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Integrating Animal Husbandry With Crops and Trees

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Per capita intake of animal protein is expected to increase globally through 2050, and the rate of increase will be more in developing or emerging economies than in developed countries. Global meat consumption between 1980 and 2050 is projected to increase from 133 million to 452 million tons, and 86% (279 million tons) of the increase will occur in developing countries. Animal-based agricultural systems occupy 45% of the global land area and contribute a large proportion of agricultural emissions. In addition to being a major source of nitrous oxide (N_2O), methane (CH_4), and other greenhouse gases (GHGs), livestock also use 8% of the global water withdrawal. The animal sector is dominated by resource-poor and small landholders of developing countries. Adverse effects of livestock on the environment are caused by the way animal husbandry is practiced, in no small part because animals are not integrated with other agricultural and forestry-based practices. Thus, improving and sustaining the livestock sector is critical to advancing the Sustainable Development Goals (SDGs) of the United Nations, especially SDG #1 (No Poverty), SDG #2 (Zero Hunger), SDG #6 (Clean Water and Sanitation), and SDG #13 (Climate Action). Separating raising of livestock from cultivating seasonal crops and perennial trees has decoupled the biogeochemical/biogeophysical cycling of carbon (C), water (H_2O), nitrogen (N), phosphorus (P), and sulfur (S). This decoupling is a causative factor of the increase in emissions of N_2O and CH_4, eutrophication and contamination of water resources, degradation of rangelands, and decline in its biodiversity. Therefore, identifying and adopting systems that integrate livestock with crops and trees are critical for reducing the environmental footprint of animal-based dietary products. Incorporating pastures/forages in the rotation cycle along with controlled grazing, called ley farming, and agroforestry, such as alley cropping, are examples of integrated farming systems. Other strategies of reducing the environmental footprint comprise the following: reducing enteric fermentation by precision feeding and matching dietary protein to animal need, processing CH_4 and N_2O emissions for other uses, and managing manure and other animal waste prudently. Other important considerations are adopting multiple GHG perspectives and minimizing gas swapping, reducing wastage of animal products, decreasing the use of antibiotics, and restoring rangeland for sequestration of atmospheric CO_2 as soil organic matter.

Keywords: gaseous emissions, food security, ecological footprint, sustainable development goals, waste management, farming systems

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INTRODUCTION

The domestication of animals, which started as early as the 12th millennium circa BP (Zeder, 2008), began with dogs and was followed by that of ruminants (i.e., goats, sheep, cattle). Chickens were domesticated about 10,000 years ago, followed by oxen and horses as beasts of burden for plowing and transportation (Rutledge and McDaniel, 2011). Over millennia, the cultivation of crops was closely integrated with that of raising livestock. Since the mid-twentieth century, however, the separation of raising livestock from the growing of crops has caused environmental issues such as the degradation of soil health, eutrophication of water, emission of greenhouse gases (GHGs) into the atmosphere, and loss of biodiversity (Peyraud et al., 2014).

Raising livestock separately may not be a sustainable option (Broom et al., 2013) economically, pedologically or ecologically. In view of the numerous demands of the growing and increasingly affluent human population, achieving food and nutritional security is seemingly at odds with the necessity of reducing the negative environmental footprint of agriculture. An important cause of this dilemma may be the simplification of agro-ecosystems, and the attendant decline in diversity of farming systems at the soil scape, landscape, and the farm scale (Lemaire et al., 2014). The adverse effects of livestock on the environment are attributed to the way in which the animals are raised, and such issues can be addressed (Dalibard, 1995). In some climates and landscapes, separating livestock from crops and trees is an important cause of the decline in diversity at the farm scale, with the attendant adverse impacts on the environment. Such a simplification and loss of biodiversity also leads to decoupling of the cycling of carbon (C) from those of water (H_2O), nitrogen (N), phosphorus (P), and sulfur (S) (Lal, 2010). Cycles of N and C, closely connected to livestock's role in land use and land use change (Steinfeld et al., 2006), may be decoupled by this simplification of the farming system. Emission of GHGs (i.e., CH_4) is exacerbated when ruminants are concentrated, which tends to uncouple the C and N cycle by releasing the digestible C as CO_2 and CH_4 and digestible N in waste as N_2O (Soussana and Lemaire, 2014). The risks of uncoupling, which has severe implications to climate change because CH_4 and N_2O have a high global warming potential (GWP), can be minimized by integrating livestock with crops and trees. Practices such as establishing vegetation buffers on agricultural fields to enhance biodiversity and conserve soil and water (i.e., agroforestry or alley cropping), can also reduce the environmental footprint of livestock raised on the same land unit (Goldstein et al., 2012).

