FORAGES AND PASTURES SYMPOSIUM: COVER CROPS IN LIVESTOCK PRODUCTION: WHOLE-SYSTEM APPROACH: Managing grazing to restore soil health and farm livelihoods[1]

W. R. Teague[2]

Texas A&M AgriLife Research, Vernon, TX 76385

ABSTRACT: To ensure long-term sustainability and ecological resilience of agroecosystems, agricultural production should be guided by policies to ensure regenerative cropping and grazing management protocols. Changing current unsustainable high-input agricultural practices to low-input practices that regenerate ecosystem function will be necessary for sustainable, resilient agroecosystems. Effective soil management provides the greatest potential for achieving sustainable use of agricultural land with rapidly changing, uncertain and variable climate. With appropriate management of grazing enterprises, soil function can be regenerated to improve essential ecosystem services and farm profitability. Affected ecosystem services include carbon sequestration, water infiltration, soil fertility, nutrient cycling, soil formation, biodiversity, wildlife habitat, and increased ecosystem stability and resilience. Collectively, conservation agriculture managed regeneratively supports ecologically healthy, resilient agroecosystems and enhances watershed function. To accomplish this, it is important for scientists to partner with farmers who have improved the environment and excel financially to convert experimental results into sound environmental, social, and economic benefits regionally and globally. Benefits include addressing questions at commercial scale; integrating component science into whole-system responses; identifying emergent properties and unintended consequences; incorporating pro-active management to achieve desired goals under changing circumstances; and including the potential of the human element to achieve superior economic and environmental goals. Developing and implementing regenerative management protocols that include ruminant grazing animals will be necessary to ensure long-term sustainability and ecological resilience of agroecosystems.

Key words: ecosystem services, grazing management, regenerative agriculture, soil health, sustainable capitalism

---

© The Author(s) 2018. Published by Oxford University Press on behalf of American Society of Animal Science. All rights reserved. For permissions, please e-mail: journals.permissions@oup.com.

J. Anim. Sci. 2018.96:1519–1530
doi: 10.1093/jas/skx060

INTRODUCTION

Although ruminants, and cattle in particular, have been accused of a litany of damaging impacts on the global environment and human well-being, on deeper investigation ruminants provide a number of important benefits for humans and the environment (CAST, 1999; Janzen, 2010; Ottoboni and Ottoboni, 2013; Teague et al., 2016). Grazingland ecosystems occupy approximately one third of the earth's land area and many are degrading primarily due to inappropriate land use practices (MEA, 2005; Delgado et al., 2011). At least 1 billion rural and urban people depend on these ecosystems for their livelihoods, often through livestock

---

[1] Based on a presentation at the Forages and Pastures Symposium: Cover Crops in Livestock Production: Whole-System Approach entitled "Managing grazing to restore soil health and farm livelihoods" held at the 2017 ASAS-CSAS Annual Meeting, July 11, 2017, Baltimore, Maryland.

[2] Corresponding author: richard.teague@ag.tamu.edu

Received October 6, 2017.

Accepted December 13, 2017.

production, or for ecosystem services that affect human well-being (Ragab and Prudhomme, 2002). Such ecosystem services include maintaining stable and productive soils; minimizing soil erosion; delivering clean water; sustaining plants; and animals and other organisms that support livelihoods as well as human aesthetic and cultural values (Daily, 1997; Grice and Hodgkinson, 2002).

This paper outlines our research team's framework to improve the understanding of how to manage grazing ecosystem resources more sustainably by improving soil health as a foundation to improving profitability. This framework entails combining small-scale reductionist research with complementary whole-system research and working in collaboration with farmers who excel in improving the environment to obtain superior economic returns. Bridging the gap between single-discipline, reductionist research, and effective resource management that capitalizes on the potential of forage-based livestock elements in agroecosystems can mitigate and adapt to the most pressing problems threatening agricultural sustainability. This approach can address questions at a commercial scale and integrate component science into whole-system responses to identify emergent properties that may result in synergistic positive outcomes and help avoid unintended consequences.

BACKGROUND

Although many U.S. rangeland soils are undergoing major loss of soil carbon (C), largely due to our current ranching methods (Jandl et al., 2014), evidence indicates that by using adaptive, goal-directed grazing methods managed specifically to reverse degradation, managers could also increase the quality of grasslands, improve economic sustainability, and promote resilience to climate change (Teague and Barnes, 2017). Grazing ecosystems around the globe coevolved with grazing ruminants (Frank et al., 2002), and although many of these ecosystems have been converted to crop production, rangeland portions of the global landscape not suitable for producing human-utilizable feedstuffs are the largest portion of the earth's surface (MEA, 2005; Mottet et al., 2017). These extensive ecosystems can only be used by humans for food and fiber production if domestic or wild grazing herbivores consume the plant resources. Consequently, where climatic, edaphic, or topographic limitations preclude cropping, ruminant livestock are the foundation of many livestock-based cultures (Herrero and Thornton, 2013; Mottet et al., 2017).

With appropriate regenerative crop and grazing management, ruminants facilitate provision of essential ecosystem services, increase soil carbon (**C**) sequestration, reduce environmental damage, and reduce overall greenhouse gas (**GHG**) emissions (Janzen, 2010; Teague et al., 2016). They can also improve human health and well-being (CAST, 1999; Ottoboni and Ottoboni, 2013; Mottet et al., 2017) by providing the following benefits: grazing converts plants inedible by humans into high-quality food that supplies essential macro- and micro-nutrients; food products from grazing animals have higher-quality protein than those from plants; ruminants often provide a cheap source of healthy protein and fat for humans; increase bio-availability of essential minerals; degrade anti-quality plant components such as phytates; food from grazing ruminants uses less concentrates than other livestock-based human food; produce vitamin B_{12} and other vitamins; and protein food from grass has the best omega 3 to 6 ratio. Although some view livestock as poor converters of feed into human food products that compete with humans for food it has been estimated that 86% of feed consumed by livestock globally is composed of materials that are not eaten by humans (Mottet et al., 2017).

Provision of all these positive outcomes is contingent on appropriate management. However, much current management is producing many unintended consequences, such as soil loss and degrade soil function, that need to be remedied for humans to live more sustainably (Janzen, 2010; Teague et al., 2016). Modern technology, knowledge, and organization have allowed us to greatly increase agricultural productivity, but much management has been designed to optimize short-term benefits from the production of food, fiber, and fuel. We have compromised the ecological integrity of global ecosystems and caused negative impacts on our social environment by not accounting for environmental and social costs.

The delivery of improved ecosystem services requires policies and management protocols for agricultural production that should 1) support ecologically healthy and resilient arable and pastoral ecosystems; 2) address environmental, social, cultural, and economic complexity; 3) avoid unintended consequences of production practices; and 4) mitigate anthropogenic GHG emissions. Failure to address unintended consequences in agriculture has contributed to serious ecological problems, most notably: soil carbon (**C**) loss; soil loss via erosion; the impairment of watershed function; widespread pollution; negatively impacted many beneficial microbes and insects; and decreased biodiversity and wildlife habitat (MEA, 2005; Janzen, 2010; Liebig et al., 2010; Delgado et al., 2011; Teague et al., 2016; Montgomery, 2017).

