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Sustainable intensification of livestock production on pastures

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Abstract. Growing human population and limited natural resources require a sustainable intensification of agricultural production systems. The "green revolution" was successful in increasing world food production, but unintended consequences, including pollution of ground water, soil erosion, climate change, and intensive use of agrochemicals, left a large footprint in the environment. Sustainable livestock intensification (SLI) implies greater productivity and more efficient use of natural resources, reducing impact of livestock systems on the environment. Approaches to reach this goal include diversification of plant species and plant functional groups, multiple ruminant species, improvement in feeding techniques and grazing management, plant breeding for improved nutrient use efficiency, integrated crop-livestock systems, and silvopasture systems. Greater use of forage legumes appears to be an opportunity for SLI in extensive C_4 grass-based pastureland commonly found in vast areas of Latin America. Grasslands in the 21st century will also be valued for multiple services they provide to humankind, and mechanisms of payment for these services are needed. A more 'holistic' approach will improve social and economic sustainability of livestock systems. Achieving long-term sustainability must match short-term profits. Diversification of the products and services provided by grassland ecosystems is a key to reach SLI in the near future.

Key Words: Cerrado, Ecosystem Services, Grassland, Savanna, Sustainability

Intensificação sustentável da produção pecuária em pastagens

Resumo. O aumento da população humana e os recursos naturais limitantes requerem uma intensificação sustentável dos sistemas de produção agrícola. A "Revolução Verde" foi bem-sucedida em aumentar a produção mundial de alimentos, mas 'efeitos colaterais' ocorreram, incluindo a poluição de águas subterrâneas, erosão do solo, aquecimento global e uso intensivo de agroquímicos, deixando marcas ambientais. Intensificação sustentável da produção animal (SLI) implica em aumento da produtividade e uso mais eficiente dos recursos naturais, reduzindo o impacto dos sistemas de produção animal no meio ambiente. Diferentes métodos podem ser usados para atingir esta meta, incluindo, mas não se limitando a, diversificação de espécies e de grupos funcionais de planta, melhorias de técnicas de alimentação e de manejo do pastejo, melhoramento de forrageiras objetivando melhoria na eficiência do uso de nutrientes, integração lavoura-pecuária e sistemas silvopastoris. Leguminosas forrageiras representam uma oportunidade para SLI em monocultivos de gramíneas C_4, comumente encontradas em vastas áreas da América Latina. Pastagens no século 21 serão reconhecidas pelos múltiplos serviços prestados para a humanidade e mecanismos de pagamento desses serviços serão viabilizados. Uma visão mais 'holística' deve ser utilizada para melhorar a sustentabilidade dos sistemas de produção animal quanto aos aspectos social e econômico. Sustentabilidade de longo prazo deve ser preferida em detrimento do lucro de curto prazo. Diversificação de produtos e serviços prestados por pastagens é fundamental para alcançar SLI em um futuro próximo.

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Palavras-chave: Cerrado, Pastagens, Savana, Sustentabilidade, Serviços ambientais,

Introduction

Human population has increased rapidly since the industrial revolution and is projected to reach 9.7 x 10^9 by 2050 (FAO, 2016). Population growth rate is not equal, with the 50 least-developed countries projected to grow 96.5% by 2050, while the population in the European Union is forecast to decrease by 2% in the same period (Dubeux *et al.*, 2011). Matching population growth rate with greater food production is a constant challenge, but the "green revolution" was instrumental in achieving this goal. Economic inequalities and differences in food storage and distribution systems among countries, however, have resulted in shortages of food in some countries and excess in others. Additionally, there have been unintended consequences of technologies implemented during the "green revolution", including nutrient pollution of ground water, soil erosion, climate change, and a much larger C footprint associated with intensive use of agrochemicals. Food supply must continue to grow to meet demand, but the challenge we currently face is to produce more without further harming the environment. In fact, agricultural systems that are able to partially offset the problems generated by intensification are preferable.

Sustainable livestock intensification (SLI) implies greater production of outputs through the most efficient use of resources while reducing negative impact on the environment (Tedeschi *et al.*, 2015). Four premises underlie SLI: 1) the need to increase production; 2) increased production must be met through greater yields per unit land area; 3) a major reduction in environmental impacts is needed; and 4) SLI denotes a goal, but does not specify which technique must be used. Approaches need to be rigorously tested and assessed (Garnett *et al.*, 2013). Sustainable systems should have the ability to coexist with other systems and must be resilient (Tedeschi *et al.*, 2015). The triple bottom line of sustainability implies that SLI must include environmental, social, and economic aspects of agriculture production systems (Dubeux *et al.*, 2011).

Based on Tedeschi *et al.* (2015), SLI is a moving target that is difficult to define because it comprises a multitude of concepts and variables that are situation specific. It is always evolving because the first-limiting variable to sustainability is not fixed; it changes as other variables change. Also, there is a relative time factor among the many variables that affect sustainability, and as a result sustainability may not be reached because the variables have different optima across time and do not converge simultaneously. Lastly, the maximization of output per unit input, which is the motto of sustainable intensification, may not yield a resilient system, i.e., a system that returns to its original position/situation. Thus, SLI may be a momentary condition of a system, and the options needed to make a system sustainable may not be the same as those required to keep it sustainable in the long term. The system evolves and so does the management needed to maintain a dynamic condition of sustainability.

