Sustainable Intensification of Livestock Systems Using Forage Legumes in the Anthropocene

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Abstract
Sustainable intensification of livestock systems implies greater efficiency in resource utilization resulting in greater output of products and other ecosystem services per unit of resource input. Strategies to improve resource use efficiency include diversification of plant and ruminant species with complementary resource use. Forages that have root systems with contrasting architecture and exploring different soil layers with complementary use of resource acquisition (e.g., nutrients, water) could enhance primary productivity. Belowground interactions with soil microbiota (e.g., mycorrhizae) is key to enhance resource utilization. Forages with complementary canopy characteristics that helps enhancing light interception and utilization could also lead to greater resource utilization. Integrating forage legumes into livestock systems is a viable way to reduce input of industrial N fertilizer, reducing the use of fossil fuels and helping to mitigate global warming, a major problem during the Anthropocene. Some forage legumes have greater concentration of secondary compounds such as condensed tannins that might reduce emission of greenhouse gases (GHG) from eructation and from excreta. Livestock are major contributors to overall GHG emissions from agricultural systems, and any reduction on those emissions without compromising animal performance is welcome. Furthermore, forage legumes might enhance cattle performance because of greater nutritive value, resulting in greater beef production per unit of GHG released. In fact, shortening the production cycle and improving cattle reproductive efficiency could have major impact reducing the overall carbon footprint of the system. Grazing systems with more diversified plant species are typically more resistant and resilient, adapting to current climate changes during the Anthropocene. There are examples of successful integration of forage legumes into livestock systems in different regions of the world, with major reduction in off-farm inputs and maintaining the system productive. These successful examples must be used to increase adoption and to improve the efficiency of current livestock systems.

Introduction
The Anthropocene is a new proposed geological epoch defined by the action of humans having a substantial global effect on the Earth's systems (Zalasiewicz et al., 2011). From the late nineteenth century, rapid growth of the human population resulted in major human activities affecting earth's surface. Life expectancy increased and human population grew exponentially in the last century. As a result, there was a major need for energy utilization and increasing food production. Consequences are severe, including loss of biodiversity of plant and animal species, habitat fragmentation, increasing freshwater use, ocean acidification, global warming, and increasing concentration of greenhouse gases in the atmosphere (Whitmee et al., 2015). The human population will reach close to 10 billion people by 2050; therefore, there is a need to increase food production while preserving life on earth. Agroecosystems can play a major role providing ecosystem services that can mitigate the negative effects of human activities. Forage legumes can add another layer of benefits by providing ecosystem services such as biological nitrogen fixation (BNF), mitigation of GHG emissions, enhanced livestock performance, and improved habitat for pollinators (Sollenberger and Dubeux, 2022). This review paper will address how forage legumes can be used to develop sustainable livestock production systems that are productive and at the same time mitigate negative effects of human activities during the Anthropocene.

Sustainable intensification using forage legumes

Livestock performance

Forage legumes have key characteristics such as BNF, presence of secondary compounds (e.g., condensed tannins), and greater nutritive value when compared with C4 warm-climate grasses (Sollenberger and Dubeux, 2022). These characteristics are desirable for the sustainable intensification process since they might result in greater output of products and services per unit of resource input. In a 4-yr study, Jaramillo et al. (2021a) demonstrated that the inclusion of forage legumes both in the warm and cool seasons enhanced the delivery of ecosystem services. Forage legumes offset 85% of N fertilizer input and kept the system productive. In the summer, the inclusion of 'Ecoturf' rhizoma perennial peanut (*Arachis glabrata* Benth.) mixed with 'Argentine' bahiagrass (*Paspalum notatum* Flügge) increased cattle average daily gain by 74% compared with cattle grazing bahiagrass in monoculture. Beef water footprint was reduced during the warm season with legume inclusion. These results are highly desirable during the sustainable intensification process. Arboreal legumes are another option, especially in the tropics. Silvopasture systems using signalgrass (*Urochloa decumbens* Stapf.) and gliricidia [*Gliricidia sepium* (Jacq.) Kunth ex Walp] resulted in greater livestock performance compared to signalgrass in monoculture, with potential to reduce carbon footprint of livestock systems (Silva et al., 2021). These are examples on how forage legumes can enhance sustainability of livestock systems keeping them productive.