IMPACTS OF CURRENT GRAZING ON ECOSYSTEM FUNCTION

Grazing by livestock and wildlife is the primary use of grazing ecosystems, provide many ecosystem services that are essential for rural and urban populations, including the significant influence management has on watershed and ecosystem function (Schlesinger et al., 1990; Wilcox, 2010). The primary cause of ecosystem degradation in these ecosystems is continuous year-round grazing which is commonly exacerbated by stocking at levels that exceed carrying capacity, but also have too few or no grazing animals (Frank et al., 2002; MEA, 2005; Teague et al., 2013).

It is widely believed that stocking at levels higher than current grazing capacity is the key management factor to be adjusted to sustain long-term profits while maintaining ecosystem function (Huffaker and Cooper, 1995; Kobayashi et al., 2007; Ritten et al., 2010). However, appropriate stocking rate alone does not avoid rangeland degradation (Müller et al., 2007, 2014; Teague et al., 2013; Díaz Solís et al., 2015; Jakoby et al., 2015; Savory and Butterfield, 2016), and it is also important to time grazing and distribution of grazing effectively because livestock in large paddocks exhibit repetitive use of preferred plants and patches. This leads to overgrazing of preferred plants and patches and is a major cause of unwanted changes in rangeland ecosystems (Norton, 1998, 2003; Barnes et al., 2008; Teague et al., 2013). This repeated consumption of preferred plants and patches results in uneven impact, such that even at low stocking rates, localized degraded patches persist over time and progressively expand, degrading the landscape (Fuls, 1992; O'Connor, 1992; Bullock et al., 1994; Bailey et al., 1998; Teague et al., 2004).

Poor grazing practices lead to soil compaction and reduced infiltration rates, exacerbating the most limiting factor in most grazing ecosystems, which is plant-available soil water (Thurow, 1991). Runoff increases soil loss and facilitates nutrient movement by surface runoff, which can lead to the eutrophication and impairment of freshwater sources (Sharpley et al., 1994; Gillingham and Thorrold, 2000; Sauer et al., 2000; Stout et al., 2000a; Burkart and Stoner, 2002; Babiker et al., 2004; James et al., 2007; Webber et al., 2010; Vadas et al., 2014). Soil erosion and nutrient losses are generally considerably less under rotational and adaptive multi-paddock (**AMP**) grazing than from continuously grazed pastures (Ritter, 1988; Mathews et al., 1994; Sovell et al., 2000; Stout et al., 2000b; Webber et al., 2010; Teague et al., 2011; Weltz et al., 2011). It is extremely important that managers adopt grazing management practices that maintain or restore soil and ecosystem function and resilience that is required for sustainable use in the long term (Havstad et al., 2007; Teague et al., 2013).

RESTORING SOIL HEALTH IS A FUNDAMENTAL BASE FOR SUSTAINABLE AGRICULTURE

The biggest limiting factor in grazing land ecosystems is not the amount of rainfall, but the amount of rainfall infiltrating the soil and how long it remains there (Thurow, 1991). But this is not the only important ecosystem function. Ensuring optimal ecosystem function requires efficient solar energy capture; effective water infiltration and retention; soil organic matter accumulation and retention; efficient nutrient cycling; and ecosystem biodiversity to facilitate these functions (Teague et al., 2013). Soil health is fundamental for ecosystem function because 90% of soil function is mediated by microbes, with a mutual dependency among microbes, plants, and animals. Plants enable microbial life and benefit from nutrient release through the synergistic interdependence among archaea, bacteria, fungi, and other microbial and eukaryotic species. How we manage plants in grazing or cropping ecosystems is critical to maintaining or regenerating full ecosystem function. The major portion of energy required to facilitate ecosystem functions comes from plants capturing energy in the process of photosynthesis and conversion into carbohydrates that provide the energy for community function.

The functions provided by the synergistic networks of soil organisms include improving soil aggregation; aeration and water-holding capacity (Altieri, 1999); stabilizing soil (Van der Heijden et al., 2008); improving nutrient acquisition and retention (Green et al., 2008; Khidir et al., 2008); cycling nutrients to improve nutrient availability (Rodriguez and Fraga, 1999; Barrow et al., 2008); enhancing tolerance to biotic and abiotic stress (De Vries et al., 2012); and buffering the impact of environmental factors on plants (Van der Heijden et al., 2008). Arbuscular mycorrhizal fungi (**AMF**) are keystone species in terrestrial ecosystems, particularly grasslands, as they maintain plant diversity, mediate interactions among plants and other microbes, and positively impact plant photosynthesis (Averill et al., 2014). Plants increase photosynthesis in symbiosis with AMF and legumes for a dual association with rhizobia and AMF that enhances photosynthesis by 50% on average (Kaschuk et al., 2009). AMF contribute directly to soil OM and through secretion of soil glycoproteins, increase water-stable soil aggregates that enhance soil water infiltration, and aeration vital to ecosystem function (Rillig, 2004).

Management decisions have important consequences for how grasslands function in supporting profitable operations and in sequestering carbon and providing ecosystem services. Notable examples of management approaches that have resulted in the restoration of degraded grasslands are available especially where ranches are managed to achieve resource conservation goals (Teague et al., 2016; Teague and Barnes, 2017). Improved management, such as AMP, has been shown to reverse the causal mechanisms of degradation by decreasing bare ground, restoring productive plant communities, increasing water infiltration rates and soil water storage capacity, increasing fungal to bacterial ratios, and increasing soil carbon (Delgado et al., 2011; Teague et al., 2011, 2013).

Positive shifts in soil microbial and biological community composition, carbon cycling, and nitrogen cycling following improved management are strongly related to the restoration of soil carbon and fertility in grasslands (Altieri, 1999; Van der Heijden et al., 2008; Nielsen et al., 2011; De Vries et al., 2012). It is also possible to adjust grazing and associated farm management to optimize the benefits provided by other key organisms such as dung beetles and earthworms that have a strong influence on ecological function (Herrick and Lal, 1995; Richardson and Richardson, 2000; Bardgett (2005); Blouin et al., 2013).

In grazing ecosystems, use of regenerative high density (AMP) grazing management has been demonstrated globally to be capable of reversing degradation processes associated with the widespread practice of continuous grazing at high stocking rates (Gerrish, 2004; Teague et al., 2011, 2013; Jakoby et al., 2014, 2015; Savory and Butterfield, 2016). AMP grazing has been successfully applied in areas with annual rainfall ranging from 250 to 1,500 mm to achieve effective resource regeneration and provision of ecosystem services. These positive outcomes include: increased primary and secondary productivity, restoration of preferred herbaceous species that were harmed by previous grazing practices, and increased soil organic carbon, soil fertility, water-holding capacity and economic profitability for ranchers (Teague et al., 2011; Teague and Barnes, 2017; Jakoby et al., 2014, 2015). Where regenerative AMP grazing has been practised in semi-arid and arid lands for some time, plant productivity and biodiversity have been elevated, plant and litter cover have increased over the landscape, and nitrogen-fixing native leguminous plant species and pollinators have increased. This has resulted in re-perennialization of ephemeral streams and watershed function (National Research Council, 2002).