Grasslands cover approximately 26% of the world's land surface and 70% of the agricultural land area (FAO, 2016). Among terrestrial agroecosystems, grasslands provide one of the greatest opportunities to increase food production, if compared with traditional cropping systems. This is particularly true for grassland ecosystems in Latin America, where livestock production occurs in large areas but with limited external inputs (Boddey *et al.*, 2004). In Brazil, there was a tremendous increase in grassland productivity in the last 50 years. Grassland area increased 61% from 1961 to 2008, but cattle population and beef productivity increased 260% and 310%, respectively, within the same period (Dubeux *et al.*, 2011). Factors related to the increase in grassland productivity included the development of new forage germplasm adapted to low-fertility acid soils, development of the seed industry, cattle breeding, and new management practices. Because of the extensive nature of these systems, the use of fertilizers is still limited. Systems are grass-based, usually with a single species from the genus *Brachiaria*. In these predominant systems of Latin America, there is still opportunity to further increase productivity using a SLI approach. There are 466 x 10^6 ha of grasslands in South America (FAO, 2016). A small increase in productivity per unit land area coupled with an increase in ecosystem services provided by these grasslands would bring an enormous benefit to the environment and prevent clearing of new forest areas to meet the demand for animal-source food. In this review, we identify and discuss some alternatives to increase productivity using a SLI approach.

Increasing primary productivity with reduced off-farm inputs

Resource acquisition and utilization

Sustainable intensification implies increased productivity with reduced environmental impact (Garnett *et al.*, 2013). One way to accomplish this goal is to use the existing resources (e.g., water, nutrients, and light) more efficiently, instead of adding additional resources to the system. Within a forage-livestock system, matching grassland resource needs with resource availability is critical to maximize the efficiency of resource use. Availability of water and nutrients varies in space (e.g., soil depth) and time, and as a result single-species pastures may not be able to use resources as efficiently as mixed-species grasslands. By combining multiple species representing different functional groups (e.g., grasses, legumes, and forbs) that access natural resources from different soil depths and in different amounts throughout the season, primary productivity can be increased compared with single-species stands (Tilman *et al.*, 1996). In a 9-year experiment comparing a two-species grass-legume mixture with a five-species grass-legume-forb mixture, Skinner and Dell (2016) observed greater productivity and soil C accumulation for the five-species mixtures. Combining deep-rooted species exploring different soil layers with grasses allows more efficient nutrient utilization in space. Nutrients from deeper layers are recycled back to the surface becoming available to shallower-rooted species (Menezes and Salcedo, 1999). In addition to differences in ability to access nutrients, plant species also have different phenologies that result in varying resource requirements during their life cycle and throughout the growing season.

In considering resource acquisition, root surface area is perhaps the single most important trait to improve nutrient and water acquisition by plants (Tinker and Nye, 2000). Root surface is a function of root length and radius; therefore, extensive root systems allow greater nutrient acquisition. Root hairs are an important component of root length. They increase total root length with relatively lower maintenance metabolic cost compared with thicker roots (Ozanne, 1980). Management practices that allow greater root development favor nutrient and water acquisition. Stocking rate of grazed grassland is an example. Because overgrazing leads to less root development reducing nutrient and water acquisition, adjustment of stocking rate is crucial (Dubeux *et al.*, 2007). Forage breeding efforts rarely focus on root development, so plants within the same species exhibiting greater shoot development usually have less root mass (Interrante *et al.*, 2009), thereby reducing resource acquisition and storing less root reserves. As a result, these plants are more prone to drought stress and more susceptible to overgrazing. Despite the importance of the root system in resource acquisition and plant survival, there are few research programs working on this topic (Dubeux *et al.*, 2006).

Once a nutrient or water is taken up by the plant, it is important to use it efficiently. Nutrient use efficiency, from the physiological standpoint, is the biomass produced per unit of nutrient taken up from the soil solution. The agronomic definition is biomass produced per unit of nutrient applied to the soil (Anghinoni and Meurer, 1999). Nutrient use efficiency also differs among plant physiological groups.

Warm-season C_4 grasses are more N-use efficient at the leaf level compared to legumes (Wedin, 2004); however, the latter usually have a competitive advantage in low-N environments due to biological N_2 fixation (BNF). Nitrogen use efficiency (NUE) is also related to the ability of the plant to internally recycle N and the mean residence time of N in the plant. Overall NUE is a function of N residence time in the plant and N productivity. Nitrogen productivity is a function of 1) productivity per unit of N allocated to photosynthetic tissue; and 2) proportion of plant N allocated to photosynthetic tissues (Lambers *et al.*, 1989). Therefore, if the plant allocates a significant portion of total N to roots and rhizomes, it will reduce N productivity because N was allocated to a non-photosynthetic tissue. This root-rhizome N pool, however, will be internally recycled and increase N residence time, which will favor NUE. Bahiagrass (*Paspalum notatum* Flügge) is an example of a C_4 grass with significant N allocated to roots and rhizomes (Blue *et al.*, 1980).

Often the combination of grasses and legumes leads to greater primary productivity because of the feedback mechanism where grasses take up soil N and stimulate legume BNF (Nyfeler *et al.*, 2011). Because nitrates are potentially leached or undergo denitrification, any process that reduces these losses might increase N use at the landscape level. In fact, Piñeiro *et al.* (2010) revised 67 paired comparisons of grazed vs. ungrazed sites and concluded that soil organic matter (SOM) C:N ratio increased at grazed sites as a result of N losses. The authors concluded that soil organic C (SOC) sequestration and grassland productivity can simultaneously increase by enhancing N retention at the landscape level.

