulnerability of grazing lands to climate change. For example, warmer and wetter climates can produce a shift in grassland species composition from C_3 to C_4 plant species. White et al. (2014) reported that herbage quantity and quality responses to climate changes were mainly influenced by warming and reduced precipitation at three northern temperate grassland sites across the Canadian prairies. Reduced precipitation decreased season-long accumulated herbage. Both reduced precipitation and warming decreased herbage quality but clipping increased quality. In tropical areas with higher rainfall, moderate grazing or higher stocking rates can be positive for soil carbon storage due to greater pasture growth. This, in turn, can increase soil attributes such as organic matter and water-holding capacity (Hebb et al., 2017). In contrast, intense grazing in arid and semi-arid grazing lands may reduce vegetation cover due to slow pasture growth, resulting in increases of wind erosion and a coarser soil texture. These factors can cause grasslands to become more vulnerable to SOC losses.

Due to the large number of combinatory factors in regulating grazing systems (vegetation x Animal Species x Environment x Management), regional management guidelines (stocking, timing, fertilization and irrigation, etc.) of multi-paddock versus continuous grazing are challenging. The debate regarding the relative ecological benefits of multi-paddock grazing compared to less intensive continuous grazing, has been prolonged by misinterpretation of concepts and terminology, evaluation of different response variables, and bioclimatic variability among regions, in addition to inherent intra- and inter-annual variability of grazing land systems (Briske et al., 2008; 2011; 2012; Teague, 2013; Mann and Sherren, 2018). This is partly because previously conducted field experiments cover only small parts of this complexity, and lack the real-world complexity to which actual grazing land are exposed. Thus, sustainable long-term grazing management strategies are still lacking, and grazing-land degradation is still immense. Therefore, efficient grazing management and grazing conservation require both a modification to the traditional management pattern and a reduction in overall livestock (Li et al. 2007; Suttie et al. 2005). Further studies should consider specific characteristics of different indicators in the context of the different regional environment (Wang and Wesche, 2016). An optimal grazing strategies exists between intensive multi-paddock grazing and continuous grazing. However, evidence is minimal that more intensive multi-paddock grazing lead to improved ecological outcomes, e.g. soil C sequestration. Considerable uncertainty exists about the impact of large herbivore grazing on SOC, especially for subtropical grazing lands and impact of grazing on partitioning of C allocation to root tissue production compared to fine root exudation (Wilson et al., 2018). Currently, the evidence on C sequestration does not justify extensive promotion and adoption of intensive multi-paddock grazing strategies, especially in arid and semi-arid regions.

4. Biogeochemical -Agroecosystem (BGC-AGC) models

Incorporating grazing management component into biogeochemical models such as DNDC (Li et al., 1993) and DayCent (Parton et al., 1998) has received much attention since these models integrate several domains, represent the current state of knowledge as a system framework and are more widely applicable than some other ago-ecosystem models (Rolinski et al, 2018; Sandor 2018; Vuichard 2007). .

Both the models require an enormous amount of diverse data, which is a formidable challenge but an essential step towards improving our understanding and ability to simulate C and N dynamics in grazed ecosystems. We are essentially dealing with four domains, i.e., plant, soil, animal (+human), and atmosphere, for which domain models exist (e.g. forage productivity by Barrett et al., 2005), and with integration of these domain models (e.g van Oijen et al., 2018). Livestock manure applied to grazing lands and faesces from grazing animals can stimulate forage production, but the long-term impacts of this practice on soil C and GHG dynamics are poorly understood. Developing grassland models can effectively support efforts to tackle climate change impacts, while increasing productivity and enhancing ecosystem services. However, both the models are limited in their plant growth domain and hence need to be calibrated for describing forage production.

4.1. Denitrification and Decomposition model (DNDC)

The DNDC is a mechanistic simulation model of C and N dynamics intended to study the biogeochemistry of soil carbon in arable lands. DNDC contains four interacting submodels: thermo-hydraulic, denitrification, decomposition, and plant growth. The soil thermo-hydraulic submodel simulates soil temperature and moisture profiles, which feed into the denitrification submodel and decomposition submodels. The decomposition submodel tracks soluble nitrogen and N pools in soil from decomposing plant residues and soil microbes growth and death, and the denitrification submodel is controlled by rainfall to calculate hourly denitrification processes, and therefore N_2 and N_2O production. All organic components distinguish four major SOC pools, namely residues, microbial biomass, humads, and humus. Each of the residue, microbes and humad pools consists of two or three sub-pools representing the relatively labile and resistant fractions of the pool. The humus pool is defined for the passive humus, which is relatively resistant and can remain so for decades to centuries in the soil. The plant growth submodel calculates daily root respiration, plant growth, N uptake by vegetation, growth intensity controlled by climate, nutrient and soil water status. Effects of agricultural practices (fertilisation, irrigation, tillage, crop rotation, and manure amendments) are incorporated into the model. Therefore, input datasets of land management practices are large sources of uncertainties in the N_2O emissions in grazing lands (Li et al., 1992; Wang et al., 2012; Yadav and Wang, 2017).

The DNDC model has been parameterized for the main types of grazing management to describe C and N turnover and GHG emissions under different grazing intensities, including the range of partitioning between above- and below-ground biomass. The combined model has been developed for soil and pasture of different grazing lands. Wang et al. (2012) modified the UK-DNDC to represent an enhanced livestock grazing function. For grazed pastures, animal grazing was parameterized according to grazing animal type, number, weight and timing. The amount of dung and urine from each animal was calculated to obtain the total amount of dung and urine produced per site. Grazing intensity per hectare was defined as the number of grazing animal number and grazing days, with corrected factors of animal weight during each grazing event.

4.2. DayCent model

DayCent is the daily time-step biogeochemical model based on CENTURY (Parton et al., 1995, 1996 1998), which consists of several submodels of SOM cycling, denitrification, nitrification, and phosphorus dynamics. It models soil C and N cycle, GHG emissions (e.g. N_2O, NO, N_2, NH_3, CH_4 and CO_2), plant growth, and net primary production in croplands, grasslands, forests and savannahs. The DayCent can simulate a wide range of crops and grasslands by altering a number of plant specific parameters. Plant production is simulated using a maximal production function constrained by temperature, water, and nutrients. Plant biomass uses five pools for live shoots and roots, and standing dead plant material and actual plant biomass production is a function of a genetic maximum defined for each crop. Plant residues are allocated into structural and metabolic pools within the SOM submodel. Each pool is divided into three SOM pools with different turnover rates/halflives. Agricultural practices (such as fertilization, tillage, irrigation, cutting and grazing) can be integrated into grazing lands on a daily basis, with aa fraction of the total boveground biomass removed to mimick biomass, and where the latter in turn, is regulated by the type of grazing system.

Owen et al. (2015) simulated long-term impacts of manure amendments on soil carbon and greenhouse gas dynamics of rangelands using DayCent in Marin and Sonoma counties, California, USA, comparing C and N stocks of manured and non-manured treatments on commercial dairies. Due to manure amendments, the total soil C and N pools increased with the onset of grazing by dairy cattle. Manure amendments increased soil C stocks by 19.0 ± 7.3 Mg C ha^{-1} and N stocks by 1.94 ± 0.63 Mg N ha^{-1}. respectively, compared to non-manured fields at 0–20 cm soil layer. N_2O emissions were proportional to total N additions and offset 75–100% of C sequestration. They also simulated long-term historical (1700–present) and future (present–2100) impacts of management on soil C and N dynamics, net primary productivity (NPP), and GHG emissions using DayCent. Modelling uncertainty was due to user adjustable parameters, such as organic matter input rates and the maximum nitrification rate. It is also due to the way the model handles some parameters, e.g. keepingsoil bulk density and pH constant through time despite their most like change. Henderson et al. (2015) using the Century and Daycent models for similar simulation scenarios, evaluating the net GHG mitigation potential for the world's native and cultivated grazing lands.