Based on data presented by Teague et al. (2011) of “across the fence” comparisons in southern tallgrass prairie in Texas, where AMP grazing was applied to areas previously degraded through prolonged continuous grazing, we calculated an average of 3.0 t C/ha/yr additional soil organic carbon in the top 90 cm of soil over a decade in AMP grazing relative to commonly practiced heavy continuous grazing (Wang et al., 2016). Following this published work, we have collected proof-of-concept sampling in the United States and Canada to determine if similar results would be observed. With AMP grazing, relative to commonly practiced heavy continuous grazing, we measured higher C levels of 7.0 t C/ha/yr over 5 yr in Mississippi; 2.5 t C/ha/yr over 20 yr in North Dakota and Canada; and 0.5 t C/ha/yr in 20 yr in New Mexico, respectively (S. Apfelbaum, unpublished data; Applied Ecological Services, https://appliedeco.com, 2016).

Dr Allen Williams (unpublished data; Livestock Management Consultants, LLC, https://joyce-farms.com, 2016), in his North America-wide, grass-fed consulting business, has collected data for 5 yr on soil OM and soil microbial biomass changes on selected clients’ properties that is presented in Figs 1 and 2, respectively. Starting values of soil OM among the locations were very different

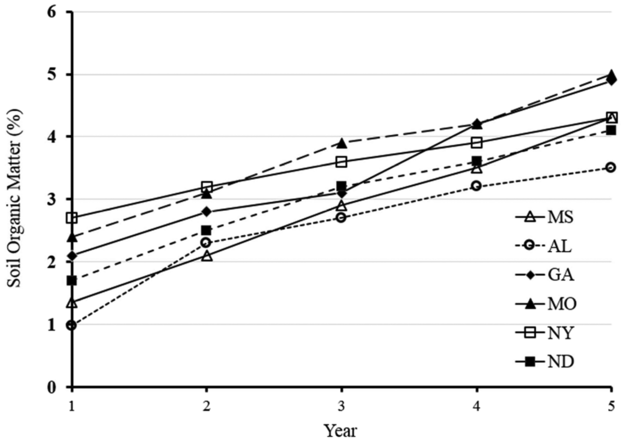

Figure 1. Increases in soil OM (%) following implementation of AMP grazing (A. Williams, unpublished data, Livestock Management Consultants, LLC, https://joyce-farms.com/).

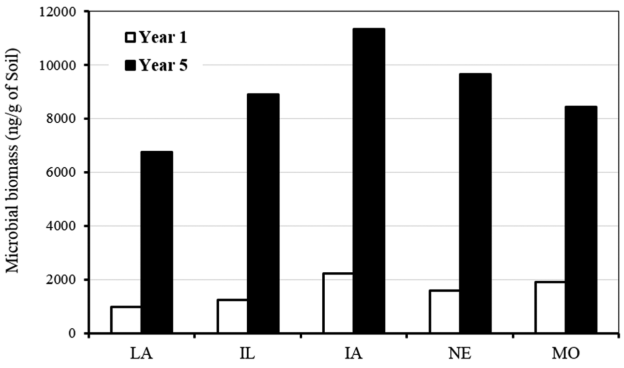

Figure 2. Increases in soil microbial biomass (ng/g of soil) following implementation of AMP grazing (A. Williams, unpublished data, Livestock Management Consultants, LLC, https://joyce-farms.com/).

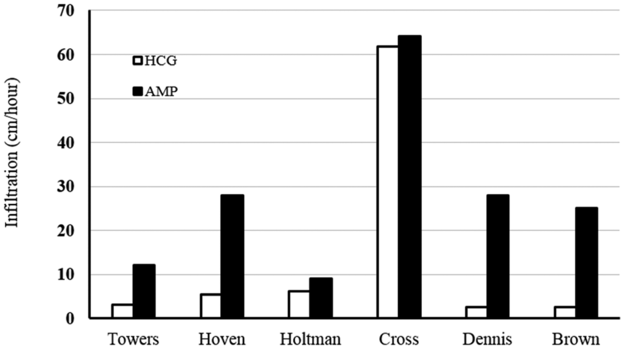

Figure 3. Soil infiltration following implementation of AMP grazing vs. that on neighbor ranches using the common practice of heavy continuous grazing (**HCG**) in the Northern Great Plains of North America (S. Apfelbaum, unpublished data, Applied Ecological Services, https://appliedeco.com).

but the rate of gain of OM was remarkably similar among locations (Fig. 1). Similarly, the increase in soil microbiology activity has increased markedly (mean = ±500% increase), indicating a very large increase in microbial function capable of driving substantial increases in ecosystem function (Fig. 2). These responses have contributed to large increases in infiltration on AMP managed ranches as shown in Fig. 3. Only sites that had initial high infiltration values, such as the Cross site (Fig. 3), or were very dry sites, such as the Holtman site (Fig. 3) prior to changing to AMP grazing, did not have appreciable increases in infiltration.

IMPROVED GRAZING IMPACTS ON WATERSHED FUNCTIONING

Improved grazing management has a substantial positive impact on watershed function. In addition to the published results from field research reported above, numerous papers reporting the impacts of different grazing management on watershed function have indicated that AMP management resulted in soil and plant conditions that improved hydrological function at both the ranch and watershed scale compared to continuous grazing (Gilley et al., 1996; Sanjari et al., 2009; Schwarte et al., 2011). At the ranch scale, Park et al. (2017a) showed that with heavy continuous grazing, annual surface runoff was the major contributor to stream flow, whereas with AMP grazing (at the same stocking level as heavy continuous grazing), water leaving the soil profile as base flow was the major source of streamflow. At the water catchment scale, heavy continuous grazing, relative to AMP grazing, increased surface runoff by 47%, decreased infiltration by 5%, and decreased streamflow by 29.5%. It was estimated that these improvements in watershed function with AMP grazing would reduce the risk of flooding downstream from 8.3 m^3/s under the baseline continuous grazing scenario relative to 6.2 m^3/s (Park et al., 2017a). The same authors (Park et al., 2017b) also showed that, at the watershed scale, changing grazing management from the baseline heavy continuous grazing to AMP reduced the average annual surface runoff, sediment, nitrogen, and phosphorus loads at the watershed outlet by 39, 34, 33, and 31%, respectively.

MANAGING GRAZING TO RESTORE ECOLOGICAL FUNCTION AND FARM LIVELIHOODS

In many countries, leading conservation farmers have used AMP grazing to achieve superior soil health, vegetation, livestock production and economic results (Teague et al., 2013; Savory and Butterfield, 2016; Teague and Barnes, 2017). Similar positive resource and economic results have been obtained by scientists who have studied the subject when research 1) was conducted at the scale of ranching operations; 2) was managed proactively as growing conditions changed to achieve desired ecosystem and production goals; 3) measured parameters indicating change in ecosystem function and not just production parameters; and 4) when treatments had been applied for sufficient time for management of the alternate grazing treatments to produce measurable differences resulting from the additive effects of positive impacts and many changes in factors like weather that influence responses over many years.