GHG emissions

Greenhouse gas concentrations in the atmosphere have increased rapidly due to human activities, with negative effects on the climate. Methane and nitrous oxide are powerful GHG, and agricultural activities are responsible for a considerable portion of global emissions, with ruminants playing a major role in the agricultural sector. Ruminants release methane in the atmosphere mainly through eructation because of methanogenic microorganisms in the rumen. Methane is also released from livestock excreta, but in smaller proportion compared to eructation (Rivera and Chará, 2021). Condensed tannins (CT), present in some forage legumes, have the potential to mitigate the emission of GHG (Boddey et al., 2020). Sericea lespedeza [SL; *Lespedeza cuneata* (Dum. Cours.) G. Don.] is a forage legume that grows well in subtropical regions and has condensed tannins. Van Cleef et al. (2021) demonstrated that methane emission per unit of CT intake decreased with increasing levels of SL. Feeding SL to beef steers also mitigated the emission of N_2O and CH_4 from cattle excreta (van Cleef et al., 2022), indicating the potential of using forage legumes containing CT as a strategy to reduce carbon footprint of livestock systems.

Biological N fixation (BNF)

Nitrogen is a key element for plant development. Although the atmosphere has 78% of nitrogen in its composition, the dinitrogen molecule with the covalent triple bond is not readily available for plant uptake. Breaking the triple bound and reducing the N_2 molecule requires energy, that comes from fossil fuels in the case of the industrial N fertilizer, or from the symbiotic relationship between plants and some microorganisms. Forage legumes associate with soil bacteria (e.g., Rhizobium, Bradyrhizobium) and reduces the atmospheric N_2, rendering it available for plant metabolism. The scientific literature has extensive information on BNF from legumes, and the level of N fixed varies with forage species, ecological conditions, management, and proportion of legumes in the pasture botanical composition. There are many examples where forage legumes can replace N fertilizer and keep the system productive (Boddey et al., 2020; Jaramillo et al., 2021a). Major benefits of BNF include the reduction of the use of fossil fuels to manufacture N fertilizer, reducing carbon footprint of livestock systems using legumes.

Nutrient cycling

Nutrient cycling is a process that helps to keep grasslands sustainable for longer periods. Most of the nutrients ingested by cattle returns to the soil via excreta, and ungrazed forages will return as litter (Dubeux et al., 2007). Forage legumes enhance N cycling compared with grass monocultures and N-fertilized grasses. Transfer of N from legumes to grasses might occur via livestock excreta, plant litter, or belowground direct transfer and root/rhizome turnover. Litter and dung decomposition results in a more efficient release of mineral N available for plant uptake compared with N fertilizer. Garcia et al. (2021) compared grazing systems using grass-legume mixture or N fertilizer. They observed that the grass-legume mixtures were more efficient in recycling N than the N-fertilized grass systems, returning 80% of the N input compared with only 40% recycled in the N-fertilized system. Nitrogen losses from fertilizer are typically high, reducing N use efficiency. Forage legumes can also reduce litter C:N ratio, enhancing N cycling via litter. Jaramillo et al. (2021b) observed that the inclusion of forage legumes during cool and warm seasons in grazing systems has the potential to return similar amounts of N through plant litter deposition as grasses receiving moderate levels of N fertilizer. Overall, the inclusion of forage legumes enhances N cycling and reduces the need for N fertilizer, helping to reduce fossil fuel emission during the Anthropocene.

Habitat for pollinators

Pollinators benefit 1/3 of global crop-based food production (Klein et al., 2007), and bees are the primary pollinators of most agricultural crops. Recent evidence indicates a decline in bee population mainly due to land-use change and habitat loss and fragmentation, agriculture intensification, pesticide application, decreased resource diversity, spread of pathogens, and climate change (Potts et al., 2010). Diversity and abundance of floral resources improve habitat for pollinators and integrating forage legumes into grasslands is a practical approach to do it (Sollenberger et al., 2019). Power et al. (2011) indicated that sowing *Trifolium* species increased bee abundance in organic dairy farming operations. Even a modest increase in conventional grassland plant diversity with legumes and forbs could enhance pollinator functional diversity, richness, and abundance. These improvements would also lead to improved pollination services affecting positively surrounding crops and wildflower reproduction (Orford et al., 2016). This evidence indicates the role of forage legumes enhancing pollinator habitat, which is a major aspect of food security during the Anthropocene.

Implications

Exponential increase of human population and related human activities have resulted in global changes that affect food security and the future of humankind. The challenge to produce more food and preserve life on earth has emerged as one of the major research topics. Sustainable intensification of food production requires greater output of products and services per unit of resource input in agroecosystems. Forage legumes have unique characteristics that enable them as a powerful tool to enhance sustainability and productivity of livestock systems. Adoption of forage legumes, however, is still limited in many global production systems. Research and extension aligned with public policies must be put in place to enhance adoption of forage legumes in livestock systems. This will help humankind to cope with the challenges of the Anthropocene.

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