The objectives of this article are to discuss: (1) the potential and challenges of increasing food and nutrition for the growing human population by raising livestock, (2) the livestock sector and the Sustainable Development Goals (SDGs) of the United Nations, (3) the conceptual basis of integrating livestock with crops and trees to increase the biodiversity of farming systems, (4) the options for sustainable management of grasslands for food and climate security, (5) the potential of integration of livestock with crops and trees to sequester carbon and reduce gaseous emissions, and (6) improved management of livestock in the tropics.

THE POTENTIAL AND CHALLENGES OF INCREASING FOOD AND NUTRITION FOR THE GROWING HUMAN POPULATION BY RAISING LIVESTOCK

Fears of widespread famine were aggravated by the rapid population growth during the 1950s and 1960s (Ehrlich, 1968). The human population of 2.56 billion (B) in 1950 increased to 3.04 B in 1960, 3.71 B in 1970, and 4.34 B in 1980 at the 10-year growth rate of 18.9, 22.0, and 20.2%, respectively. The fears of widespread famine were averted by the spectacular increase in yields of cereal crops, achieved through the Green Revolution during the 1960s (Pingali, 2012). However, the world population has increased to 7.8 B in 2020 and is projected to be 9.8 B by 2050 and 11.2 B by 2100 (UN, 2019b). Whereas 820 million people are prone to undernourishment (FAO, 2017), about 2 B are suffering from malnourishment because of deficiencies in protein, micronutrients, and vitamins (Ritchie and Roser, 2019). However, the livestock sector can play an important role in eliminating hunger and malnourishment.

Since the 1960s, large parts of natural lands have been converted into agro-ecosystems to feed the growing world population. In addition to reducing biodiversity, conversion of natural ecosystems at a larger scale has also depleted and contaminated water resources, polluted air, and exacerbated the emission of GHGs into the atmosphere. There has also been a growing interest in increasing animal products to address malnourishment. The global population of livestock (i.e., cattle, sheep, goats, pigs, poultry) has increased drastically since the 1950s. This increase in both populations (i.e., human and animals) has also led to a growing concern whether the biosphere has the capacity to support such large populations of domesticated livestock and people.

The human population has increased from about 10–20 million at the dawn of settled agriculture to about 7.8 B (∼10,000 times) in 2020 (UN, 2019a), and there is an equally alarming growth of the population of domesticated livestock. While the cattle population has declined from a of high of 1.4 B in 2011, it still remains at ∼1 B in 2019 (The Economist, 2011; Shahbandeh, 2019). The global average stock of chicken is estimated at 19 B, and that of sheep and pigs at about 1 B. Global demand for animal-based produce is projected to double by 2050 (Herrero et al., 2009) because of the increasing affluence and the change in dietary preferences (Rojas-Downing et al., 2017). The global population of bovines is projected to increase from 1.9 B in 2010 to 2.4 B in 2030, 2.6 B in 2040, and 2.64 B in 2050 (Rosegrant et al., 2009; Thornton, 2010). The human population is increasing at an average global annual rate of 1.2%, but the population of domesticated livestock is increasing at an annual rate of 2.4%. The geographical distributions of livestock population also vary widely depending on biophysical, socio-economic, and cultural factors (Gilbert et al., 2018).