4.3 Comparison of process-based BGC-AES models

Abdalla et al. (2010) compared DayCent and DNDC to simulate N_2O emissions from cut and extensively grazed pasture located at the Teagasc Oak Park Research Centre, Co. Carlow, Ireland. DayCent underestimated N_2O flux for the control plots (deviation of -57% from measured) while DNDC over-predicted the measured flux with relative deviations of +132 and +258%, largely due to overestimation of the SOC. Therefore, both models required calibration for their response to N fertilizer and simulated background flux. Sandor et al. (2018) examined eight process-based models at five grassland sites (in France, New Zealand, Switzerland, United Kingdom and United States) to compare the sensitivity of modelled C and N fluxes to changes in the grazing animals (from 100% to 50% of the initial livestock densities) in combination with decreasing N fertilization levels (reduced to zero from the initial levels). They found that simulated patterns of enteric methane emission were characterized by high model-to-model variability. They alerted to the limitation of management variables and the lack of comprehensive validation data sets. Nevertheless, it is important to compare alternative modeling approaches for grassland and analyze their response uncertainty to variation in grazing management and explore the possibility of using models to determine sound mitigation practices. Grant et al. (2016) compared DayCent and DNDC models using data from long-term experiments in three locations on the Canadian prairies. They found that both models provided good results when used to investigate inter-annual crop production, soil carbon change, and N_2O emissions for N fertilized wheat systems. Main processes, such as microbial processes (nitrification or dentrification) ,and their interactions with one another equires to be further improved to estimate carbon change and trace gas fluxes.

Ehrhardt et al. (2018) conducted an international model comparison and benchmarking exercise of 24 process-based biogeochemical models for assessing uncertainties in crop and pasture ensemble model simulations of productivity and N_2O emissions. Across sites and crop/grassland types, 23%–40% of the uncalibrated individual models were within two standard deviations of observed yields, while 42 (rice) to 96% (grasslands) of the models were within 1 standard deviations of measured N_2O emissions. A higher uncertainty of grasslands many be due to spatio-temporal variabilities of animal movement and grazing intensities (historical integration and/or trajectories) that are likely to affect soil processes as well as productivity. However, the principles have to be maintained in spite of the significant uncertainties of underlying processes at multiple spatial and temporal scales (Wang et al., 2012). From this point of view, the process-based model can be improved for the relationships (or their absence) through the expression of the spatial and temporal trajectories of the stochastic grazing processes studied by clarifying the ambiguity of the grazing and stocking rates or grazing intensity.

Ehrhardt et al. (2018) questioned the use of model ensembles for upscaling projections of agricultural productivity and N_2O emissions from field scale to larger spatial units due to soil spatial variability which is likely to reduce the accuracy of model projections. Current biogeochemical models usually do not differentiate the effects of grazing intensities on hydrological processes (Shrestha and Wang, 2018b; Shrestha et al., 2018), which often creates a great challenge to the prediction of future feedbacks among the grazing intensity, nutrient runoff and the C and N cycle. Biogeochemical models models may need to differentially treat with grazing intensity in order to develop a more precise process-based mechanism for forecasting the feedback of grassland ecosystems to hydrological processes.

5. Watershed-scale Modeling

In many watersheds, grasslands above headwater streams and ponds can contribute to flooding control, trapp sediments and pollutants, retain nutrients, and maintain biological diversity, which extends into downstream reaches, lakes and estuaries (Riley et al., 2018). Watershed-scale modeling is a powerful instrument for simulating changes in nutrient runoff and water quality from grazing lands under diverse environmental and management scenarios (Islam et al., 2018). The Soil Water Assessment Tool (SWAT) and the Variable Infiltration Capacity (VIC) are two typical of watershed models (Arnold et al., 1998; Shrestha and Wang, 2018a; Eum et al., 2016). The SWAT is a land surface-atmosphere interactions model that has its origin in hydrological science, while the VIC is a process-based hydrologic model that considers the energy and water balance across the land surface (Eum et al., 2016; 2017; Dibike et al., 2018).

5.1. Soil & Water Assessment Tool (SWAT)

The Soil & Water Assessment Tool (SWAT) is a hydrological model at a watershed and river basin-scale. Digital Elevation Model (DEM), land use, and soil are used for generation of hydrological response units (HRUs) which includes a unique combination of land use, soil and slope. It is widely used in assessing the quality and quantity of surface and ground water, soil erosion prevention and control as well as in predicting the environmental impact of land use, land management practices, non-point pollutant sources and climate change (Arnold et al., 1998; Neitsch et al., 2011; Shrestha and Wang, 2018a).

The SWAT uses the conceptual C and N pools with varying turnover rates (Neitsch et al., 2011). In the original SWAT, the addition of manure, fertilizers, and litters are partitioned into five nitrogen pools: NH_4^+, NO_3^-, active, stable and fresh and into one-pool soil organic matter pool. Nutrient cycling (i.e., C and N) are closely linked to soil, plant and microbial processes in the SWAT to combine the soil factors (i.e, soil temperature, soil moisture, aeration and clay fraction). Fresh N is associated with plant residue and microbial biomass. The stable and active pools represents the soil humus.

The conceptual C and N pools in the SWAT were originally developed for assessing nutrient runoff and leaching related to water quality. The response of grasslands and rangelands have been simulated using manure applications from domestic animals, direct shedding (excretion) by livestock, estimating directly release to streams or groundwater and runoff to surface water system (Chanasyk et al., 2003; Shrestha et al., 2018b; Shrestha and Wang, 2019). Chanasyk et al. (2003) simulated surface runoff from grassland watersheds under three grazing intensities: ungrazed (control), intensive and very intensive (2.4 and 4.8 animal unit months per hectare, respectively) in Southern Alberta. Their surface runoff patterns showed large summer storm runoff rates from intensive grazed compared to other watersheds and large snowmelt-induced runoff from very intensive grazed. Dakhalla and Parajuli (2019) simulated streamflow, total sediment (TS), total phosphorus (TP), and total nitrogen (TN) load in Big Sunflower River watershed (BSRW). The animal population densities were calculated using the animal populations multiplied by the amount of grassland in the watershed. Runoff and sediment in small irrigated watershed in the Canadian prairie was investigated by Rahbeh et al. (2013) using SWAT. The irrigation activity did not change the water partitioning among the existing hydrological pathways but had temporal effects on the magnitudes of runoff and, more importantly, deep percolation and the subsequent groundwater discharge in the main reach. Shrestha and Wang (2019) simulated nutrient runoff and water quality in the Athabasca river basin (ARB), Alberta, Canada. Future climate of the ARB was projected to be warmer and wetter, relative to the base period. They found that climate changes can lead to decreased carbonaceous biochemical oxygen demand (cBOD) concentrations, mainly due to dilution and increased degradation. Further, a warmer future climate increased the tempearature which in turn reduced the dissolved oxygen (DO) concentrations. Therefore, under a changing climate, these cold regions could be more vulnerable than others because some special geographic features of the regions, such as glaciers, freezing soils and peatland, are more sensitive to changes in temperature and precipitation (Cui and Wang, 2019). This can impose serious threats on the water resources, sustainable goods production and ecosystem services that depend on regional water quality. Park et al. (2017a; 2017b) simulated effects of alternate grazing management practices on water quality at the ranch and watershed scales. They compared four grazing practices: heavy continuous (HC), light continuous (LC) and adaptive multi-paddock (MP) grazing, and no grazing (EX). Their results showed that grazing management practices can change vegetation cover and soil properties as well as watershed hydrological processes. The sediment and nutrient runoff at the watershed outlet can be reduced by 34% to 40% compared to using MP instead of HC grazing. Therefore, heavy grazing management with high stocking rates can cause substantially higher levels of runoff, sediment and nutrient losses to surface water systems.

5.2. Variable Infiltration Capacity (VIC) Model

As a large-scale process-based hydrologic model, the VIC model has basic features of land surface models (LSMs) that simulate the exchange of surface water and energy fluxes at the soil-atmosphere interface (Liang et al., 1994; 1996). The VIC model is also capable of capturing subgrid variabilities in land surface vegetation classes, soil moisture storage capacity, and topography (i.e.g, reflecting orographic precipitation and temperature lapse rates). In particular, VIC has notable strength in modelling hydrologic processes in cold regions (e.g., frozen soil, limited thaw depths, or where snow accumulation, ablation, and melting processes are common) (Cherkauer and Lettenmaier, 1999, Cherkauer et al., 2003).

Over the last decades, VIC has been updated many times and improvements made to multiple soil layers (Liang et al., 1996), dynamically coupling with a two-layer energy balance snow model (Andreadis et al., 2009), frozen soil (Cherkauer and Lettenmaier, 1999), permafrost algorithm (Adam and Lettenmaier, 2008), soil temperature heterogeneity method (Cherkauer et al., 2003), water table depth from soil moisture and texture (Bohn et al., 2013), blowing snow algorithm (Bowling et al., 2004), and elevation bands algorithm (Nijssen et al., 2001). VIC has also been recently updated to include a dynamic lake/wetland model that simulates permanent lakes, seasonal flooding of vegetated land and timely-varying exposed fraction of land covers within a grid cell (Bowling and Lettenmaier, 2010). Along with the improvements, the VIC model has been extensively applied for assessment of climate and land-cover changes on hydrologic systems (Eum et al., 2016; 2017; Shrestha et al., 2014), drought (Sheffield et al., 2004), and floods (Park and Markus, 2014; Schumann et al., 2013).