Recent evidence suggests that the warm-climate C_4 grass *Brachiaria humidicola* (Rendle) Schweick can suppress soil-nitrification by releasing inhibitors from roots (Subbarao *et al*., 2009). Nitrification inhibitors might reduce N losses from warm-climate pastures commonly found in South America, contributing to SLI.

Phosphorus use efficiency (PUE) is also important considering the usually limited content of this element in tropical soils (Ozanne, 1980). Plants responsive to P fertilization are not necessarily efficient at using P. Plants with greater PUE usually develop under low soil P. Phosphorus acquisition, translocation, and internal utilization are important aspects of the general PUE (Dubeux *et al*., 2006). Shenoy and Kalagudi (2005) indicated that there is inter- and intra-specific genetic variability for these traits. This variability must be explored in order to develop plants with greater PUE. Forage development programs, however, usually select plants responsive to P fertilization and not plants with greater PUE. Different strategies might be used to increase soil P acquisition by plants. Phosphate solubilization in the rhizosphere (Mark *et al*., 2003) and mycorrhizae associations that lead to greater exploration of the soil profile (Sylvia, 1999; Norby and Jackson, 2000) are also important mechanisms to increase PUE by plants and must be incorporated into forage development programs.

Use of legumes and silvopasture systems

In South America, there is an underexploited opportunity to combine multiple species in pasturelands. Typically, cultivated pastures in South America are single genus such as *Brachiaria* grass monocultures. Lessons learned from forage legume research in warm-climates in the last 30 years could direct future research and development efforts away from grass monocultures. Shelton *et al*. (2005) reported successful legume adoption examples and included reasons for success and failure. In Brazil, *Arachis pintoi* Krapov. & W. C. Greg. provides a success story regarding legume adoption (Valentim and Andrade, 2005). Likewise, tree legumes can be used in silvopasture systems to add N to the system and provide other ecosystem services (Apolinário *et al*., 2015; Costa *et al*., 2016a). Inclusion of forage legumes in grazing systems presents one of the greatest potential opportunities for SLI of livestock systems in Latin America.

Silvopasture systems (SPS) meet most of the criteria for SLI considering their potential to increase primary productivity and offset greenhouse gas emissions from livestock. Because of greater efficiency in resource utilization, combining trees with herbaceous vegetation often leads to greater land-use efficiency. These systems, however, are still underexploited in South America (Dubeux *et al*., 2015, 2016). If the tree component is a N_2-fixing legume, the reduction in N fertilizer inputs will mitigate the C footprint of the SPS, since N fertilizers emit 3.3 to 6.6 CO_2-eq per unit of N (Lal, 2004).

Increased primary productivity and allocation of C to tree components that have longer mean residency time (e.g., tree trunk, branches, and roots) results in greater potential of SPS to become a C sink. In a silvopasture system using tree legumes [*Mimosa caesalpiniifolia* Benth or *Gliricidia sepium* (Jacq.) Kunth], Apolinário *et al*. (2015) observed an aboveground biomass of 53.7 and 51.0 Mg DM ha^{-1} five years after planting, with the majority of this biomass (~90%) allocated to trunk and branches. These numbers do not include the root system, which should add at least 10-20% more biomass (Mokany *et al*., 2006). Assuming 42% C in the biomass and 50 Mg ha^{-1} in five years, the annual C accumulation (aboveground only) would be 4.2 Mg C ha^{-1} or 15.4 Mg CO_2-eq. Adding the root component would increase this number by 15-20%. Although not measured in the research, this C accumulation should be more than sufficient to offset the methane emissions from livestock.

Costa *et al*. (2016a) reported that the average stocking rate for this SPS system was 1.9 animal units (AU) ha^{-1} (1 AU = 450 kg body weight). A daily average emission of 200 g CH_4 ha^{-1} d^{-1} was assumed (Lassey, 2007), considering that these were non-lactating animals averaging 450 kg. This number might be overestimated for warm-climate grasslands. Total methane emission for these SPS would be 139 kg CH_4 ha^{-1} yr^{-1} at a stocking rate of 1.9 AU ha^{-1}. Considering the global warming potential of 23 kg CO_2/kg CH_4 (Ramaswamy *et al*., 2001), the annual CH_4 emission from livestock in these systems would be 3,190 kg CO_2-eq yr^{-1}. Although this is far from being a life cycle analysis, these numbers (15.4 Mg CO_2-eq. ha^{-1} yr^{-1} of above-ground accumulation vs. 3.19 Mg CO_2-eq. ha^{-1} yr^{-1} of CH_4 emission by livestock) indicate the potential of SPS systems using tree legumes as a potential C sink.

It is important to recognize, however, that the observed rates of aboveground biomass accumulation during the first five years of the SPS are not likely to be sustained indefinitely. From the economic standpoint, SPS can generate extra revenue through sale of timber, wood for fuel, and fruit. In fact, Apolinário *et al*. (2015) indicated that *Mimosa caesalpiniifolia* Benth. timber is used commercially for fence posts, and the income generated from the SPS could double the gross annual income expected from livestock grazing signalgrass (*Brachiaria decumbens* Stapf.) monoculture. Silvopastures also provide other ecosystem services such as below-ground C sequestration, forage for pollinators, and nutrient cycling (Dubeux *et al*., 2016).