Along with the livestock population, the amount of livestock produce is also growing rapidly. Between 2000 and 2050, global production is projected to increase from 229 to 465 million tons of meat and 580 to 1043 million tons of milk (FAO, 2006; Steinfeld et al., 2006). More than 60 B land animals are used worldwide for meat, egg, and dairy production, and the global population of livestock may exceed 100 B by 2050 (Yitbarek, 2019), when the world's meat production is projected to double (FAO, 2019). All trends from 1980 to 2002 indicate that meat consumption increased from 47 million to 132 million tons in developing countries (NAS, 2015). All trends from 1980 to 2050 indicate that meat consumption is projected to increase from 86 million to 120 million tons in developed countries and 47 million to 326 million tons in developing countries (NAS, 2015). By 2050, the increase in meat production may be 290% for pig meat, 200% for sheep and goats, 180% for beef and buffalo meat, 180% for milk, 700% for poultry meat, and 90% for egg (Yitbarek, 2019). Similar to meat products, production of milk is also increasing globally. With a current average milk consumption of 100 kg per person per year (Reay and Reay, 2019), the projected increase in population will increase milk production as well. Each liter of fresh milk is equivalent to 3 kg of GHG emissions (Reay and Reay, 2019).

The strong nexus between livestock and anthropogenic climate change can neither be denied nor ignored. Indeed, livestock impact climate change, and the rapidly changing climate is also impacting livestock. It is precisely in this context that integrating livestock with crops and trees can play an important role in re-greening of the planet (Janzen, 2011). Harnessing the positive effects of livestock-based farming systems (e.g., nutritious food, eliminating hunger and hidden hunger) can lead to sustainable management of crops and trees and reduce the environmental footprint of farming (Herrero et al., 2009). In addition, sustainable management of rangelands by adopting ecologically based principles of animal husbandry can strengthen the provisioning of ecosystem services (ESs) from these fragile and ecologically-sensitive but economically important ecoregions (Havstad et al., 2007).

LIVESTOCK SECTOR AND SUSTAINABLE DEVELOPMENT GOALS OF THE UNITED NATIONS

The highly dynamic livestock sector is rapidly changing in response to the ever-increasing demands of the growing population, especially in developing countries. Thus, judicious management and eco-intensification of livestock-based systems can also address the daunting challenge of advancing the SDGs of the United Nations (**Figure 1**) because site-specific integration of crops with livestock is critical to advancing several SDGs. Specifically, prudent management of livestock can advance SDG #1 (No Poverty) by improving income of small landholders as well as that of commercial farmers. For small landholders in developing countries, livestock are not only a source of nourishment, they are also a source of renewable energy through draft animals, use of dung as household fuel, and also a source of manure as an amendment for crops. In addition to addressing the vulnerability of 820 million under-nourished people, most of them concentrated in South Asia and Sub-Saharan Africa (FAO, 2017), judicious production and use of animal-based diet can also alleviate malnutrition (hidden hunger) affecting 2 B people globally. Thus, livestock are critical to advancing SDG #2 (Zero Hunger).

The livestock industry, which consumes 8% of the global water supply (Schlink et al., 2010), has a strong impact on SDG #6 (Clean Water and Sanitation). Livestock production involves the use of both blue and green water (Falkenmark, 2003). Nearly one-third of the total water footprint of agriculture in the world is related to animal products (Mekonnen and Hoekstra, 2012), and beef has a larger water footprint than poultry and pork (Gerbens-Leenes et al., 2013). Therefore, reducing the water footprint of livestock, an important consideration of eco-intensification of livestock-based systems (Doreau et al., 2012), can advance SDG #6. Judicious management of livestock and rangelands is critical to improving the quality and renewability of water through buildup of soil organic matter content that can enhance soil water storage and denature and filter pollutants.

In addition to water, reducing emissions of GHGs from the livestock sector is pertinent to advancing SDG #13 (Climate Action). Because of its importance, the interaction between climate change and the livestock sector is now widely recognized (Thornton et al., 2009). Livestock are responsible for a large part of agricultural emissions (Gill et al., 2010; Havlík et al., 2014). Agriculture contributes about 10–12% of the current anthropogenic emissions. Some estimate that direct livestock non-carbon dioxide emissions caused about 19% of the total modeled warming of 0.81^{O}C from all anthropogenic emissions in 2010 (Reisinger and Clark, 2018). GHG emission per unit of livestock product is more in ruminants than that in monogastric animals (Gill et al., 2010). Because of the high global warming potential (GWP) of CH_4 and N_2O, it is appropriate to combine the cumulative effect of all GHGs into CO_2-equivalent (Pitesky et al., 2009).