It is noted that the VIC has been modified to dynamically couple with carbon cycle processes that simulate photosynthesis, autotrophic respiration, and heterotrophic respiration with three soil carbon reservoirs (Bohn et al., 2013). Wetlands are recognized as carbon sinks, which store excess carbon from the atmosphere (Fung et al., 1991). Corresponding to the volumes of wetlands, the carbon stored in wetlands is released to the atmosphere in the form of methane. In other words, degradation and drainage of wetlands leads to methane release to the atmosphere. In addition, fluxes of GHGs are highly dependent on soil moisture and temperature (Ringeval et al., 2011), Therefore, modeling of dynamic lake/wetland areas is crucial to simulate GHG fluxes. Bohn et al., (2013) integrated a modified wetland methane emission model (Walter and Heimann, 2001) employing soil temperature, net primary productivity (NPP), and water table distribution derived from the VIC model for the Western Siberian Lowland. To employ the effects of grazing management into the VIC model, biochemical parameters need to be modified and a biogeochemical model (e.g., DayCent) need to be linked to further simulate a set of essential fluxes affected by the grazing management practices.

6. Current Trends in modelling for better management of grazing grasslands

Grazing systems contain complex interactions among grazing practices, biogeochemical processes, and hydrological drivers, often in unpredictable ways. The spatial and temporal heterogeneity of grazing lands coupled with highly variable management inputs minimizes the likelihood that a given management practice will consistently produce similar outcomes in all cases (Briske et al., 2014). Despite many successes in long-term experiments and modelling, the sustainability of grazing ecosystems is very complex due to a huge number of possible combinations of soil, water, climate, pasture species, livestock and farm practices. These field data represent a small part of the huge number of possibilities, and therefore remain inadequate to validate these models. Moreover, management of grazing lands requires highly adaptive approaches. The C and N cycles are strongly interrelated and dependent on soil, climate, and grazing management condition as well as on the timescale (Kayser et al., 2018). System modelling is key to effectively facilitate the learning required to create management strategies that fit specific economic and ecological conditions, and in turn, accommodate the inherent uncertainties of grazing land systems. Therefore, many process-based models have been developed. A current trend is to integrate biogeochemical and hydrological processes coupled with highly grazing management practices and monitoring networks. Challenges integrating BGC-AES and Hydrological Catchment Models exist in four categories: 1) Confusion and inconsistence in terms of grazing management goals and management practices, 2) extreme complexity in integration of animal movement and grazing intensity and excretion based on the highly adaptive nature of grazing practitioners, 3) linking SOM decomposition with soil microbial activities in land surface models, and 4) integration of biogeochemical and hydrological processe for the spatial and temporal heterogeneity at catchment scale.

6.1 Confusion and inconsistence in terms of grazing management goals

Different goals, abilities, values and opportunities of grazing research and management are multi-layered, multi-scale and complex. This could cause multiple and ambiguous meanings in both the objective physical, biological, and social realm, as well as the subjective realm of individual human perception in spite of attempts to standardize definitions. For example, the persistence of the multi-paddock rotational grazing debate is, at least in part, due to a wide range of goals and values among those individual responsible for managing grazing lands.

The multi-paddock grazing are suitable for increasing plant and livestock production while the continuous grazing are for maintaining ecological benefits, such as wild animal movement, biodiversity and wild conservation and slow pasture growth at low management due to arid conditions. However, the goals of continnous grazing in most ranchers' practices are also to increase plant and livestock production while this is economically viable to make sufficient returns to support their operation. Consistent with producer experience, published data from small paddock trials on both temporal and spatial aspects of grazing management demonstrate at least some capacity, even if not consistent across all conditions, for higher production under multi-paddock rotational grazing if applied appropriately, compared to continuous grazing. Though the benefits of multi-paddock grazing management on commercial livestock production have been realized in many countries, they may be limited by experimental grazing research and knowledge gaps. Because the vast majority of grazing experiments conducted since 1980 have examined intensive multi-paddock grazing systems with short-duration (Briske et al. 2008), they do not necessarily work for specific ecological purposes (e.g. biodiversity, C stocks and GHGs) in large scale. Many recent studies suggest that multi-paddock grazing benefits neither vegetation nor animal production relative to continuous grazing. Thus, the debate regarding the benefits of multi-paddock grazing has eluded resolution within the US rangeland profession for more than 60 yr (Briske et al., 2011; Broadbent et al., 2019; Teague et al. 2013). Roche et al. (2016) also showed considerable debate remains over the efficacy of multi-paddock grazing systems to enhance conservation and agricultural production goals on grazing lands. Particularly, the majority of grazing experiments are short in duration, and use rigid rotational protocols to increase replicability. Rigid rotation is not consistent with adaptively managed grazing strategies. Furthermore, they likely do not measure intensively enough to assess the full 'landscape' scale responses occurring (Teague et al. 2013). Nor do they contain the adaptive/flexible treatments that ranchers actually employ under real world variability. Therefore, it should not be surprising while research findings often suggest multi-paddock grazing management is not superior to continuous grazing. Conflicting management practices may address different goals of sustainable grassland functions (Crohn and Bianchi, 2008).

A quantitative accounting of the potential managerial contributions to the success of multi-paddock rotational grazing systems using system modelling is a prerequisite for addressing the controversy. Such a system model should consider interactions between natural variables, such as climate, soil, and pasture, and human variables, such as goal setting, stocking, experiential knowledge, and decision making. It should be indicated that effects of spatial and temporal scales on both economic and ecological goals should be studied between the trials and on-ranch adaptive grazing management strategies (Mann and Sherren, 2018; Qi et al., 2017, 2018). Conducting trial research on multi-paddock rotational grazing should be complementary with systems-level simulation modeling. These methods are particularly applicable where results of multi-paddock rotational grazing are used for assessing rangelands over decadal time frames at large scale. Resolving the discrepancies between the grazing systems research and management knowledge base will require an adequate framework to evaluate and manage complex adaptive systems (Briske et al., 2011). This is involving multiple economic and ecological goals, which requires substantive communication and novel approaches to participatory research between scientists and managers. Detailed comparisons of grazing methods and practical experiences of successful practitioners of multi-paddock grazing systems should identify numerous areas that explain why such different perceptions have arisen. Many researchers have failed to sufficiently account for these management factors, either in their treatment applications or in the evaluation of their results. To define the potential impact, researchers must quantify the management strategies for best achieving whole-farm business and ecosystem results under different perception and goals of grazing management.

6.2. Animal movement and grazing intensities

Variables associated with grazing intensity included a mixture of grazing management (stocking rates, and pasture recovery time) and animal preferences (water and pasture) and ranch characteristics (land types, climate regions, and ecoregions).

Variation and movement in animals and pastures are major sources of uncertainties that can bias results if inappropriate experimental designs or sampling techniques are used. Multi-paddock grazing requires logistic details: the paddock size, position and gate sites, stocking rate, and timing of movement through the rotation. Timing is dependent on a number of variables, such as stocking rate and forage quality and quantity. However, the key component required for modelling GHGs, nutrient cycle and soil health and grass regrowth is the movement and preferences of animals within a paddock, which is the grazing heterogeneity. The animal grazing depends primarily on the distribution of palatable species and water sources but also on the strategy and type of animal. Knowledge of the grazing intensity and distribution is also essential for animal moving frequency based on desired animal number and rate of weight gain to develop process-based models for rotational grazing system. The failure to account for related plant and animal processes at appropriate temporal and spatial scales can result in incorrect representaion in the process-based models for grazing land management. The lack of effective monitoring animal movement at a large spatial scale severely limits research on the mechanism, model development, and simulation of animal behaviors. Without that, the grazing intensity cannot be quantified, which results in insufficient analysis and simulation of processes dependent on animal movement and grazing intensity. Improvement in remote sensing-based monitoring of animal movement and pasture quality might be helpful to analyze and understand these couple processes and mechanisms. Collaborations in multi-disciplinary and multi-partnerships will show the way.

The complexity within these models originate from the multiplicity of factors involved and resulting spatial and temporal variabilities of animal activities in time, in other words, their prior use patterns and trajectories. As a consequence, causal relationships between animal activity and grazing intensity are difficult to establish, but remain fundamental to building the grazing model and understanding these causal links. From this point of view, the process-based model can be improved for the relationships (or their absence) through the expression of the spatial and temporal trajectories of the grazing processes studied, including clarifying the ambiguity of specific grazing practices such as stocking rates or grazing intensity, as well as the length of the grazing period.