Multi-herbivore systems

Efficient utilization of standing biomass is one important step toward SLI. Grazing efficiency can be measured as the proportion of the herbage accumulation that is consumed by grazing livestock (Dubeux *et al*., 2006). Rangelands or multi-species cultivated pastures have forage opportunities for grazers and browsers. Muir *et al*. (2015) suggested increasing herbivory diversity on cultivated pastures as a SLI approach. These authors reviewed the literature in rangelands or natural grassland systems and concluded that sequential or simultaneous introduction of multiple herbivore species leads to greater productivity, diversity, and resilience of plant as well as animal populations. Other studies have shown that, compared to single-ruminant systems, mixed stocking by two or more animal species achieved greater utilization of otherwise unused grassland resources (Animut and Goetsch, 2008), increased animal productivity and efficiency of forage use (Abaye *et al*., 1993), and positively impacted vegetation dynamics (Fraser *et al*., 2007). Favorable outcomes most often occur in heterogeneous plant communities, when differences in preference exist among animal species (Animut and Goetsch, 2008). This was illustrated in mixed swards of blackberry (*Rubus fruticosas* L.) briar, rhizoma peanut (*Arachis glabrata* Benth.), and various grasses. When cattle (*Bos* spp.) and goats (*Capra hircus*) grazed this mixture, bites of cattle grazing alone were 92% rhizoma peanut or grass while goats grazing/browsing alone selected briar 59% of the time. When cattle and goats grazed concurrently, 29 to 34% of total animal bites were blackberry. Thus a resource essentially avoided by cattle grazing alone (blackberry) contributed significantly to forage utilization under mixed-animal-species grazing (Krueger *et al*., 2014). With the current trend to increase plant species richness and diversity of plant functional groups, adding another layer of diversity (i.e., grazers and browsers or selective and bulk feeders) would likely benefit the system, increasing its resilience and productivity. Limitations to adoption of mixed-animal-species grazing include lack of landowner tradition and grassland scientist training as well as limited data on cultivated pastures in many environments (Sollenberger *et al*., 2012).

Native vs. cultivated pastures

In South America, grasslands occupy 466 x 10^6 ha (FAO, 2016), and the majority of this vast area is characterized by low-input systems, using grass monocultures and/or rangelands. In this scenario, poor grazing management leading to overgrazing and loss of soil fertility is commonly observed (Boddey *et al*., 2004). Management practices that promote SLI in South American grasslands have potential to increase the importance of these grasslands as providers of animal-source food for local populations as well as ecosystem services. In Brazil, cultivated pastures have surpassed the area of natural grasslands, with a large expansion occurring from the 1970s to 2000s (Dias Filho, 2014). In other South American countries, however, natural grasslands still comprise the majority of the grassland area (FAO, 2016). In Brazil, despite the greater proportion of cultivated pastures, 52.5% of grasslands has a stocking rate < 0.4 AU ha^{-1}, 77.6% has < 0.8 AU ha^{-1}, and only 4% of the area has a stocking rate > 1.5 AU ha^{-1} (Dias-Filho, 2014). Therefore, it is reasonable to conclude that low-input systems still predominate in South American countries, including Brazil. Low-input grassland ecosystems are very responsive to improvements in management and/or inputs since the current productivity is below system potential. Significant limitations are low soil fertility, poor grazing management, reduced plant species diversification, and low inputs. Improvements in these areas have great potential to increase productivity and overall efficiency, considering that these systems are far removed from their potential productivity.

Integrated crop-livestock systems

Integration of crops and livestock can improve nutrient cycling while reducing chemical inputs. Integrated systems are less sensitive to fluctuations in prices of inputs and outputs when compared with more specialized systems. Ryschawy *et al*. (2012) surveyed 48 farms in France, including integrated crop-livestock and specialized farms (crop or livestock) and found that integrated systems were more resilient and appear to be a way for an environmentally and economically sustainable agriculture. In Florida, a sod-based rotation system of bahiagrass-cotton (*Gossypium hirsutum* L.)-peanut (*Arachis hypogaea* L.) using conservation tillage over 12 years improved SOM from < 1% to 2.3% as well as soil physical characteristics. Grazing exclusion cages within this system compared grazed vs. non-grazed areas. Grazing improved cotton yield with less fertilizer inputs in non-irrigated areas (George *et al*., 2013). Earthworm population was also greater in the sod-based rotation compared with the traditional cotton-peanut rotation (Katsvairo *et al.*, 2007). In the Brazilian Cerrados, integrated crop-livestock systems are used not only as a tool to recover degraded pastureland, but also to optimize land use and improve profits. Carvalho *et al*. (2010) demonstrated that integrated crop-livestock systems in agricultural areas function as a C sink with accumulation rates ranging from 0.82 to 2.58 Mg C ha^{-1} yr^{-1}. Constraints for the adoption of integrated crop-livestock systems include the infrastructure needed for both agriculture and livestock operations and more complex management/marketing skills. Leasing farm lands for specialized producers might reduce these bottlenecks. In North Florida, for example, producers grazing stocker cattle often lease agricultural land during the cool season to establish annual pastures, returning the land in the spring for row-crop production.

Livestock and the environment

Greenhouse gas emissions from livestock: facts and potential for mitigation

Livestock production contributes to climate change in several ways. It accounts for about two-thirds of direct agricultural emissions of nitrous oxide (FAO, 2006) and about 14.5% of total anthropogenic greenhouse gas (GHG) emissions when supply chains are included (Gerber *et al.*, 2013b). These estimates are contentious. Goodland (2014) believed the contribution of ruminants to the GHG (i.e., nitrous oxide and methane) is much larger than initially suggested. He pointed out some flaws in the current calculations by FAO that under-predict the estimates. For instance, the 18% reported by FAO (2006) is based on anthropogenic GHG emissions and it does not include a true whole-life cycle of livestock. In that case, Goodland (2014) indicated that livestock products would account for 51% of annual worldwide anthropogenic GHG emissions. This value indicates that adoption of SLI may be more critical than originally perceived.