CONCEPTUAL BASIS OF INTEGRATING LIVESTOCK WITH CROPS AND TREES

Livestock use 30% of the Earth's entire land surface as permanent pastures; 33% of arable land is used to produce feed for the livestock (FAO, 2006), and thus livestock have a large environmental footprint (Smith et al., 2013). Pelletier and Tyedmers (2010) projected that the livestock sector will even more strongly impact the environment by 2050 with regards to three issues: (i) climate change, (ii) reactive nitrogen mobilization, and (iii) appropriation of plant biomass at a global scale. Pelletier and Tyedmers also predicted that the livestock sector alone may overshoot humanity's "safe operating space" by 2050 in each of these three domains. While (FAO, 2006) estimates in the report "Livestock's Long Shadow" have been strongly debated (Maday, 2019), emissions of GHGs from the livestock sector, especially that of CH_4 and N_2O, can be reduced and managed by adapting the integrated systems presented herein.

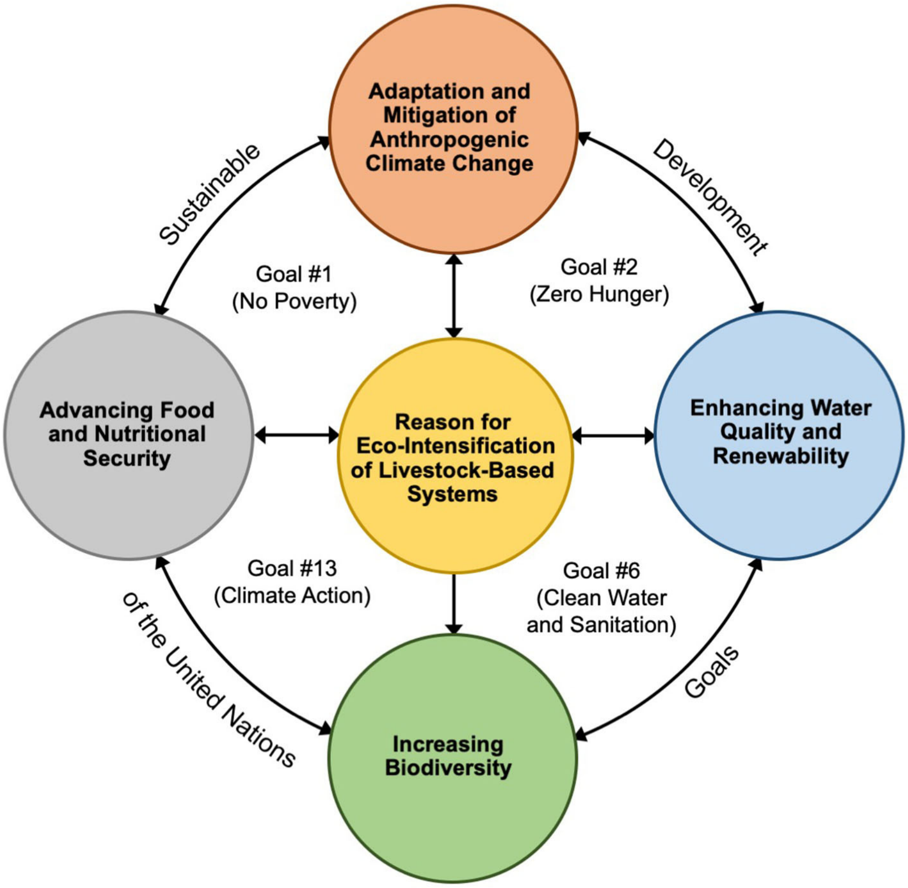

FIGURE 1 | Eco-intensification of livestock-based systems to advance the Sustainable Development Goals of the United Nations.

It is also pertinent to carefully choose site-specific sustainable livestock production to reduce or mitigate emissions, and to develop policies that promote climate change adaptation and mitigation options (Rojas-Downing et al., 2017). Some concerns about the impacts of animal-based diet (Pitesky et al., 2009; Gerber et al., 2013b; Eshel et al., 2014; Hedenus et al., 2014) can be addressed through a judicious integration of crops with livestock. The latter can lead to an increase in the quantity and quality of food production and economic returns while also reducing pressure on land and water resources (Franzluebbers, 2007; Provenza et al., 2019).