6.3. SOM decomposition kinetics

There are three areas of interest for possible improvements of C and N models: i) soil biology, comprising SOM heterogeneity, decomposition kinetics; ii) soil hydrology, lateral flow and its effects on reaction rates; and iii) grazing management, which affect manure distribution and heterogeneity by modifying soil physical, chemical and biological properties (Brilli et al., 2017; Bhanja et al., 2019a, 2019b; Shrestha et al., 2018a, 2018b).

Current land-surface models usually do not differentiate the effects of grazing intensities on belowground C and N cycles (Lal, 2004; Henderson et al., 2015; Tagesson et al., 2015; Luo et al., 2016). This can lead to a great challenge to the prediction of future feedbacks between the climate and the C cycle. Future land-surface models may need to differentially treat with grazing intensity in order to develop a more precise process-based mechanism for forecasting the feedback of grassland ecosystems to climate change. Over the past several decades, much effort has been made in developing process-based models of key biogeochemical processes of SOM turnover, such as, DNDC (Li et al., 1992), CENTURY and Daycent (Parton, 1996, Parton et al., 1998), Roth-C (Jenkinson and Coleman, 2008), VIC (Bohn et al., 2013), and SWAT (Neitsch et al., 2011), are based on conceptual pools of C and N turnover at varying rates. Each pool can be assigned a mean residence time (MRT) within the spatially averaged soil, and is affected by the reactivity and environmental constraints on the decomposition of the SOM (Davidson and Janssens, 2006).

Inconsistent results are due to the underlying assumptions of these carbon pools for the kinetics of SOM decomposition rates and their 'volume averaged' or 'mass averaged' approaches in the conventional process-based models, which are still subject to debate (Davidson and Janssens, 2006). Microbial activities substantially depend upon spatio-temporal variations in water, temperature and substrate availability (Davidson et al., 2012, 2014). Brilli et al. (2017) suggested that future development of C and N models should explicitly account for soil microbial biomass to drive SOM turnover, the effect of N shortage on SOM decomposition, the improvements related to the production and consumption of gases and an adequate description of gas transport in soil. This implied possible limitations in the underlying hypotheses from the literature in the cases where discrepancies between model and observation. Despite this extensive analysis, knowledge basic mechanisms driving C and N cycles in agricultural systems is still far from complete and key questions remain about the cascade of events that finally lead to biological responses. Some recent studies (Bhanja et al., 2019a, 2019b) formulated the sequential oxidation-reduction potential (ORP) and chemical reactions undergoing at the soil-water zone using dual Arrhenius and Michaelis-Menten (DAMM) kinetics to contribute towards more reliable estimates of C and N cycles from grazing systems.

6.4. Integration of biogeochemical and hydrological processe for the spatial and temporal heterogeneity at catchment scale

Modelling of different grazing ecosystems is challenging as there are intrinsically different parameterization of grazing intensity that represents grazing animal activities (Wang et al., 2012; Tian et al., 2018; Luo et al., 2016); to date, mainstream soil carbon models of grazing systems have not recognized these distinctions in their simulations of soil carbon dynamics due to grazing management practices and livestock excreta deposition, which could result in uncertainties on soil C and N cycles in managed grasslands. Developing grazing grassland models to effectively support efforts to enhance ecosystem services while increase productivity will require engagement with stakeholders and policy-makers, as well as modellers and experimental researchers across many disciplines (Kipling et al., 2016).

Groffman et al. (2009) showed the importance of the effects of hydrological processes on C and N cycles, which may need to be incorporated into regional and global models for predicting effects of human disturbance on global grasslands and assessing the climate-biosphere feedbacks. More importantly, typical water cycle regions are river basins acting as natural water system boundaries. Therefore, models could be able to simulate the lateral flow and distribution of water, nitrogen and carbon within landscapes, stream flows, and sediment and nutrients runoff in river networks. Further work remains on spatially representative from different grazing ecosystems. It is, therefore, of paramount importance that interactions between different processes and controls of soil carbon and nutrient cycles and nutrient runoff to surface water are reflected in the models. Quantifying such interactions between biogeochemical and hydrological processes should be a research priority (Shrestha and Wang, 2018a).

In grassland ecosystems, the major sources of GHGs (N_2O, CO_2 and CH_4) emissions, aside from enteric methane production, are livestock excreta deposition, manure application, and mineral application (Dangal et al, 2019). Current challenges are finding ways to estimate interaction between biogeochemical and hydrological processes. In recent years, a fully-coupled soil carbon and nitrogen module of an agroecosystem model, (i.e., DAYCENT) has been incorporated into SWAT (Shrestha and Wang, 2018b; Shrestha et al., 2018). The coupling algorithms of nitrification and denitrification from the Daycent models explicitly link the DAYCENT and SWAT model, which simulates carbon and nitrogen partitioning, to modules of soil carbon and nitrogen turnover in grazing lands. A more detailed microbial and thermodynamic kinetics of SOM turnover has been developed by using DAMM kinetic within the SWAT framework (Bhanja et al., 2019a, 2019b). Here the variables of the SWAT, NH_4^+ and NO_3^-, are directly coupled with the submodels of nitrification and denitrifications (Shrestha et al., 2018a; 2018b; Bhanja et al., 2019a, 2019b). Their models are based on the SWAT model framework at a watershed scale and therefore, the lateral hydrological flow and substrate fluxes have been considered.

7. Concluding remarks

During the last decades, intensively managed grazing systems have been studied extensively in terms of livestock productivity, pasture diversity, GHG emission, carbon storage and erosion. We integrated a diverse body of experimental evidence in spite of data and assumptions seemingly inconsistent and disconnected from current guidelines. We hypothesized that modelling can help to identify the main factors (environmental, management) that affect grassland and rangeland productivity and degradation. This review alerted to some important deficiencies, experimental and systematic knowledge gaps in this area. Our aim was to suggest directions in which future experiments, monitoring, and modelling needs to go to improve knowledge transfer for better management guidelines.

We reviewed two main grazing management systems: continuous grazing and multi-paddock grazing finding two main reasons for knowledge and knowledge transfer gaps: 1) SCALE: farm or rangeland management, 2) USER: researchers or farmers. This can cause some confusion in the debate of future research needs. Results in most multi-paddock grazing research are generated under specific environmental conditions at plot or farm scale, which cannot be scaled to other systems, rangelands. However, using models these results can be extrapolated to other environments (climate, soil and weather conditions). Particularly, differently managed grasslands using multi-paddock or continuous grazing, clarified key ambiguities of grazing management and converged directions of future research and knowledge transfer.

The growing appreciation of climate change impacts and natural ecosystem restoration, criteria like biodiversity and soil health should be considered in the allocation of managed/farmed versus natural grasslands ecosystem services. The best grazing management is not simply a trade-off or optimization between livestock productivity and environmental impacts but accounts for improving other ecosystem services. The choice of sustainability criteria and ecosystem service values can change the valuation of grazing ecosystems from high livestock productivity (multi-paddock with high stocking) to environmental conservation (continuous rangeland with low stocking). Effective grazing management offers great potential to achieve sustainable use of grasslands and rangelands to meet increasing food demands, mitigate climate change and provide ecosystem services. The future of grazing research requires an integrated approach to whole systems' analysis for variable outcomes of grazing systems.

The principle to link well-established multi-paddock grazing experiments with models have widely been applied but need to be challenged and become an effective guideline. This review critically evaluated and discussed the methods to describe interactions between livestock productivity and landscape degradation for currently used grazing systems. Research showed that multi-paddock grazing is well described by a combination of variables, such as stocking rates, timing, animal activities, and diversity to optimize livestock and pasture productivity. The complex grazing systems need a comprehensive evaluation that explicitly incorporates qualitative and quantitative knowledge of the management, and technological and biophysical components of grasslands systems. System models are key to effectively integrate multi-layer evidence to create management strategies that fit specific socio-economic and ecological settings and account for the inherent uncertainties of grassland or rangeland ecosystems. However, much remains to be done to build these generic models and evaluation criteria due to the variety of pedo-climatic properties, grazing practice, and pasture growth. Scientists and stakeholders should collaborate closely with farmers and ecologists to bridge the knowledge gaps and connect with progresses in this multidisciplinary field.

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References

Alberta Agriculture, Food and Rural Development (AAFRD). Beneficial Management Practices: Environmental Manual for Alberta Cow/Calf Producers. 2004.

Abdalla, M.; Jones, M.; Yeluripati, J.; Smith, P.; Burke, J.; Williams, M. Testing DayCent and DNDC model simulations of N_2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture, Atmospheric Environment 2010, 44, 2961-2970.