Selecting the most efficient animals (or feeding systems) is likely the single most important GHG mitigation strategy available to the livestock industry (Tedeschi *et al.*, 2015). There are many technical options to mitigate GHG by ruminants, as recommended by Gerber *et al*. (2013a): (1) feed supplementation (e.g., dietary lipids, nitrates, and ionophores), (2) feed and feed management strategies (e.g., forage quality, feed processing, and precision feeding), and (3) manure-related strategies (e.g., precision feeding such as better matching of protein requirement by the animal and supply of protein; using condensed tannins to enhance rumen-bypass protein; shifting N from urine to feces; or reducing fermentable organic matter excreted). Tedeschi *et al*. (2003, 2011) listed potential mitigation strategies, including (1) ionophores that generate a shift in volatile fatty acids production in the rumen, (2) probiotics that increase animal production and decrease lactate production in the rumen, (3) essential oils to modify the dynamics of protein degradation in the rumen, (4) vaccines, (5) saponins, and (6) condensed tannins.

Gurian-Sherman (2011) indicated these technologies could effectively decrease methane emission by 15 to 30%. One major impediment to achieving SLI, however, is the large discrepancy among producers; some are extremely efficient while the majority lack management and technical guidance to improve productivity, leading to unsustainable production systems. In fact, Gerber *et al*. (2013b) indicated that GHG emissions could be reduced by one-third globally if less-efficient producers adopt cutting-edge or regional best practices. Technology adoption and application might be the most significant hurdles to overcome in advancing SLI.

Antibiotics

Climate change is perhaps the most critical environmental issue facing humanity because of its potential for widespread and catastrophic impacts to future generations (FAO, 2006). Unfortunately, climate change is not the only problem humankind faces. Antibiotics have dramatically improved the livelihood of many people around the world through a significant decrease in child mortality rates and increased life expectancy. Antibiotics have also reduced the morbidity and mortality of livestock, indirectly bringing about greater rates of gain and production efficiency (Mathew *et al.*, 2007). These achievements have not occurred without some detrimental costs, however. Scientists and medical practitioners are concerned with a surge of infectious diseases due to increased antibiotic resistance (Mathew *et al.*, 2007). The WHO (2015) indicated that antibiotic resistance happens when bacteria mutate and become resistant to the antibiotics used to treat the infections they cause. Despite tremendous efforts in the past to increase the availability of healthy and high-quality animal products to the human population through the use of antibiotics, humankind may face severe consequences from antibiotic-resistant bacteria, the so-called superbugs (Ferber, 2000). Early in 2016, a superbug that was resistant to colistin, an old antibiotic used to treat especially dangerous infections, was identified (http://nyti.ms/1WYztmv), leading some to suggest that humankind was on the brink of the abyss. Because of the imminent threat to the humanity, SLI must develop critical strategic plans and take actions to prevent antibiotic resistance, for example, by adopting the national "One Health" surveillance effort (http://www.onehealthinitiative.com) in addition to other environmental measurements to be sustainable.

Nutrient use efficiency by livestock: how to improve it

From a nutritional perspective, many strategies can be applied to successfully implement SLI. These include precision feeding, smart precision feeding, nutrient synchronization, algae supplementation, phase feeding, and compensatory growth, among many more.

Precision feeding is likely the best practical strategy to decrease methane emissions indirectly. It seeks to provide adequate amounts of energy and nutrients (protein, minerals, and vitamins) needed by the animals based on physiological stage of production. It also helps to maintain a healthy rumen that maximizes ruminal microbial turnover (Hristov *et al*., 2013). In a nutshell, precision feeding means matching nutrient requirements with nutrient supply. Also, smart precision feeding takes advantage of the animal's physiology and adaptation when formulating diets for the precision feeding strategy. For instance, studies with grazing, lactating beef cows found that supplementing ruminally degraded protein (RDP) every four days was enough to maintain animal productivity (Coleman and Wyatt, 1982; Krehbiel *et al*., 1998). This is possible because increased N recycling into the rumen occurs when ruminants are under shortage of N, and the recycling has no detrimental effect on the ruminant animal.

Nutrient synchronization, especially ruminally degradable carbohydrate and protein, is a key concept that is often ignored, though variable results for cattle consuming high-forage diets have been reported (Hersom, 2008). When successfully applied, enhancement in microbial crude protein synthesis is the main outcome. To the ruminant animal, microbial yield per unit of organic matter consumed is an excellent indicator of efficiency (Hoover and Stokes, 1991) because more amino acids will be present in the small intestine to be absorbed for muscle or milk production. Supplementation with ruminally degradable protein (non-protein N or true protein) will usually increase animal performance when N is the first-limiting nutrient (Olson *et al*., 1999; Bandyk *et al*., 2001). Nitrate, rather than urea, might be an alternative for N supplementation while reducing methane emissions, but the cost will likely limit application of this technology (Callaghan *et al*., 2014).