Most emissions from the livestock sector occur in commodity (meat, milk) production or the supply-side. However, gaseous emissions are also affected by the demand-side, or the consumer population, which is not only growing in numbers but is also undergoing a nutrition transition in favor of the animal-based diet. Therefore, several studies have suggested that merely addressing the supply-side emissions from the livestock sector may be insufficient to limit the temperature rise to $<2^\circ$C, and addressing the demand-side is also necessary (Kiff et al., 2016; Scherer and Verburg, 2017). Indeed, demand-side mitigation measures—including preferences for a plant-based diet, along with eating more poultry and fish than red meat, or grass-fed rather than grain-fed meat – have a greater potential to reduce emissions (1.5–15.6 Gt CO_2-eq /yr) (1 Gt = gigaton = billion ton) than do supply-side measures (1.5–4.3 Gt CO_2-eq/yr) (Smith et al., 2013). An integrated and judicious management of crops and livestock may mitigate some of the negative environmental impacts on the supply-side when crops are grown separately from that of raising the livestock (Herrero and Thornton, 2013).

Ruminant production systems are under pressure for several reasons: (i) methane emission, (ii) inefficient use of land, (iii) feed-food competition, and (iv) weakening of key ecosystems services through large-scale conversion of grasslands to crop production for livestock. However, livestock can produce human food of high nutritional quality from marginal lands that are mostly unsuitable for crop production. Thus, a viable strategy may involve the following: (i) raising animals from feed that is non-edible for humans, (ii) grazing livestock on land not suitable for crop production, and (iii) reducing emissions of GHGs (CH_4, N_2O). Some site-specific grassland-based ruminant production systems are much more efficient than concentrate-based systems for producing protein (Peyraud and Peeters, 2016). The challenge

TABLE 1 | Examples of integrated livestock systems with crops and trees (Compiled from Kang et al., 1990; Leakey, 1996; McCown, 1996; Bajracharya et al., 1998; Garrett et al., 2004; Fike et al., 2016; Jose and Dollinger, 2019; Munsell and Chamberlain, 2019; USDA-NRCS, 2020).

Integrated system	Description
Sod-based	2–10 years of sod rotated with 1–8 years of cropping, or sod-inter-cropping
Cover crops as forage	Cover crop grazing by livestock to accomplish both production and soil conservation objectives
Ley farming	The growing of grass or legumes in rotation with grain crops as a soil conservation measure and to enhance soil fertility
Pasture cropping	Land management system that integrates cropping with pasture production and allows grain cultivation as a part of perennial agriculture
Dual purpose cereal crops	Growing of cereals (i.e., wheat, rye) as pastures from late autumn to early spring and then harvesting for grains
Agroforestry	Intentional integration of trees, forages, crops, and livestock with specifically designed spatial arrangements
Alley cropping	Planting rows of trees at wide spacings and on contour with grain crops grown in the alleyways between the rows. Trees are specifically chosen for fodder, biological nitrogen fixation, fuel wood, or fiber.

lies in developing sustainable systems of forage production that also lead to positive responses to societal demands for consuming more natural products (Peyraud and Peeters, 2016).

Site-specific options for integrated crop-livestock systems can also achieve synergies between agricultural production and environmental quality (Lemaire et al., 2014). **Table 1** outlines examples of sustainable intensification of livestock-based systems, involving judicious combinations of sod/forages with crops and trees, which address some concerns of ruminant production systems. The term "sod" refers to the soil surface when covered with grass, sward, or turf. By using grassland-based ruminant-livestock systems (GRLS) models of African Guinea Savanna, Bateki et al. (2019) observed that sustainable intensification of livestock, integrated with crops and trees, could increase food security of the growing African population.