In contrast, most, but not all grazing studies in the scientific literature have concluded that rotational grazing is no better than light continuous grazing (Gammon and Roberts, 1978; Gammon, 1984; Briske et al., 2008, 2011). However, these sub-optimal results are based on a sub-set of rotational grazing management studies that were generally designed and conducted in reductionist ways that were not managed to provide best outcomes for each treatment as outlined in the following paragraph. These studies were conducted in ways not likely to have been applied by successful exponents of AMP grazing, and thus they did not reflect the successes achieved with AMP on commercial ranches (Teague et al., 2013; Savory and Butterfield, 2016). The design and management of experiments profoundly impacts the results obtained, with favorable outcomes achieved by managing for specific goals (Teague et al., 2013). The potential of multi-paddock grazing can be optimized if studies are managed to achieve the best possible results based on protocols that have been demonstrated by successful farmers to provide superior resource and economic results (Teague and Barnes, 2017).

The best examples of benefits from improving grazing management have been produced by farmers managing to specifically enhance soil health and ecosystem function. This is the foundation to improving profitability, and these leading farmers have achieved substantial improvements in ecosystem function; plant species composition and productivity; soil carbon and fertility; water infiltration and water-holding capacity; biodiversity; wildlife habitats; and profitability (Teague et al., 2013; Teague and Barnes, 2017). Their method is to use multiple paddocks per herd with short grazing periods and long recovery periods, adaptively changed when residual biomass, animal numbers and other management elements such as growing conditions change within and between years. It is becoming increasingly clear that the key to sustainable use and recovery from degradation involves using well-planned and adaptively managed multi-paddock grazing management protocols, and adjusting stock numbers to match forage biomass to achieve desired resource and financial goals while avoiding unintended consequences such as soil loss and decline in function, and reduced plant biomass and species composition (Earl and Jones, 1996; Tainton et al., 1999; Jacobo et al., 2006; Provenza, 2008; Barnes and Hild, 2013; Ferguson et al., 2013; Teague et al., 2013, 2015; Jakoby et al., 2014, 2015; Martin et al., 2014; Müller et al., 2014; Díaz Solís et al., 2015; Savory and Butterfield, 2016; Wang et al., 2016).

Research that has been conducted following protocols that have provided desired resource and economic improvements by conservation farmers have substantiated farm-based results. Using a spatial simulation model, Jakoby et al. (2014) determined that appropriate grazing with a large number of paddocks per herd that included short grazing periods and adequate recovery facilitated resource improvement and gave the best economic results. However, economic risk was decreased only when management adjustments accounted for paddock forage quality and seasonality over the modeled landscape (Jakoby et al., 2015). Similarly, the model of Teague et al. (2015) showed that too long a period of grazing or recovery resulted in poorer animal performance or plant recovery, with negative economic consequences, as acknowledged by experienced consultants working with farmers (W. Davis, personal communication, Davis Consulting, https://waltdavisranch.com/; D. Pratt, personal communication, Ranch Management Consultants, https://www.ranchmanagement.com/).

Modeling of adaptive stocking with many paddocks per herd was shown by Jakoby et al. (2015) to be less sensitive to overstocking than constant stocking, and that advantages of AMP compared to continuous grazing are less important at low stocking rates, but become increasingly important as stock numbers increase, improving net economic returns. Modeling by Wang et al. (2016) concluded that, at the scale of commercial ranches, AMP grazing with short periods of grazing and sufficient periods of postgrazing recovery improved grass composition and productivity, as well as livestock DM consumption relative to continuous grazing, especially with heavier stocking rates and lower initial standing crop and forage composition. However, the advantages of AMP grazing are less evident with favorable rainfall conditions, light stocking, low concentrations of undesirable plants, and inadequate recovery periods. With their spatial model, Jakoby et al. (2015) identified several viable low-risk management choices are possible with continuous grazing or few paddocks per herd, but they require relatively low stocking rates that result in low productivity and economic returns. In contrast, under both low- and high-risk management strategies, multi-paddock grazing using large paddock number and a reasonably high stocking rate with short graze periods and long rest periods maintained or improved resource condition, gave superior economic outcomes, lowered income variability, and provided a greater likelihood of attaining a minimum income goal.

IMPROVING GRAZING TO DECREASE THE CARBON FOOTPRINT OF AGRICULTURE

One of the major concerns in grazingland ecosystems is the substantial amount of GHGs emitted by ruminant livestock (Capper, 2012; Capper and Bauman, 2013; Eshel et al., 2014; Ripple et al., 2014). Although many scientists have concluded that ruminant production systems are a particularly large source of GHG emissions, others have shown it is possible to convert many ruminant-based production chains into net C sinks by changing management (Wang et al., 2014, 2015; Rowntree et al., 2016; Teague et al., 2016). Previous assessments of capacity for CH_4 uptake in grazed rangeland ecosystems have not considered improved livestock management practices and thus underestimated potential for CH_4 uptake. Optimal fertilization, appropriate adaptive stocking, moderate grazing with adequate recovery, and intensification of livestock grazing management significantly contribute to mitigation potential (Delgado et al., 2011; Wang et al., 2014; Rowntree et al., 2016).

As soils can be a significant sink of carbon depending on management practices (Conant et al., 2001; Liebig et al., 2010; Teague et al., 2011; Machmuller et al., 2015), soil carbon (C) dynamics are an important component of calculating accurate beef life-cycle assessments (**LCA**; Wang et al., 2015; Teague et al., 2016; Rowntree et al., 2016). However, changes in C have usually been unaccounted for in LCAs (Stackhouse-Lawson et al., 2012; Capper and Bauman, 2013; Eshel et al., 2014; Ripple et al., 2014), even though it has been shown to have a large impact on net GHG footprints when explicitly included in calculations of net carbon footprints of alternate combinations of agricultural management options (Liebig et al., 2010; Pelletier et al., 2010; Lupo et al., 2013; Wang et al., 2015; Rowntree et al., 2016). When conducting LCA assessments on emissions from ruminants in a food production chain, it is fundamentally important to include all elements in the chain influencing the net carbon footprint in the whole system under review (Teague et al., 2016). This includes accounting for the beneficial ecosystem services such as those from carbon sequestered in grazing ecosystems that well-managed grazing systems can provide (e.g., Teague et al., 2011; Machmuller et al., 2015).

Under appropriate management, a grass-fed ruminant model can not only provide for the feed requirements of the livestock but also be ecologically beneficial and regenerative. Ruminants grazing perennial grasslands that do not receive any inputs that can reduce soil carbon levels and sequestration, such as inadequate ground cover, inorganic amendments, pesticides, or medications that diminish soil ecological function have a more negative carbon footprint (Teague et al., 2016). Liebig et al. (2010) shown that cattle on continuously grazed native rangeland in the Northern Great Plains of the United States had a net margin of C sequestered over emissions of 0.607 mg CO_{2equiv}/ha/yr for moderate stocking, and 0.134 mg CO_{2equiv}/ha/yr for heavy stocking (using Natural Resource Conservation Service protocols). Where the grazing management has resulted in improved ecosystem function and productivity, as reported above, the margin of increased C sequestered over ruminant emissions is considerably greater. In southern tallgrass prairie in Texas Wang et al. (2015) report net C sink of 2.0 mg C/ha/yr when converting from heavily stocked continuous grazing to AMP grazing at the same stocking rate, and net sink of 1.7 mg C/ha/yr following conversion from heavy to light stocking with continuous, season-long grazing. Similarly, Rowntree et al. (2016) working with beef cattle on cultivated perennial pastures in Michigan, report soil C gains of 3 mg C/ha/yr with AMP grazing under rainfed or irrigated conditions. For a net zero GHG footprint, sensitivity analyses indicated that soil in the rainfed and irrigated AMP grazing systems would need to sequester 1 and 2 mg C/ha/yr, respectively.