Abdalla, M.; Hastings, A.; Chadwick, D.R.; Jones, D.L.; Evans, C.D.; Jones, M.B.; Rees, R.M.; Smith, P. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands, Agriculture, Ecosystems & Environment 2018, 253, 62-81.

Adam, J.C., Lettenmaier, D.P., 2008. Application of New Precipitation and Reconstructed Streamflow Products to Streamflow Trend Attribution in Northern Eurasia. Journal of Climate 21, 1807–1828. https://doi.org/10.1175/2007JCLI1535.1

Andreadis, K.M., Storck, P., Lettenmaier, D.P., 2009. Modeling snow accumulation and ablation processes in forested environments: VIC SNOW MODEL. Water Resources Research 45. https://doi.org/10.1029/2008WR007042

Anderson, J.M. The effects of climate change on decomposition processes in grassland and coniferous forests. Ecological Applications 1991, 1, 326–347.

Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment part I: model development. J. Am. Water Resour. Assoc. 1998, 34, 73-89.

Badgery, W.B.; Mitchell, D.; Millar, G.D.; Broadfoot, K.; Michalk, D.L.; Cranney, P.; Brown, W. Designing a grazing-system experiment for variable native pastures and flexible lamb-production systems. Animal Production Science 2017, 57(9), 1785-1798.

Badiou, P.; McDougal, R.; Pennock, D.; Clark, B. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetlands Ecol Manage 2011, 19, 237–256.

Barrett, P.D.; Laidlaw, A.S.; Mayne, C.S. GrazeGro: a European herbage growth model to predict pasture production in perennial ryegrass swards for decision support. European Journal of Agronomy 2005, 23, 37-56.

Becker, W.; Kreuter, U.; Atkinson, S.; Teague, R. Whole-Ranch Unit Analysis of Multi-paddock Grazing on Rangeland Sustainability in North Central Texas. Rangeland Ecology & Management 2017, 70, 448-455.

Belknap, J.; Welter, J.R.; Grimm, N.B.; Barger, N.; Ludwig, J.A. Linkages between microbial and hydrologic processes in arid and semiarid watersheds. Ecology 2005, 86, 298–307

Bhanja, S.N.; Wang, J.; Shrestha, N.K.; Zhang, X. Microbial kinetics and thermodynamic (MKT) processes for soil organic matter decomposition and dynamic oxidation-reduction potential: Model descriptions and applications to soil N_2O emissions, Environmental Pollution 2019a, 247, 812-823.

Bhanja, S.N.; Wang, J.; Shrestha, N.K.; Zhang, X. Modelling microbial kinetics and thermodynamic processes for quantifying soil CO_2 emission. Atmospheric Environment 2019b, 209, 125–135.

Biondini ME, Patton BD, Nyren PE (1998) Grazing intensity and ecosystem processes in a northern mixed-grass prairie. USA Ecol Appl 8:469–479.

Bikila, N.G.; Tessema, Z.K.; Abule, E.G. Carbon sequestration potentials of semi-arid rangelands under traditional management practices in Borana, Southern Ethiopia. Agriculture, Ecosystems & Environment 2016, 223, 108-114.

Bohn, T.J., Podest, E., Schroeder, R., Pinto, N., McDonald, K.C., Glagolev, M., Filippov, I., Maksyutov, S., Heimann, M., Chen, X., Lettenmaier, D.P., 2013. Modeling the large-scale effects of surface moisture heterogeneity on wetland carbon fluxes in the West Siberian Lowland. Biogeosciences 10, 6559–6576. https://doi.org/10.5194/bg-10-6559-2013

Borken, W.; Matzner, E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. Global Change Biology 2009, 15, 808-824.

Bowling, L.C., Lettenmaier, D.P., 2010. Modeling the Effects of Lakes and Wetlands on the Water Balance of Arctic Environments. Journal of Hydrometeorology 11, 276–295.

Bowling, L.C., Pomeroy, J.W., Lettenmaier, D.P., 2004. Parameterization of blowing-snow sublimation in a macroscale hydrology model. Journal of Hydrometeorology 5, 745–762.

Cherkauer, K.A., Bowling, L.C., Lettenmaier, D.P., 2003. Variable infiltration capacity cold land process model updates. Global and Planetary Change 38, 151–159.

Brilli, L.; Bechini, L., Bindi, M.; Carozzi, M.; Cavalli, D.; Conant, R.; Dorich, C.D.; Doro, L.; Ehrhardt, F.; Farina, R.; Ferrise, R.; Fitton, N.; Francaviglia, R.; Grace, P.; Iocola, I.; Klumpp, K.; Léonard, J.; Martin, R.; Massad, R.S.; Recous, S.; Seddaiu, G.; Sharp, J.; Smith, P.; Smith, W.N.; Soussana, J.-F.; Bellocchi, G. Review and analysis of strengths and weaknesses of agro-ecosystem models for simulating C and N fluxes. Sci. Total Environ. 2017, 598, 445–470.

Briske, D.D.; Derner, J.D.; Brown, J.R.; Fuhlendorf-Doff, S.D.; Teague, W.R.; Havstad, K.M.; Gillen, R.L.; Ash, A.J.; Willms. W.D., Rotational Grazing on Rangelands: Reconciliation of Perception and Experimental Evidence. Rangeland Ecology & Management 2008, 61(1), 3-17.

Briske, D.D.; Sayre, N.F.; Huntsinger, L.; Fernandez-Gimenez, M.; Budd, B.; Derner, J.D. Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. Rangeland Ecol. Manage. 2011, 64, 325–334.

Briske, D.D.; Bestelmeyer, B.T.; Brown, J.R.; Fuhlendorf, S.D.; Polley, H.W. 2013. The Savory method can not green deserts or reverse climate change: a response to the Allan Savory TED video. Rangelands 2013, 35(5), 72–74.

Briske, D.D.; Ash, A.J.; Derner, J.D.; Huntsinger, L. Commentary: A critical assessment of the policy endorsement for holistic management, Agricultural Systems 2014, 125,50–53.

Broadbent, T.S.; Bork, E.; Cooke, J.E.; Willms, W.D. Grass Yields Under Clipping and Watering Explain Varied Efficacy of Management Intensive Grazing on Rangelands. Rangeland Ecology & Management 2019, DOI: 10.1016/j.rama.2018.11.009

Chanasyk, D.S.; Mapfumo, E.; Willm, W. Quantification and simulation of surface runoff from fescue grassland watersheds. Agricultural Water Management 2003, 59(2), 137-153.

Cherkauer, K.A., Lettenmaier, D.P., 1999. Hydrologic effects of frozen soils in the upper Mississippi River basin. Journal of Geophysical Research: Atmospheres 104, 19599–19610.

Cuo, L., Beyene, T.K., Voisin, N., Su, F., Lettenmaier, D.P., Alberti, M., Richey, J.E., 2011. Effects of mid-twenty-first century climate and land cover change on the hydrology of the Puget Sound basin, Washington. Hydrological Processes 25, 1729–1753. https://doi.org/10.1002/hyp.7932

Crohn, D.M.; Bianchi, M.L. Research priorities for coordinating management of food safety and water quality. Journal of Environmental Quality 2008, 37(4), 1411-1418.

Cui, G.; Wang, J. Improving the DNDC biogeochemistry model to simulate soil temperature and emissions of nitrous oxide and carbon dioxide in cold regions. Science of the Total Environment 2019, 687, 61-70.

Cuo, L., Lettenmaier, D.P., Alberti, M., Richey, J.E., 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes 23, 907–933. https://doi.org/10.1002/hyp.7228

Dakhlalla, A.O.; Parajuli, P.B. Assessing model parameters sensitivity and uncertainty of streamflow, sediment, and nutrient transport using SWAT. Information Processing in Agriculture 2019, 6, 61-72.

Dangal, S.R.S.; Tian, H.; Xu, R.; Chang, J.; Canadell, J. G.; Ciais, P., et al. Global nitrous oxide emissions from pasturelands and rangelands: Magnitude, spatiotemporal patterns, and attribution. Global Biogeochemical Cycles 2019, 33. https://doi.org/10.1029/2018GB006091

Da Trindade, J.K.; Pinto, C.E.; Neves, F.P.; Mezzalira, J.C.; Bremm, C.; Genro, T.C.M.; Tischler, M.R.; Nabinger, C.; Gonda, H.L.; Carvalh, P.C.F. Forage Allowance as a Target of Grazing Management: Implications on Grazing Time and Forage Searching. Rangeland Ecology & Management 2012, 65, 382-393. https://doi.org/10.2111/REM-D-11-00204.1

Davidson, E.A.; Janssens, I.A. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 2006, 440, 165-173.