Another alternative is the supplementation of algae to grazing animals consuming low-crude protein tropical grasses. For example, *Spirulina platensis* and *Chlorella pyrenoidosa* had CP concentration of 67.5 and 58% DM, respectively, and *Schizochytrium* sp. had crude lipid concentration of 19.8 % DM. Average daily gain of *Bos indicus* steers fed with speargrass hay increased linearly with supplementation of *S. platensis* (Costa *et al*., 2016b). Even lactating dairy cows grazing highly digestible pastures benefit from *Saccharomyces cerevisiae* supplementation by increasing milk lactose without affecting milk yield (Irvine *et al*., 2011).

Under feedlot conditions, it is common to underfeed protein during the beginning of the feeding period and overfeed it toward the end (CAST, 2002), which consequently mismatches the requirement of protein by the animals. Hence, phase feeding is another feeding strategy that seeks to match protein requirement (i.e., decrease dietary concentration) as the feedlot feeding progresses. As indicated above, genotyping feed-efficient animals may be the most promising alternative to drive up output per input ratio (Tedeschi *et al*., 2015). In addition, feed-efficient animals will also reduce their C footprint by reducing methane emission Hegarty *et al*. (2007), predicted to be 16 g CH_4 (kg DM)$^{-1}$ d^{-1} less for efficient animals (low residual feed intake). However, efficient animals selected under confinement conditions using the residual feed intake technique may not express their potential under grazing conditions (Wiley *et al*., 2016), and might not reduce methane emission as expected.

Grazing management

Grazing management, particularly the adjustment of stocking rate, is the single most important management tool in pasture-based livestock systems. Stocking rate affects the pathway of nutrient cycling: litter vs. excreta (Dubeux *et al*., 2007). Greater stocking rate (and grazing pressure) shifts nutrient flow towards excreta whereas under-stocked pastures have greater nutrient return via litter (Thomas, 1992). An even distribution of manure in the pasture is desired because nutrients will be recycled throughout the pasture, improving the odds of uniform forage growth and avoiding overgrazing patches (Rouquette, 2015). For example, location of shade and water in warm-climate grasslands has an overriding effect on excreta distribution. Dubeux *et al*. (2014) assessed excreta spatial distribution under continuous vs. rotational stocking methods on Pensacola bahiagrass in Florida, and concluded that the position of shade and water had a greater effect on animal behavior and excreta distribution in the landscape than did stocking density-mediated effects on competition for forage. In South America, over-grazing predominates in vast pastureland areas (Dias-Filho, 2014). Under these conditions, a greater proportion of nutrients recycles via excreta instead of litter (Thomas, 1992). Because nutrient losses from excreta are greater, particularly N losses, overgrazed, non-fertilized, warm-season grass monoculture pastures tend to decline with time (Boddey *et al*., 2004), especially in low-fertility soils. These pastures can have litter with high C/N and lignin/N ratios that immobilizes soil nutrients to support microbial degradation. This process renders the soil nutrients unavailable for plant uptake and reduces pasture productivity. Unfortunately, this is the case for large pasture areas in South America (Dias-Filho, 2014). Adequate grazing management and introduction of N_2-fixing forage legumes would be viable SLI alternatives in these areas.

Greater forage quality is obtained in forage harvested at an early maturity stage when soluble carbohydrate and protein concentrations are high, and cell wall lignification is low (Van Soest, 1994). The hypothesis under an SLI program is that grazing immature forages would limit the production of ruminal methane, thus, mitigating GHG emissions. Archimède *et al*. (2011) indicated that animals consuming C_4 grasses produced 17% more enteric methane than those consuming C_3 grasses and that animals consuming warm-climate legumes produced 20% less methane than those consuming C_4 grasses (i.e., C_4 grass > C_3 grass = warm-climate legumes). Also, Waghorn *et al*. (2002) reported that sheep fed the legume *Lotus pedunculatus* Cav. emitted 16% less methane than those fed ryegrass (11.5 versus 25.7 g methane/kg DM, respectively). Again, in the context of South America grasslands, introduction of legumes would be a viable option to mitigate methane emission leading to SLI.

Ecosystem services provided by grazinglands

Carbon sequestration

Perennial grasslands are often net C sinks (Soussana *et al*., 2004, 2007; Peichl *et al*., 2011), but many factors affect their capacity to be sustained sinks including soil formation processes and parent material, climate, previous land management, soil texture, species planted, ecosystem age, and management intensity (Follett *et al*., 2001; Kucharik, 2007). In general, management improvements intended to increase forage production increase soil C content (Conant *et al*., 2001; Allard *et al*., 2007; Ammann *et al*., 2007). These can include increasing species richness or introducing more productive plants (Fisher *et al*., 1994; Adewopo *et al*., 2014, 2015), fertilization (Ammann *et al*., 2007, 2009), or changes in livestock management (Wright *et al*., 2004; Franzluebbers and Stuedemann, 2009). The remainder of this section will briefly address some of these management interventions that affect carbon sequestration.

Literature reports vary widely regarding the effect of plant species richness on soil C. In some cases, soil C gains are associated with species-rich grassland mixtures (Steinbeiss *et al*., 2008; Cong *et al*., 2014). The presence of highly productive species, plants with particular rooting characteristics or legumes, may strongly influence the positive impact of increasing species richness on soil C (De Deyn *et al*., 2009, 2011; Skinner and Dell, 2016). Other studies have found little or no beneficial impact of species richness on soil C (Skinner *et al*., 2006; Bonin *et al*., 2014). Thus, the evidence is mixed regarding the effect of species richness on soil C, but clearly in some environments and in the presence of key plant species, it can play a positive role.