Most cattle in North America are finished in feedlots on grain-based feeds and proponents of this finishing method claim that this results in lower GHG emissions per kilogram beef produced and a lower carbon footprint because it reduces the overall production time to slaughter and enteric fermentation during this time, relative to grass-based finishing (Capper, 2012; Stackhouse-Lawson et al., 2012; Capper and Bauman, 2013; Eshel et al., 2014; Ripple et al., 2014). However, these authors do not consider the full food-chain carbon footprint of grain-based finishing as it does not account for the full GHG emissions associated with the production of grain-based feeds, inorganic fertilizer and other elements adding to the C footprint, and soil erosion (Teague et al., 2016). Ruminant dams and their offspring spend most of their lives on perennial grass during which the C sequestered by the grassland they graze exceeds their emissions (Wang et al., 2015; Rowntree et al., 2016). This needs to be considered when calculating the complete carbon footprint through any food-chain option being considered.

In developed countries that routinely finish ruminants on grains, another factor decreasing the C footprint of any production chain is that any crop-based finishing of ruminants that is based on regenerative cropping practices with a negative GHG footprint (C sink) also diminishes the carbon footprint considerably (Gattinger et al., 2012; Aguilera et al., 2013). Such modification of agroecosystem production systems and conversion to regenerative cropping and AMP-based grass-finished livestock would also provide other important ecological benefits (DeRamus et al., 2003) as outlined earlier in this document. In addition, supplies of human food products would be increased by 70% if crop production currently used for animal feed and other uses such as biofuels were instead used for human food products, providing sufficient resources for billions of people (West et al., 2014).

The limited availability of experimental data on soil C and GHG dynamics in grazing and cropping agroecosystems has been an obstacle in filling this critical gap in data needed to conduct more accurate LCA in grazing ecosystems and ruminant production systems. These include the background environmental consumption of CH_4 by methanotrophs, such as in-and-near termite mounds (Jamali et al., 2011), and the larger scale atmospheric photooxidation of CH_4 in the presence of water vapor (Cox et al., 1976).

WORKING WITH OUTSTANDING FARMERS

Working in collaboration with farmers who have simultaneously improved the biophysical conditions of their environments in different ecological and cultural settings while achieving superior economic returns is fundamentally important (Van der Ploeg et al., 2006). Not only have they developed improved management protocols but they have determined how to cash-flow the transition, and learnt how to avoid unintended consequences, while transitioning from low to high soil health. Effective farm management to achieve best outcomes in the farm business requires goal-directed adaptive flexibility combined with understanding farm landscape responses to alternative management actions and their interactions with biophysical processes that evolve over time. Small-scale, component research using reductionist protocols rarely incorporates any adaptive management-related factors, thus limiting the discovery of positive or negative interacting effects. Research that has been conducted for short periods at small scale, in isolation of interacting elements, and with variability purposely reduced, provides no guarantee that they would deliver this promise in a commercial setting or avoid unintended consequences. Consequently, the effective study of farm management cannot be determined using classical, replicated experiments that reduce variability and scale of enquiry to understand limited situations but need to be augmented by goal-oriented, management-scale applied research and linked simulation model investigations.

Scientific research protocols and routines, and lack of systems training preclude most research scientists from being able to fully understand, represent, or manage research projects to achieve the best possible outcomes of innovative management options (van der Ploeg et al., 2006). In contrast, farmers are less constrained by convention and are more likely to test different combinations of practices and approaches within realistic whole-ranch systems (Teague et al., 2011; Teague and Barnes, 2017). Working collaboratively with financially successful conservation farmers can facilitate studying biological and economic interactions that can be optimized through change to achieve synergisms at this higher level of integration. Working with leading farmers can facilitate development of more sustainable future agricultural practices (van der Ploeg et al., 2006). Benefits include 1) addressing questions at commercial scale; 2) integrating component science into whole-system responses; 3) identifying emergent properties and unintended consequences; 4) incorporating pro-active management to achieve desired goals under changing circumstances; 5) enhancing the potential of the human element to achieve superior economic and environmental goals; and 6) extend the usefulness of information developed in research to the people managing the land.

SUMMARY AND CONCLUSIONS

Effective soil management provides the greatest potential for achieving sustainable use of agricultural land with rapidly changing, uncertain, and variable climate. With appropriate management of grazing and cropping enterprises, soil function can be regenerated to improve essential ecosystem services and support local populations, simultaneously reducing the use of costly and potentially damaging purchased inputs. Affected ecosystem services include capture of solar energy, soil water infiltration, soil stabilization, nutrient cycling, nutrient retention, soil formation, carbon sequestration, biodiversity, and wildlife habitat. Permanent cover of forage plants is highly effective in reducing soil erosion and increasing soil infiltration. Ruminants consuming only grazed forages under appropriate management results in considerably more carbon sequestration than emissions. Incorporating forages with ruminants to manage regeneration of ecological function in agroecosystems can elevate soil C and improve soil ecological function. Minimizing the damage of poor grazing management, tillage, and inorganic fertilizers and biocides can enhance biodiversity and wildlife habitat if incorporated within goal-oriented planning and monitoring protocols (Savory and Butterfield, 2016).

To ensure long-term sustainability and ecological resilience of agroecosystems, agricultural production should be guided by policies that ensure regenerative cropping and grazing management protocols. Changing current unsustainable high-input agricultural practices to low-input regenerative practices enhances soil and ecosystem function and resilience, improving long-term sustainability and social resilience. A primary challenge is increasing the scale of adoption of land management practices that have been documented to affect soil health positively. In areas where no cropping is possible, grazing of ruminants in a manner that enhances soil health will reduce the C footprint of agriculture much more than reducing domesticated ruminant numbers to reduce enteric GHG emissions, while providing highly nutritious food that has sustained pastoral livelihoods and cultures for centuries. Ruminant livestock are an important tool for achieving sustainable agriculture and with appropriate grazing management. They can increase C sequestered in the soil to more than offset ruminant GHG emissions while they support and improve other essential ecosystem services for local populations such as increase water infiltration, reduce soil erosion, improve nutrient cycling, soil formation, carbon sequestration, biodiversity, and wildlife habitat.

Research conducted on managed landscape shows that ecologically managed AMP grazing strategies incorporating short, high-impact grazing with long recovery periods can regenerate ecosystem function on commercial-scale agroecological landscapes. These include 1) build soil carbon concentrations and soil microbial function; 2) enhance water infiltration and retention; 3) control erosion more effectively; 4) build soil fertility; 5) enhance watershed hydrological function; 6) improve livestock production and economic returns and the resource base; 7) enhance wildlife and biodiversity; and 8) increase soil function as a net GHG sink.