Davidson, E.A.; Samanta, S.; Caramori, S.S.; Savage, K. The Dual Arrhenius and MichaeliseM enten kinetics model for decomposition of soil organic matter at hourly to seasonal time scales. Glob. Chang. Biol. 2012, 18, 371-384.

Davidson, E. A.; Savage, K.E.; Finzi, A.C. A big-microsite framework for soil carbon modeling, Global Change Biol. 2014, 20(12), 3610–3620, doi:10.1111/gcb.12718.

De Bruijn, S.J.; Bork, E.; Grekul, C.W. Neighbor defoliation regulates Canada thistle (Cirsium arvense) in pasture by mediating interspecific competition. Crop Protection 2010, 29(12), 1489-1495.

De Klein, C.; Eckard, R. Targeted technologies for nitrous oxide abatement from animal agriculture. Animal Production Science 2008, 48(2), 14–20. https://doi.org/10.1071/EA07217

de Groot, R.S.; Alkemade, R.; Braat, L.; Hein, L.; Willemen, L. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 2010, 7, 260-272. https://doi.org/10.1016/j.ecocom.2009.10.006

Dibike, Y.B.; Eum, H.-I.; Prowse, T. Modelling the Athabasca watershed snow response to a changing climate. Journal of Hydrology: Regional Studies 2018, 15, 134-148. DOI: 10.1016/j.ejrh.2018.01.003

Ehrhardt, F.; Soussana, J.-F.; Bellocchi, G.; Grace, P.; McAuliffe, R.; Recous, S.; Sándor, R.; Smith, P.; Snow, V.; Migliorati, M. de A.; Basso, B.; Bhatia, A.; Brilli, L.; Doltra, J.; Dorich, C.D.; Doro, L.; Fitton, N.; Giacomini, S.J.; Grant, B.; Harrison, M.T.; Jones, S.K.; Kirschbaum, M.U.F.; Klumpp, K.; Laville, P.; Léonard, J.; Liebig, M.; Lieffering, M.; Martin, R.; Massad, R.S.; Merbold, E.M.L.; Moore, A.D.; Myrgiotis, V.; Newton, P.; Pattey, E.; Rolinski, S.; Sharp, J.; Smith, W.N.; Wu,; L.; Zhang, Q. Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N_2O emissions. Global Change Biology 2018, 24(2), e603-e616

Eum, H.-I.; Dibike, Y.; Prowse, T.D. Comparative evaluation of the effects of climate and land-cover changes on hydrologic responses of the Muskeg River Alberta, Canada. J. Hydrol.: Reg. Stud. 2016, 8, 198-221.

Eum, H.-I.; Dibike, Y.; Prowse, T.D. Climate-induced alteration of hydrologic indicators in the Athabasca river basin, Alberta, Canada. J. Hydrol. 2017, 544, 327-342.

Flanagan, L.B.; Sharp, E.J.; Gamon, J.A. Application of the photosynthetic light-use efficiency model in a northern Great Plains grassland. Remote Sensing of Environment 2015, 168:239-251.

Forbes, J.M. Voluntary food intake and diet selection in farm animals. Wallingford, UK: CABI Publishing; 2007.

Fung, I., John, J., Lerner, J., Matthews, E., Prather, M., Steele, L.P., Fraser, P.J., 1991. Three-dimensional model synthesis of the global methane cycle. Journal of Geophysical Research: Atmospheres 96, 13033–13065.

Gao, X.; Thomas, B.W.; Beck, R.; Thompson, D.J.; Zhao, M.; Willms, W.D.; Hao, X. Long-term grazing alters soil trace gas fluxes from grasslands in the foothills of the Rocky Mountains, Canada, Land Degrad Dev 2018, 29 (2), 292-302.

Gardener, C.J. Diet selection and liveweight performance of steers on Stylosanthes hamata- native grass pastures. Aust J Agric Res 1980, 31, 379-392.

Grant, B.B.; Smith,W.N.; Campbell, C.A.; Desjardins, R.L.; Lemke, R.L.; Kröbel, R.; McConkey, B.G.; Smith, E.G.; Lafond, G.P.; Del Grosso, S.; Ahuja, L.; Parton,W. Comparison of DayCent and DNDC models: case studies using data from long-term experiments on the Canadian prairies. Advances in Agricultural Systems Modeling 6. Synthesis and Modeling of Greenhouse Gas

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 July 2019 doi:10.20944/preprints201907.0003.v1

Emissions and Carbon Storage in Agricultural and Forest Systems to Guide Mitigation and Adaptation, pp. 21–58, 2016.

Gourlez de la Motte, L.; Mamadou, O.; Beckers, Y.; Bodson, B.; Heinesch, B.; Aubinet, M. Rotational and continuous grazing does not affect the total net ecosystem exchange of a pasture grazed by cattle but modifies CO_2 exchange dynamics. 2018, 253, 157-165.

Groffman, P.M.; Butterbach-Bahl, K.; Fulweiler, R.W.; Gold, A.J.; Morse, J.L.; Stander, E.K.; Tague, C.; Tonitto, C.; Vidon, P. Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models. Biogeochemistry 2009, 93, 49-77.

Hebb, C.; Schoderbek, D.F.; Hernandez-Ramirez, G.; Hewins, D.B.; Carlyle, C.N.; Bork, E.W. Soil physical quality varies among contrasting land uses in Northern Prairie regions. Agriculture, Ecosystems & Environment 2017, 240, 14-23.

Heitschmidt, R.K.; Walker, J.W. Grazing management: technology for sustaining rangeland ecosystems. Rangeland Journal 1996, 18, 194-215.

Henderson, B.B.; Gerber, P.J.; Hilinski, T.E.; Falcucci, A.; Ojima, D.S.; Salvatore, M.; Conant, R.T. Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. Agriculture, Ecosystems & Environment 2015, 207, 91-100. https://doi.org/10.1016/j.agee.2015.03.029.

Hewins, D.B.; Lyseng, M.P.; Schoderbek, D.F.; Alexander, M.; Willms, W.D.; Carlyle, C.N.; Chang, S.X.; Bork, E.W. Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Scientific Reports 2018, 8, No 1336 (2018).

IPCC 2007. Climate change 2007: the physical science basis, contribution of working group I to thefourth assessment repor t of the Intergovernmental Panel on Climate Change: frequently asked questions. In: S Solomon, M Qin, Z Manning, M Chen, K Marquis, T Avery, M Tignor, H Miller, editor. Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK: Cambridge University Press; p. 996.

Jacobo, E.J.; Rodríguez, A.M.; Bartoloni, N.;.Deregibus, V.A. Rotational Grazing Effects on Rangeland Vegetation at a Farm Scale. Rangeland Ecol Manage 2006, 59, 249–257.

Jenkinson, D.S.; Coleman, K. The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. Eur. J. Soil Sci. 2008. 59, 400-413.

Jones, S. K.; Rees, R.M.; Skiba, U.M; Ball, B.C. Greenhouse gas emissions from a managed grassland. Global and Planetary Change 2005, 47(2-4), 201-211. https://doi.org/10.1016/j.gloplacha.2004.10.011

Kayser, M.; Müller, J.; Isselstein, J. Grassland renovation has important consequences for C and N cycling and losses. Food and Energy Security 2018, in press

Kipling, R.P., et al. Key challenges and priorities for modelling European grasslands under climate change. Science of the Total Environment 2016, 566–567, 851–864.

Lal, R. Soil carbon sequestration to mitigate climate change, Geoderma 2004, 123, 1 –22.

Latham, J.; Cumani, R.; Rosati, I.; Bloise, M. Global Land Cover SHARE (GLC-SHARE) database Beta-Release Version 1.0 – 2014. FOA report. http://www.fao.org/uploads/media/glc-share-doc.pdf

Li, C.; Frolking, S.; Frolking, T.A. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. Journal of Geophysical Research Atmosphere 1992, 97, 9759-9776.

Li, C.; Hao, X.; Ellert, B.H.; Willms, W.D.; Zhao, M.; Han, G. Changes in soil C, N, and P with long-term (58 years) cattle grazing on rough fescue grassland. J. Plant Nutr. Soil Sci. 2012, 175, 339–344

Li, W.J.; Ali, S.H.; Zhang, Q. Property rights and grassland degradation: a study of the Xilingol Pasture, Inner Mongolia. China J Environ Manage 2007, 85, 461–470.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research: Atmospheres 99, 14415–14428.

Liang, X., Wood, E.F., Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. Global and Planetary Change 13, 195–206.