As noted earlier, legumes may be one of those key functional groups that affect soil C. There have been relatively few quantitative studies of the impact of legume introduction on SOC accumulation, particularly under grazing (Jensen *et al*., 2012). Cong *et al*. (2014) suggested that the consensus of a limited number of studies is that forage legumes increase the rate of soil C sequestration. They argued that most grassland ecosystems are N limited and by including legumes, plant productivity increased resulting in greater soil C accumulation. Their conclusion was supported by De Deyn *et al*. (2009, 2011) who worked with birdsfoot trefoil (*Lotus corniculatus* L.), white clover (*Trifolium repens* L.), and red clover (*Trifolium pratense* L.). Others showing benefits of legumes include Fisher *et al*. (1994) in Colombia, Tarré *et al*. (2001) in Brazil, and Wright *et al*. (2004) in the USA.

Defoliation management affects the rate of change in SOC and total soil N. In Georgia, USA, Franzluebbers and Studemann (2009) compared bermudagrass (*Cynodon* spp.) that was unharvested, hayed monthly, or grazed at low (5.8 steers ha^{-1}) or high (8.7 steers ha^{-1}) stocking rates. Grazing led to greater levels of SOC in the surface 15 cm of soil than in ungrazed pastures. The difference in SOC concentration between low and high stocking rates (21.6 vs. 19.9 g kg^{-1}) became significant after 12 years of imposing treatments. In Texas, Wright *et al.* (2004) evaluated stocking rate effects on soil C and N in bermudagrass pastures. Over a 26-year period, high stocking rate resulted in smaller increases in soil C and N than did low stocking rate. Although there is evidence that grazed grasslands accumulate SOC more rapidly than hayed areas and that high stocking rates reduce SOC accumulation, the mechanisms driving SOC accumulation are not well understood.

Greater N fertilization of grasslands generally increases soil C accumulation (Ammann *et al*., 2007). An overriding principle relative to the effect of N fertilizer is that greater N application increases plant C fixation and forage accumulation, but it also results in greater ecosystem respiration (Peichl *et al.* 2011; Skinner, 2013), with the net effect on C sequestration depending on the relative magnitude of the changes in photosynthesis and respiration.

Water catchment and filtration

Improving or maintaining water quality is an important regulating ecosystem service of grasslands, but management plays a role in delivery of this service. Greater vegetative cover reduces nutrient movement into waterways (CAST, 2002), thus grazing intensity is a key management variable affecting surface water quality and greater grazing intensity increases nutrients in runoff (Schepers *et al*., 1982). Stocking method may also play a role. Continuous stocking to maintain a 5-cm height resulted in 34% greater total P in runoff than rotational stocking with a 5-cm post-grazing stubble and 3.7 times greater runoff than rotational stocking with a 10-cm post-grazing stubble (Haan *et al*., 2006). The latter did not differ from a non-grazed sward. Percentage surface cover by forage was correlated negatively with total-P load in runoff, leading to the conclusion that pasture management should ensure sufficient residual forage mass to reduce the kinetic energy of rainfall. These results do not implicate continuous stocking, in general, as a water quality hazard; instead, they indicate that this method in combination with high grazing intensity reduces cover and endangers surface waters. The nearly three-fold lower P in runoff associated with leaving 10- vs. 5-cm stubble under rotational stocking (Haan *et al*., 2006) supports grazing intensity as the key factor affecting this response.

Sediment loss from grasslands can be influenced by ground cover, sward height, treading damage, surface slope, and soil moisture (Haan *et al*., 2006). Greater sediment loading was associated with increasing grazing intensity and resulted in greater total organic C and chemical oxygen demand in runoff (Schepers *et al*., 1982). Sediment loss in Texas increased with increasing stocking rate (Warren *et al*., 1986) and was nearly two times greater from a continuously stocked sward maintained at a height of 5 cm than from a rotationally stocked treatment with a 5-cm post-grazing sward height (Haan *et al*., 2006). Maintaining good vegetative cover is a critical factor limiting soil loss from pastureland (Owens and Shipitalo, 2009), but additional research is needed to quantify effects of species diversity, growth habit, height, and percent cover on water quality.

BNF and nutrient cycling

Presence of sown or native legumes in grasslands provides biologically fixed N to the ecosystem (Muir *et al*., 2011). This service is highly valued because N is often the most limiting nutrient in grasslands and the C footprint associated with N fertilizer is large (Lal, 2004). Legumes also play an important role in nutrient cycling. Jensen *et al.* (2012) indicated that legume residues are rapidly degraded, releasing N for subsequent plant growth, and have C/N ratios that are more similar to those of soil microorganisms and SOM than those of non-legume species. Therefore, they suggested that inclusion of legumes in farming systems might lead to greater soil C accumulation over time, a response that would increase soil nutrient and water retention and eventual availability to plants.

Biodiversity and wildlife

An important ecosystem service of grasslands is providing wildlife habitat and food supply and sustaining biodiversity of plant species. It is possible to manage grazed grasslands for the benefit of both livestock and wildlife (Sollenberger *et al*., 2012). Managing grazing intensity plays a critical role. For example, high grazing intensity reduced avian abundance due to loss of preferred habitat for nesting, destruction of nests due to trampling, and fewer invertebrate food sources (Fuller and Gough, 1999). Species-rich grasslands are often favored for wildlife because they include plants with varying growth habits that are grazed differently by different herbivores, thus creating a diverse landscape that can provide niches for a wide range of wildlife species. Söderström *et al.* (2001) indicated that the importance of landscape composition for mobile organisms, such as birds, implies that management strategies should focus on providing diverse habitats within the wider countryside and not exclusively on single pastures or the grazing management of those pastures.