Collectively, conservation agriculture aimed at regenerating soil health and ecosystem function supports ecologically healthy resilient agroecosystems, improves net profitability, and enhances watershed function. To accomplish this, it is important for scientists to collaborate with environmentally progressive managers who have excelled financially by improving their resource base, identify the processes associated with improvement, and convert experimental results into sound environmental, social, and economic benefits regionally and globally.

LITERATURE CITED

Aguilera, E., L. Lassaletta, A. Gattinger, and B. S. Gimeno. 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric. Ecosyst. Environ. 168:25–36.

Altieri, M. A. 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74:19–31.

Averill, C., B. L. Turner, and A. C. Finzi. 2014. Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. Nature. 505:543–545.

Babiker, I. S., M. A. A. Mohamed, H. Terao, K. Kato, and K. Ohata. 2004. Assessment of groundwater contamination by nitrate leaching from intensive vegetable cultivation using geographical information system. Environ. Int. 29:1009–1017.

Bailey, D. W., B. Dumont, and M. F. Devries. 1998. Utilization of heterogeneous grasslands by domestic herbivores: theory to management. Ann. Zootechnol. 47:321–333.

Bardgett, R. D. 2005. The biology of soil: a community and ecosystem approach. New York (NY): Oxford University Press.

Barnes, M., and A. Hild, editors. 2013. Strategic grazing management for complex creative systems. Rangelands 35:1–66.

Barnes, M. K., B. E. Norton, M. Maeno, and J. C. Malechek. 2008. Paddock size and stocking density affect spatial heterogeneity of grazing. Rangel. Ecol. Manag. 61:380–388.

Barrow, J. R., M. E. Lucer, I. Reyes-Vera, and K. Havstad. 2008. Do symbiotic microbes have a role in plant evolution, performance and response to stress? Commun. Integr. Biol. 1:69–93.

Blouin, M., M. E. Hodson, E. A. Delgado, G. Bakerd, L. Brussaard, K. R. Butt, J. Dai, L. Dendooven, G. Peres, J. E. Tondoh, et al. 2013. A review of earthworm impact on soil function and ecosystem services. Eur. J. Soil. Sci. 64:161–182.

Briske, D., J. Derner, J. Brown, S. Fuhlendorf, et al. 2008. Benefits of rotational grazing on Rangelands: an evaluation of the experimental evidence. Rangel. Ecol. Manag. 61:3–17.

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

Bullock, J. M., B. C. Hill, M. P. Dale, and J. Silvertown. 1994. An experimental study of vegetation change due to sheep grazing in a species-poor grassland and the role of seedling recruitment into gaps. J. Appl. Ecol. 31:493–507.

Burkart, M. R., and J. D. Stoner. 2002. Nitrate in aquifers beneath agricultural systems. Water Sci. Technol. 45:19–28.

Capper, J. L. 2012. Is the grass always greener? Comparing the environmental impact of conventional, natural and grass-fed beef production systems. Animals 2:127–143.

Capper, J. L., and D. E. Bauman. 2013. The role of productivity in improving the environmental sustainability of ruminant production systems. Annu. Rev. Anim. Biosci. 1:469–489.

Conant, R. T., K. Paustian, and E. T. Elliott. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11:343–355.

Council for Agricultural Science and Technology (CAST). 1999. Animal agriculture and global food supply. Task Force Report 135. CAST, Ames, IA.

Cox, R. A., R. G. Derwent, A. E. J. Eggleton, and J. E. Lovelock. 1976. Photochemical oxidation of halocarbons in the troposphere. Atmos. Environ. 10:305–308.

Daily, G. C., editor. 1997. Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC.

Delgado, J. A., P. M. Groffman, M. A. Nearing, T. Goddard, et al. 2011. Conservation practices to mitigate and adapt to climate change. J. Soil Water Conserv. 66:118A–129A.

DeRamus, H. A., T. C. Clement, D. D. Giampola, and P. C. Dickison. 2003. Methane emissions of beef cattle on forages: efficiency of grazing management systems. J. Environ. Qual. 32:269–277.

De Vries, F. T., J. Bloem, et al. 2012. Extensive management promotes plant and microbial nitrogen retention in temperate grassland. PLoS One 7:51201. doi:10.1371/journal.pone.0051201

Díaz Solís, H., W. E. Grant, M. M. Kothmann, W. R. Teague, and J. A. Diaz-Garcia. 2015. Strategies to reducing GHG emissions in semi-arid rangelands of Mexico. Terra Latinoam. 34:73–81.

Earl, J. M., and C. E. Jones. 1996. The need for a new approach to grazing management-is cell grazing the answer? Rangel. J. 18:327–350.

Eshel, G., A. Shepon, T. Makov, and R. Milo. 2014. Land, irrigation water, greenhouse gas, and reactive 179 nitrogen burdens of meat, eggs, and dairy production in the United States. Proc. Natl. Acad. Sci. U.S.A. 111:11996–12001.

Ferguson, B. G., S. A. W. Diemont, R. Alfaro-Arguello, J. F. Martin, J. Nahed-Toral, D. Alvarez-Solis, and R. Pinto-Ruiz. 2013. Sustainability of holistic and conventional cattle ranching in the seasonally dry tropics of Chiapas, Mexico. Agric. Syst. 120:38–48.

Frank, D. A., S. J. McNaughton, and B. F. Tracy. 2002. The ecology of the Earth's grazing ecosystems. BioScience 48:513–521.

Fuls, E. R. 1992. Ecosystem modification created by patch-overgrazing in semi-arid grassland. J. Arid Environ. 23:59–69.

Gammon, D. M. 1984. An appraisal of short duration grazing as a method of veld management. Zimb. Agric. J. 82:59–64.

Gammon, D. M., and B. R. Roberts. 1978. Patterns of defoliation during continuous and rotational grazing of the Matopos Sandveld of Rhodesia. 1. Selectivity of grazing. Rhod. J. Agric. Res. 16:117–131.

Gattinger, A., A. Muller, M. Haeni, C. Skinner, A. Fleissbach, N. Buchmann, P. Mader, M. Stolze, P. Smith, N. E. Scialabba, et al. 2012. Enhanced top soil carbon stocks under organic farming. Proc. Natl. Acad. Sci. U.S.A. 109:18226–18231.

Gerrish, J. 2004. Management-intensive grazing: the grassroots of grass farming. Green Park Press, Ridgeland, MS.

Gilley, J. E., B. D. Patton, P. E. Nyren, and J. R. Simanton. 1996. Grazing and haying effects on runoff and erosion from a former conservation reserve program site. Biol. Syst. Eng. 12:681–684.

Gillingham, A. G., and B. S. Thorrold. 2000. A review of New Zealand research measuring phosphorus in runoff from pastures. J. Environ. Qual. 29:88–96.

Green, L. E., A. Porras-Alfaro, and R. L. Sinsabaug. 2008. Translocation of nitrogen and carbon integrates biotic crust and grass production in desert grassland. J. Ecol. 96:1076–1085.