Lyseng, M.P.; Bork, E.W.; Hewins, D.B.; Alexander, M.J.; Carlyle, C.N.; Chang, S.X.; Willms, W.D. Long-term grazing impacts on vegetation diversity, composition, and exotic species presence across an aridity gradient in northern temperate grasslands. Plant Ecology 2018, 219 (6), 649-663.

Luo, Y., et al. Toward more realistic projections of soil carbon dynamics by Earth system models, Global Biogeochem. Cycles 2016, 30, 40–56, doi:10.1002/2015GB005239.

Mann, C.; Sherren, K. Holistic Management and Adaptive Grazing: A Trainers' View. Sustainability 2018, 10, 1848.

Maseyk, K.; Lin, T.; Rotenberg, E.; Grünzweig, J.M.; Schwartz, A.; Yakir, D. Physiology-phenology interactions in a productive semi-arid pine forest. New Phytologist 2008, 178, 603–16.

McDonald, S.E.; Reid, N.; Waters, C.M.; Smith, R.; Hunter, J. Improving ground cover and landscape function in a semi-arid rangeland through alternative grazing management. Agriculture, Ecosystems & Environment 2018, 268, 8-14.

McSherry, M.E.; Ritchie, M.E. Effects of grazing on grassland soil carbon: a global review. Global Change Biology 2013, 19, 1347–1357.

Müller, B.; Frank, K.; Wissel, C. Relevance of rest periods in non-equilibrium rangeland systems - A modeling analysis. Agricultural systems 2007, 92, 295-317.

Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R., 2011. Soil & water assessment tool theoretical documentation, version 2009, Grassland, soil and water research laboratory-agricultural research service. Blackland Research Center-Texas AgriLife Research

Nijssen, B., Bowling, L.C., Lettenmaier, D.P., Clark, D.B., El Maayar, M., Essery, R., Goers, S., Gusev, Y.M., Habets, F., van den Hurk, B., Jin, J., Kahan, D., Lohmann, D., Ma, X., Mahanama, S., Mocko, D., Nasonova, O., Niu, G.-Y., Samuelsson, P., Shmakin, A.B., Takata, K., Verseghy, D., Viterbo, P., Xia, Y., Xue, Y., Yang, Z.-L., 2003. Simulation of high latitude hydrological processes in the Torne–Kalix basin: PILPS Phase 2(e). Global and Planetary Change 38, 31–53. https://doi.org/10.1016/S0921-8181(03)00004-3

Oertel, C.; Matschullat, J.; Zurba, K.; Zimmermann, F.; Erasmi, S. Greenhouse gas emissions from soils—A review. Chemie der Erde 2016, 76,327–352.

Orr, R.J.; Murray, P.J.; Eyles, C.J.; Blackwell, M.S.A.; Cardenas, L.M.; Collins, A.L.; Dungait, J.A.J.; Goulding, K.W.T.; Griffith, B.A.; Gurr, S.J.; Harris, P.; Hawkins, J.M.B.; Misselbrook, T.H.; Rawlings, C.; Shepherd, A.; Sint, H.; Takahashi, T.; Tozer, K.N.; Whitmore, A.P.; Wu, L.; Lee, M.R.F. The North Wyke Farm Platform: effect of temperate grassland farming systems on soil moisture contents, runoff and associated water quality dynamics. European Journal of Soil Science 2016, 67, 374–385.

Owen, J.J.; Parton, W.J.; Silver, W.L. Long-term impacts of manure amendments on carbon and greenhouse gas dynamics of rangelands. Global Change Biology 2015, 21, 4533-4547. https://doi.org/10.1111/gcb.13044

Park, D., Markus, M., 2014. Analysis of a changing hydrologic flood regime using the Variable Infiltration Capacity model. Journal of Hydrology 515, 267–280. https://doi.org/http://dx.doi.org/10.1016/j.jhydrol.2014.05.004

Park, J.Y.; Ale, S.; Teague, W.R.; Dowhower, S.L. Simulating hydrologic responses to alternate grazing management practices at the ranch and watershed scales. Journal of Soil and Water Conservation 2017a, 72,102-121.

Park, J.Y.; Ale, S.; Teague, W.R. Simulated water quality effects of alternate grazing management practices at the ranch and watershed scales. Ecological Modelling 2017b, 360, 1-13.

Parton, W.J.; Scurlock, J.M.O.; Ojima, D.S.; Schimel, D.S.; Hall, D.O.; Group Members SCOPEGRAM. Impact of climate change on grassland production and soil carbon worldwide. Global Change Biology 1995, 1, 13–22. https://doi.org/10.1111/j.1365-2486.1995.tb00002.x

Parton, W.J. The CENTURY model. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models. Springer, Berlin. 1996

Parton, W.J.; Hartman, M.; Ojima, D.; Schimel, D. DAYCENT and its land surface submodel: description and testing. Glob. Planet. Chang. 1998, 19, 35-48.

Patton, B.D.; Dong, X.J.; Nyren, P.E.; Nyren, A. Effects of grazing intensity, precipitation, and temperature on forage production. Rangeland Ecol Manage 2007, 60, 656–665.

Petrosillo, I.; Zaccarelli, N.; Zurlini, G. Multi-scale vulnerability of natural capital in a panarchy of social–ecological landscapes. Ecological Complexity 2010, 7, 359-367. https://doi.org/10.1016/j.ecocom.2010.01.001

Qi, A.; Murray, P.; Richter, G.M. Modelling productivity and resource use efficiencyfor grassland ecosystems in the UK. Eur. J. Agron. 2017, 89, 148–158.

Qi, A.; Holland, R.A.; Talor, G.; Richter, G.M. Grassland futures in Great Britain – Productivity assessment and scenarios for land use change opportunities. Science of the Total Environment 2018, 634, 1108-1118.

Rahbeh, M.; Chanasyk, D.; Miller, J. Modelling the effect of irrigation on the hydrological output from a small prairie watershed, Canadian Water Resources Journal 2013, 38(4), 280-295

Riley, W.D.; et al. Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, and options for restorative action. Science of the Total Environment 2018, 645, 1598-1616.

Ringeval, B., Friedlingstein, P., Koven, C., Ciais, P., de Noblet-Ducoudré, N., Decharme, B., Cadule, P., 2010. Climate-CH 4 feedback from wetlands and its interaction with the climate-CO 2 feedback. Biogeosciences 8, 2137–2157.

Roche, L.M.; Cutts, B.B.; Derner, J.D.; Lubell, M.N.; Tate, K.W. On-Ranch Grazing Strategies: Context for the Rotational Grazing Dilemma. Rangeland Ecology & Management 2015, 68, 248–256.

Rolinski, S.; Muller, C.; Heinke, J.; Weindl, I.; Biewald, A.; Bodirsky, B.L.; Bondeau, A.; Boons-Prins, E.R.; Bouwman, A.F.; Leffelaar, P.A.; Roller, J.A.; Schaphoff, S.; Thonicke, K. Modeling vegetation and carbon dynamics of managed grasslands at the global scale with LPJmL 3.6. Geoscientific Model Development 2018, 11, 429-451.

Sándor R, Ehrhardt, F., Brilli, L.; Carozzi, M.; Recous, S.; Smith, P.; Snow, V.; Soussana, J.; Dorich, C.; Fuchs, K.; Fitton, N.; Gongadze, K.; et al. The use of biogeochemical models to evaluate mitigation of greenhouse gas emissions from managed grasslands. Science of the Total Environment 2018, 642, 292-306.

Savian, J.V.; Schons, R.M.T.; Marchi, D.E.; Freitas, T.S.; Neto, G.F.S.; Mezzalira, J.C.; Berndt, A.; Bayer, C.; Carvalho, P.C.F. Rotatinuous stocking: A grazing management innovation that has high potential to mitigate methane emissions by sheep. Journal of Cleaner Production 2018, 186, 602-608. https://doi.org/10.1016/j.jclepro.2018.03.162

Schumann, G.J.-P., Neal, J.C., Voisin, N., Andreadis, K.M., Pappenberger, F., Phanthuwongpakdee, N., Hall, A.C., Bates, P.D., 2013. A first large-scale flood inundation forecasting model. Water Resources Research 49, 6248–6257. https://doi.org/doi:10.1002/wrcr.20521, 2013

Sheffield, J., Goteti, G., Wen, F., Wood, E.F., 2004. A simulated soil moisture based drought analysis for the United States. Journal of Geophysical Research: Atmospheres 109.