Forage for pollinators

Pollinators benefit 35% of global crop-based food production (Klein *et al*., 2007), and insects, particularly bees (*Hymenoptera: Apoidea*), are the primary pollinators of most crops and wild plants. Unfortunately, recent evidence indicates declining populations of both wild and domesticated pollinators (Potts *et al*., 2010). Grasslands can mitigate this decline by providing a food source for pollinators. Grasslands with greater plant species richness generally provide greater foraging opportunities for bees (Hudenwenz *et al*., 2012). Ebeling *et al*. (2008) observed a linear increase in the frequency of pollinator visits with the increase of blossom cover and the number of flowering plant species. Grassland improvement by sowing flower-rich species (e.g., forage legumes) is an option to improve habitat for pollinators (Potts *et al*., 2009). Grazing and herbicide management should attempt to optimize the frequency of flowering plants that are simultaneously beneficial for cattle and pollinators. Reduced harvesting frequency and delayed grazing have increased the presence of flowering plants and improved pollinator abundance (Hudewenz *et al*., 2012; Sjödin, 2008).

Social and economic aspects of livestock production

Socioeconomic and political factors have always influenced livestock production systems (Sayre *et al*., 2013) but today's market pressures to sacrifice long-term stability in favor of short-term production tend to prioritize individual economics over sociocultural values. This is an alarming trend. Although short term economic return is essential for the viability of livestock systems in Latin America, the long-term importance of broader social and cultural values do not necessarily preclude profit.

Low incidence of forage legume use in cultivated pasture or poor persistence of native legumes in rangeland (Muir *et al*., 2014) are examples of this disconnect between social and economic considerations. Legumes fix their own atmospheric N_2 and provide highly digestible crude protein to livestock, so they should be readily integrated into sustainable livestock production. They could arguably combat poverty and environmental degradation associated with dependence on external inputs and overgrazing (Peters *et al*., 2001). Legumes have failed, however, to live up to their potential in much of the world vis-à-vis the comparatively widespread use of grasses (Thomas and Sumberg, 1995; Pengelly *et al*., 2003; Peters and Lascano, 2003). White *et al*. (2013) reported that 86% of tropical cultivated pastures are found in Brazil, yet very few of these contain legumes, with managers preferring instead to depend on industrial N fertilizer for short-term profit. Why is this?

Another underutilized technology that could conceivably intensify sustainable livestock production is using pastures and rangeland for more than simply animal husbandry. Multiple economic and environmental benefits, beyond animal products alone, can arise from livestock systems. Pastures and rangelands can be used for myriad financial and environmental purposes including improved hydrology, C sequestration, wildlife, genetic diversity preservation, forestry, and tourism, among many others. Yet these additional benefits have only rarely been proposed by researchers and extensionists; when they have been eventually adopted, land managers have often been the pioneers. As a result, single-forage and single-animal livestock systems are the rule (Muir *et al*., 2015), with few additional economic and environmental benefits accruing to the land manager or society. This preference for monocultures and single uses dominates not just livestock systems but also the research and extension efforts that support them. This again begs the question, why?

These are but two examples of missed opportunities to sustainably intensify livestock production. There are many others, including extension ambivalence to organic farming (Lillard, 2011) and research irrelevance to local socio-economic realities. Peters and Lascano (2003) argued that researchers, extensionists and their institutions mandated to develop sustainable technologies have largely failed to include the land manager except as an end-user. According to these and other authors (Pengelly *et al*., 2003; Muir *et al*., 2014), involving the land manager in prioritizing and testing new ideas may avoid efforts that are irrelevant from the start.

A related bottleneck is the current overly simple view within research and extension that land managers are, above all, "producers" (see examples at OSU, 2016 and LSU, 2016). In the USA, for example, extension agents are often discouraged from referring to their target audience of farmers, ranchers or land managers as anything other than "producers." A paradigm shift away from this over-simplification may resolve much of the disconnection between short-term economics and long-term sustainability when seeking to intensify livestock production in Latin American. Recognizing that land managers, beyond short-term livestock harvest, consider themselves natural resource stewards that will pass along a legacy to future generations (Burkes, 2005; Sayre *et al*., 2013) should increase research and extension effectiveness at fostering complex technology adoption and sustainable socioeconomic policies.

Some proposed solutions to this disconnect in Latin America can be found in literature from around the world. Technology education often fails to keep up with land manager paradigms (Goodwin and Gouldthorpe, 2013); thus, some, like Hayati and Rezaei-Moghaddam (2006), have called for a shift in agricultural extension attitudes to a more agile "environmental sociology perspective" capable of adjusting quickly to changing socioeconomic realities. This direction parallels the "environmental modernization" movement that rejects the "demodernization" stance some environmentalists espoused that sacrificed productivity in favor of fewer inputs (Rezaei-Moghaddam *et al*., 2005). We propose that sustainable livestock intensification following the environmental modernization approach can attain greater production today without sacrificing future natural resource stewardship. In order to achieve this, some, such as Klein (2001) and Mukherjee and Maity (2015), propose greater private sector involvement in technology development and dissemination, especially as international development and government funding and interest fade. These more agile approaches not only enhance long-term environmental sustainability but also more readily diversify and adjust livestock socioeconomics to ever-changing markets.

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