Grice, A. C., and K. C. Hodgkinson, editors. 2002. Global rangelands: progress and prospects. CABI, Oxon, UK.

Havstad, K. M., D. P. C. Peters, R. Skaggs, J. Brown, B. Bestlemeyer, E. Fredrickson, J. Herrick, and J. Wright. 2007. Ecological services to and from rangelands of the United States. Ecol. Econ. 64:261–268.

Herrero, M., and P. K. Thornton. 2013. Livestock and global change: emerging issues for sustainable food systems. Proc. Natl. Acad. Sci. U.S.A. 110:20878–20881.

Herrick, J. E., and R. Lal. 1995. Soil physical property changes during dung decomposition in a tropical pasture. Soil Sci. Soc. Am. J. 59:908–912.

Huffaker, R., and Cooper, K. 1995. Plant succession as a natural range restoration factor in private livestock enterprises. Am. J. Agric. Econ. 77:901–913.

Jacobo, E. J., A. M. Rodríguez, N. Bartoloni, and V. A. Deregibus. 2006. Rotational grazing effects on rangeland vegetation at a farm scale. Rangel. Ecol. Manag. 59:249–257.

Jakoby, O., M. F. Quaas, S. Baumgärtner, and K. Frank. 2015. Adapting livestock management to spatio-temporal heterogeneity in semi-arid rangelands. J. Environ. Manage. 162:179–189.

Jakoby, O., M. F. Quaas, B. Müller, S. Baumgärtner, and K. Frank. 2014. How do individual farmers' objectives influence the evaluation of rangeland management strategies under a variable climate? J. Appl. Ecol. 51:483–493.

Jamali, H., S. J. Livesley, S. P. Grover, T. Z. Dawes, L. B. Hutley, G. D. Cook, and S. Arndt. 2011. The importance of termites to the CH_4 balance of a tropical savanna woodland of Northern Australia. Ecosystems. 14:698–709. doi:10.1007/s10021-011-9439-5

James, E., P. Kleinman, T. Veith, R. Stedman, and A. Sharpley. 2007. Phosphorus contributions from pastured dairy cattle to streams of the Cannonsville Watershed, New York. J. Soil Water Conserv. 62:40–47.

Jandl, R., M. Rodeghiero, C. Martinez, M. F. Cotrufo, F. Bampa, B. vanWesemael, R. B. Harrison, I.A. Guerrini, DdeB. Richter, L. Rustad, et al. 2014. Current status, uncertainty and future needs in soil organic carbon monitoring. Sci. Total Environ. 468:376–383.

Janzen, H. H. 2010. What place for livestock on a re-greening earth? Anim. Feed Sci. Technol. 166–167:783–796.

Kaschuk, G., T. W. Kuyper, P. A. Leffelaar, M. Hungria, and K. E. Giller. 2009. Are the rates of photosynthesis stimulated by the carbon sink strength of rhizobial and arbuscular mycorrhizal symbioses? Soil. Biol. Biochem. 41:1233–1244.

Khidir, H. H., D. M. Eudy, A. Porras-Alfaro, J. Herrera, D. O. Natvig, and R. L. Sinsabaugh. 2008. A general suite of fungal endophytes dominate the roots of two dominant grasses in a semiarid grassland. J. Arid Environ. 74:35–42.

Kobayashi, M., R. E. Howitt, L. S. Jarvis, and A. L. Emilio. 2007. Stochastic rangeland use under capital constraints. Am. J. Agric. Econ. 89:805–817.

Liebig, M. A., J. R. Gross, S. L. Kronberg, R. L. Phillips, et al. 2010. Grazing management contributions to net global warming potential: a long-term evaluation in the northern great plains. J. Environ. Qual. 39:799–809.

Lupo, C. D., D. E. Clay, J. L. Benning, and J. J. Stone. 2013. Life-cycle assessment of the beef cattle production system for the Northern Great Plains, USA. J. Environ. Qual. 42:1386–1394.

Machmuller, M. B., M. G. Kramer, T. K. Cyle, N. Hill, D. Hancock, and A. Thompson. 2015. Emerging land use practices rapidly increase soil organic matter. Nat. Commun. 6:6995. doi:10.1038/ncomms7995

Martin, R., B. Müller, A. Linstädter, and K. Frank. 2014. How much climate change can pastoral livelihoods tolerate? Modelling rangeland use and evaluating risk. Global Environ. Change. 24:183–192.

Mathews, B. W., L. E. Sollenberger, V. D. Nair, and C. R. Staples. 1994. Impact of grazing on soil nitrogen, phosphorus, potassium, and sulfur distribution. J. Environ. Qual. 23:1006–1013.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Montgomery, D. R. 2017. Growing a revolution: bringing our soils back to life. WW Norton & Company, New York, NY.

Mottet, A., C. de Haan, A. Falcucci, G. Tempio, C. Opio, and P. Gerber. 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food. Sec. 14:1–8.

Müller, B., K. Frank, and C. Wissel. 2007. Relevance of rest periods in non-equilibrium rangeland systems: a modelling analysis. Agric. Syst. 92:295–317.

Müller, B., J. Schulze, D. Kreuer, A. Linstädter, and K. Frank. 2014. How to avoid unsustainable side effects of managing climate risk in drylands – the supplementary feeding controversy. Agric. Syst. 139:153–165.

National Research Council. 2002. Riparian areas: functions and strategies for management. National Academic Press, Washington, DC. p. 415.

Nielsen, U. N., E. Ayres, D. H. Wall, and R. D. Bardgett. 2011. Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity-function relationships. Eur. J. Soil. Sci. 62:105–116.

Norton, B. E. 1998. The application of grazing management to increase sustainable livestock production. Anim. Prod. Sci. 22:15–26.

Norton, B. E. 2003. Spatial management of grazing to enhance livestock production and resource condition: a scientific argument. In: Allsopp, N., A. R. Palmer, S. J. Milton, K. P. Kirkman, G.I.H. Kerley, C. R. Hurt, and C. J. Brown, editors. Proceedings of the 7th International Rangeland Congress, Durban, South Africa. Document Transfer Technologies, Irene, Republic of South Africa. p. 810–820.

O'Connor, T. G. 1992. Patterns of plant selection by grazing cattle in two Savanna grasslands: a plant's eye view. J. Grassl. Soc. South. Afr. 9:97–104.

Ottoboni, A., and F. Ottoboni. 2013. The modern nutritional diseases and how to prevent them. 2nd ed. Vicente Books, Fernley, NV.

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

Park, Y., S. Ale, W. R. Teague, and J. Jeong. 2017b. Evaluating the ranch and watershed scale impacts of using traditional and adaptive multi-paddock grazing on runoff, sediment, and nutrient losses in North Texas. Agric. Ecosyst. Environ. 240:32–44.

Pelletier, N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agric. Syst. 103:380–389.

Provenza, F. D. 2008. What does it mean to be locally adapted and who cares anyway? J. Animal Sci. 86:271–284.

Ragab, R., and C. Prudhomme. 2002. Soil and water: climate change and water resources management in arid and semi-arid regions: prospective and challenges for the 21st century. Biosyst. Eng. 81:3–34.