Schönbach, P.; Wan, H.W.; Schiborra, A.; Gierus, M.; Bai, Y.F.; Muller, K.; Glindemann, T.; Wang, C.J.; Susenbeth, A., Taube, F. Short-term management and stocking rate effects of grazing sheep on herbage quality and productivity of Inner Mongolia steppe. Crop & Pasture Science 2009, 60, 963-974.

Schönbach, P.; Wan, H.W.; Gierus, M.; Bai, Y.F.; Müller, K.; Lin, L.J.; Susenbeth, A.; Taube, F. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. Plant and Soil 2011, 340, 103-115.

Scurlock, J.M.O.; Hall, D.O. The global carbon sink: a grassland perspective. Global Change Biology 1998, 4(2), 229-233. DOI: 10.1046/j.1365-2486.1998.00151.x

Shen, J.; Treu, R.; Wang, J.; Thorman, R.; Nicholson, F.; Bhogal, J. Modelling of nitrous oxide emissions from three United Kingdom farms following application of farmyard manure and green compost, Sci Total Environ. 2018a, 637–638, 1566–1577.

Shen, J.; Treu, R.; Wang, J.; Nicholson, F.; Bhogal, J.; Thorman, R. Modeling Nitrous Oxide from Digestate and Slurry Applied to Three Agricultural Soils in the United Kingdom: Fluxes and Emission Factors. Environmental Pollution 2018b, 243 (Part B): 1952-1965.

Shrestha, N.K.; Wang, J. Predicting sediment yield and transport dynamics of a cold climate region watershed in changing climate, Science of The Total Environment 2018a, 625,1030–1045

Shrestha, N.K.; Wang, J. Current and future hot-spots and hot-moments of nitrous oxide emission in a cold climate river basin. Environ. Pollut. 2018b, 239, 648-660.

Shrestha, N.K.; Thomas, B.W.; Du, X.; Hao, X.; Wang, J. Modeling nitrous oxide emissions from rough fescue grassland soils subjected to long-term grazing of different intensities using the Soil and Water Assessment Tool (SWAT). Environ Sci and Pollut Research 2018, 25 (27), 27362-27377.

Shrestha, N.K.; Wang, J. Water Quality Management of a Cold Climate Region Watershed in Changing Climate. Journal of Environmental Informatics 2019, DOI: 10.3808/jei.201900407

Shrestha, R.R., Schnorbus, M.A., Werner, A.T., Zwiers, F.W., 2014. Evaluating Hydroclimatic Change Signals from Statistically and Dynamically Downscaled GCMs and Hydrologic Models. Journal of Hydrometeorology 15, 844–860. https://doi.org/10.1175/JHM-D-13-030.1

Singer, M.J.; Munns, D.N. Soils: an Introduction. 6 edn, (Pearson Prentice Hall), 2006.

Smith, T. Rotation vs. Continuous Grazing: Even the experts disagree on grazing management practices. Hereford World 2007, https://hereford.org/static/files/02_07_RotationVsContinuous.pdf

Suttie, J.M.; Reynolds, S.G.; Batello, C. Grasslands of the world. FAO, Rome, p514. 2005. http://www.fao.org/3/y8344e/y8344e00.htm (accessed on 20 March 2019).

Tagesson, T.; Fensholt, R.; Cropley, F. et al. Dynamics in carbon exchange fluxes for a grazed semi-arid savanna ecosystem in West Africa. Agriculture Ecosystems and Environment 2015, 205, 15–24

Teague, R.; Provenza, F.; Norton, B.; Steffens, T.; Barnes, M.; Kothmann, M.; Roath, R. Benefits of multi-paddock grazing management on rangelands: limitations of experimental grazing research and knowledge gaps. In: Schroder, H.G. (Ed.), Grasslands: Ecology, Management and Restoration. Nova Science, New York, pp. 41-80. 2009.

Teague, W.R.; Dowhower, S.L.; Baker, S.A.; Haile, N.; DeLaune, P.B.; Conover, D.M. Grazing management impacts on vegetation, soil biota and soil chemical: physical and hydrological properties in tall grass prairie. Agric. Ecosyst. Environ. 2011, 141, 310–322.

Teague, R.; Provenza, F.; Kreuter, U.; Steffens, T.; Barnes, M. Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? Journal of Environmental Management 2013, 128, 699-717.

Teague, W.R.; Apfelbaum, S.; Lal, R.; Kreuter, U.P.; Rowntree, J.; Davies, C.A.; Conser, R.; Rasmussen, M.; Hatfield, J.; Wang, T.; Wang F.; Byck, P. The role of ruminants in reducing agriculture's carbon footprint in North America. Journal of Soil and Water Conservation 2016, 71, 156-164.

Teague, W.R. Forages and Pastures Symposium: Cover Crops in Livestock Production: Whole-system Approach: Managing grazing to restore soil health and farm livelihoods. Journal of Animal Science 2018, 96, 1519–1530, https://doi.org/10.1093/jas/skx060

Thomas, B. Maritime pasture manual. Department of Agriculture, Nova Scotia, Canada, 2009.

Tian, H.; et al. Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty, Glob Change Biol 2019, 25 (2), 640-659.

van Oijen, M.; Bellocchi, G.; Höglind, M. Effects of Climate Change on Grassland Biodiversity and Productivity: The Need for a Diversity of Models. Agronomy 2018, 8, 14.

Vuichard, N.; Soussana, J.F.; Ciais, P.; Viovy, N.; Ammann, C.; Calanca, P.; Clifton-Brown, J.; Fuhrer, J.; Jones, M.; Martin, C. Estimating the greenhouse gas fluxes of European grasslands with a process-based model: 1. Model evaluation from in situ measurements. Global Biogeochemical Cycles 2007, 21(1), GB1004.

Walter, B.P., Heimann, M., Matthews, E., 2001. Modeling modern methane emissions from natural wetlands: 1. Model description and results. Journal of Geophysical Research: Atmospheres 106, 34189–34206.

Wang, J.; Cardenas, L.M.; Misselbrook, T.H.; Cuttle, S.; Thorman, R.E.; Li, C. Modelling nitrous oxide emissions in grazed grassland systems, Environ Pollut 2012, 162, 223–233.

Wang, R.; Gamon, J.; Emmerton, C.; Li, H.; Nestola, E.; Pastorello, G.; Menzer, O. Integrated Analysis of Productivity and Biodiversity in a Southern Alberta Prairie. Remote Sens. 2016, 8(3), 214

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 July 2019 doi:10.20944/preprints201907.0003.v1

Wang, X.; VandenBygaart, A.J.; McConkey, B.C. Land Management History of Canadian Grasslands and the Impact on Soil Carbon Storage, Rangeland Ecol Manage 2014, 67, 333–343.

Wang, X.; McConkey, B.G.; VandenBygaart, A.J.; Fan, J.; Iwaasa, A.; Schellenberg, M. Grazing improves C and N cycling in the Northern Great Plains: a meta-analysis. Scientific Reports 2016, 6, 33190, DOI: 10.1038/srep33190

Wang, Y.; Wesche, K. Vegetation and soil responses to livestock grazing in Central Asian grasslands: a review of Chinese literature. Biodiversity and Conservation 2016, 25, 2401–2420.

White, S.R.; J.F. Cahill, Jr.; Bork, E.W. Implications of Precipitation, Warming, and Clipping for Grazing Resources in Canadian Prairies. Agronomy Journal 2014, 106(1), 33-42.

Williams, J.W.; Jackson, S.T. Novel climates, no-analog communities, and ecological surprises. Front Ecol Environ 2007, 5, 475–482.

Wilson, C.H.; Strickland, M.S.; Hutchings, J.A.; Bianchi, T.S.; Flory, S.L. Grazing enhances belowground carbon allocation, microbial biomass, and soil carbon in a subtropical grassland, Glob Change Biol 2018, 24(7), 2997-3009.

Yadav, D.; Wang, J. Modelling carbon dioxide emissions from agricultural soils in Canada, Environ Pollut 2017, 230, 1040–1049.

Yang, Y.; Tilman, D.; Furey, G.; Lehman, C. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications 2019, 10, Article number: 718 (2019)

Zhang, B.; Thomas, B.W.; Beck, R.; Liu, K.; Zhao, M.; Hao, X. Labile soil organic matter in response to long-term cattle grazing on sloped rough fescue grassland in the foothills of the Rocky Mountains, Alberta, Geoderma 2018, 318, 9-15.

Zhou, G.; Zhou, X.; He, Y.; Shao, J.; Hu, Z.; Liu, R.; Zhou, H.; Hosseinibai, S. Grazing Intensity Significantly Affects Belowground Carbon and Nitrogen Cycling in Grassland Ecosystems: A Meta-Analysis. Global Change Biology 2017, 23, 1167–1179.