Richardson, P. Q., and R. H. Richardson. 2000. Dung beetles improve the soil community in Texas and Oklahoma. Ecol. Restor. 18:116−117.

Rillig, M. C. 2004. Arbuscular mycorrhizae and terrestrial ecosystem processes. Ecol. Lett. 7:740–754.

Ripple, W. J., P. Smith, H. Haberl, S. A. Montzka, C. MacAlpine, and D. H. Boucher. 2014. Ruminants, climate change and climate policy. Nat. Clim. Change. 4:2–5.

Ritten, J. P., W. M. Frasier, C. T. Bastian, and S. T. Gray. 2010. Optimal rangeland stocking decisions under stochastic and climate impacted weather. Am. J. Agric. Econ. 92:1242–1255.

Ritter, W. F. 1988. Reducing impacts of non-point source pollution from agriculture. J. Environ. Sci. Health. 23:645–667.

Rodriguez, H., and R. Fraga. 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnol. Adv. 17:319–339.

Rowntree, J. E., R. Ryals, M. S. DeLonge, W. R. Teague, M. B. Chiavegato, P. Byck, and T. Wang. 2016. Potential mitigation of Midwest grass-finished beef production emissions with soil carbon sequestration in the United States of America. Future Food J. Food Agric. Soc. 4:31–38.

Sanjari, G., B. Yu, H. Ghadiri, C. A. A. Ciesiolka, and B. Yu. 2009. Effects of time-controlled grazing on runoff and sediment loss. Soil. Res. 47:796–808.

Sauer, T. J., T. C. Daniel, D. J. Nichols, C. P. West, P. A. Moore, and G. L. Wheeler. 2000. Runoff quality from poultry litter-treated pasture and forest sites. J. Environ. Qual. 29:515–521.

Savory, A., and J. Butterfield. 2016. Holistic management. 3rd ed. Island Press, Washington, DC.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford. 1990. Biological feedbacks in global desertification. Science. 247:1043–1048.

Schwarte, K. A., J. R. Russell, J. L. Kovar, D. G. Morrical, et al. 2011. Grazing management effects on sediment, phosphorus, and pathogen loading of streams in cool-season grass pastures. J. Environ. Qual. 40:1303–1313.

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: issues and options. J. Environ. Qual. 23:437–451.

Sovell, L. A., B. Vondracek, J. A. Frost, and K. G. Mumford. 2000. Impacts of rotational grazing and riparian buffers on physio-chemical and biological characteristics of Southeastern Minnesota, USA, Streams. Environ. Manage. 26:629–641.

Stackhouse-Lawson, K. R., C. A. Rotz, J. W. Oltjen, and F. M. Mitloehner. 2012. Carbon footprint and ammonia emissions of California beef production systems. J. Anim Sci. 90:4641–4655.

Stout, W. L., S. L. Fales, L. D. Muller, R. R. Schnabel, and S. R. Weaver. 2000b. Assessing the effect of management intensive grazing on water quality in the Northeast U.S. J. Soil Water Conserv. 55:238–243.

Stout, W. L., S. R. Weaver, W. J. Gburek, G. J. Folmar, and S. R. Weaver. 2000a. Water quality implications of dairy slurry applied to cut pastures in the northeast USA. Soil Use Manage. 16:189–193.

Tainton, N. M., A. J. Aucamp, and J. E. Danckwerts. 1999. Principles of managing veld. In: Tainton, N. M, editor. Veld management in South Africa. University of Natal Press, Pietermaritzburg, South Africa. p. 169–193.

Teague, W. R., S. Apfelbaum, R. Lal, U. P. Kreuter, J. Rowntree, C. A. Davies, R. Conser, M. Rasmussen, J. Hatfield, T. Wang, et al. 2016. The role of ruminants in reducing agriculture's carbon footprint in North America. J. Soil Water Conserv. 71:156–164.

Teague, W. R., and M. Barnes. 2017. Grazing management that regenerates ecosystem function and grazingland livelihoods. Afr. J. Range Forage Sci. 34:77–86.

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

Teague, W. R., S. L. Dowhower, and J. A. Waggoner. 2004. Drought and grazing patch dynamics under different grazing management. J. Arid Environ. 58:97–117.

Teague, R., B. Grant, and H. Wang. 2015. Assessing optimal configurations of multi-paddock grazing strategies in tallgrass prairie using a simulation model. J. Environ. Manage. 150:262–273.

Teague, R., F. Provenza, U. Kreuter, T. Steffens, and M. Barnes. 2013. Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? J. Environ. Manage. 128:699–717.

Thurow, T. 1991. Hydrology and erosion. In: Heitschmidt, R. K., and J. W. Stuth, editors. Grazing management: an ecological perspective. Timberland Press, Portland, OR. p. 141–159.

Vadas, P. A., D. L. Busch, J. M. Powell, and G. E. Brink. 2014. Monitoring runoff from cattle-grazed pastures for a phosphorus loss quantification tool. Agric. Ecosyst. Environ. 199:124–131.

Van der Heijden, M. G. A., R. D. Bardgett, and N. M. Van Straalen. 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol. Lett. 11:296–310.

Van der Ploeg, J. D., P. Verschuren, F. Verhoeven, and J. Pepels. 2006. Dealing with novelties: a grassland experiment reconsidered. J. Environ. Policy Plan. 8:199–218.

Wang, C., G. Han, S. Wang, X. Zhai, J. Brown, K. M. Havstad, X. Ma, A. Wilkes, M. Zhao, S. Tang, et al. 2014. Sound management may sequester methane in grazed rangeland ecosystems. Sci. Rep. 4:4444. doi:10.1038/srep04444

Wang, T., W. R. Teague, S. C. Park, and S. Bevers. 2015. GHG mitigation and profitability potential of different grazing systems in Southern great plain. Sustainability 7:13500–13521.

Wang, T., W. R. Teague, and S. C. Park. 2016. Evaluation of continuous and multipaddock grazing on vegetation and livestock performance – a modeling approach. Rangel. Ecol. Manag. 69:457–464.

Webber, D. F., S. K. Mickelson, S. I. Ahmed, J. R. Russell, W. J. Powers, R. C. Schultz, and J. L. Kovar. 2010. Livestock grazing and vegetative filter strip buffer effects on runoff sediment, nitrate, and phosphorus losses. J. Soil Water Conserv. 65:34–41.

Weltz, M. A., L. Jolley, D. Goodrich, K. Boykin, M. Nearing, J. Stone, P. Guertin, M. Hernandez, K. Spaeth, F. Pierson, et al. 2011. Techniques for assessing the environmental outcomes of conservation practices applied to rangeland watersheds. J. Soil Water Conserv. 66:154A–162A.

West, P. C., J. S. Gerber, P. M. Engstrom, N. D. Mueller, K. A. Brauman, K. M. Carlson, E. S. Cassidy, M. Johnston, G. K. MacDonald, D. K. Ray, et al. 2014. Leverage points for improving global food security and the environment. Science 345:325–328.

Wilcox, B. P. 2010. Transformative ecosystem change and ecohydrology: ushering in a new era for watershed management. Ecohydrology. 3:126–130.