Agroforestry is a set of technologies in which trees are sequentially or simultaneously integrated with crops and/or livestock in a wide range of integrated systems (Leakey, 1996). Alley cropping is a system of planting trees on the contour at a wide spacing (4–10 m apart) with a food crop grown in the alley ways between the rows of trees. Planting several rows of trees and shrubs, which can also be used as forage, is a system that integrates livestock with both crops and trees. Trees can also be harvested as a source of fuel wood. Such a complex system is an example of an agro-silvopastorial system (Okali and Sumberg, 1985; Kang et al., 1990). In temperate alley cropping systems, tree species may include hard wood veneer or lumber species; softwood species for fiber production, or fruits and nuts for food (USDA, 2020). Trees grown on the contour can also be used as filter strip and for contour farming in strip cropping (USDA-NRCS, 2020). Grain crops (i.e., corn, soybean, cowpeas) are grown when the trees are young. When the ground is shaded, forages can be harvested and cattle grazed, and the prunings can also be used as green manure for cereals (i.e., corn). Leguminous trees serve as a source of nitrogen to enhance soil fertility.

Models are needed for simultaneous quantification of C and N flows and how they are affected by different livestock-crop-tree management systems. Several whole-farm based models have tried to estimate gaseous emissions (Snow et al., 2014; Bateki et al., 2019), but there is a need for more data on nutrient and C flows at the field level (Snow et al., 2014).

OPTIONS FOR SUSTAINABLE MANAGEMENT OF GRASSLANDS FOR FOOD AND CLIMATE SECURITY

Site-specific options are needed for sustainable intensification of livestock systems in diverse socio-economic and biophysical regions prone to climate change. For example, livestock-based systems occupy 45% of the global land area; grasslands/savannas suitable for grazing cover 37% of Earth's surface area (NAS, 2015). These ecosystems are highly diverse and occur within the seasonally dry tropical to sub-tropical equatorial regions (Whitley et al., 2017). Savanna ecoregions, open-canopy and fire-dependent biomes, are also prone to climate change that may alter phenology, root-water access and fire dynamics (Whitley et al., 2017). Principal environmental drivers affecting biomass/feedstock productivity in savanna regions are water and nutrient availability, vapor pressure deficit, solar radiation and fire (Devi Kanniah et al., 2010). Therefore, understanding these controls and their management through eco- intensification is critical for enhancing net primary productivity (NPP) under the changing global environment (Kanniah et al., 2013). Important controls include restoring soil functions, conserving water to minimize the risks of drought, and adopting improved species of forages and meat of better nutritional quality (Herrero and Thornton, 2013; Provenza et al., 2019).

Climate change is already adversely impacting agro-pastoral production in Africa (Stige et al., 2006; O'Mara, 2012). Under these conditions, Teague et al. (2011) observed that multi-paddock (MP) grazing may be an option for sustainable intensification. Teague and colleagues reported that MP grazing at a high stocking rate increased SOC content and cation exchange capacity of soil compared with light continuous and heavy continuous grazing. Similarly, Kleppel (2019) reported that microbial biomass in MP grazed soils was higher, more diverse, and contained relatively more fungal than bacterial biomass than did conventional management and hay field. A 2-year study in South Africa by Chaplot et al. (2016) showed that topsoil SOC stocks were significantly increased in soil with either livestock exclosure and NPK fertilization or high density and short duration grazing compared with annual burning, livestock exclosure and livestock exclosure with topsoil tillage. This was accomplished by high intensity, short duration grazing

TABLE 2 | Global land area under grasslands and the estimates of C sequestration (Adapted from Grace et al., 2006; Lal, 2008).

Ecosystem	Area (10^6 km^2)	Estimated carbon sink (Gt C/y)	Average carbon sink (ton C/ha·y)
Tropical savannas and grasslands	27.6	0.39	0.14
Temperate grasslands	15.0	0.21	0.14
Tropical forests	10.4	0.35	0.34
Boreal forests	13.7	0.47	0.34
Mediterranean shrublands	2.8	0.11	0.38
Crops	13.5	0.20	0.07
Deserts	27.7	0.20	0.07
Total	149.1	2.55	—

Gt = gigaton = billion ton.

(HDSD, 1200 cows per ha for only 3 days per year) followed by complete exclosure for the remainng 362 days each year (Chaplot et al., 2016). On the basis of a global assessment of holistic planned grazing, however, Hawkins (2017) concluded that only rangelands with higher precipitation have the resources to support MP grazing at a high stocking rate.

THE POTENTIAL FOR INTEGRATING LIVESTOCK WITH CROPS AND TREES TO SEQUESTER CARBON AND REDUCE GASEOUS EMISSIONS

Restoration and sustainable management of grasslands can play an important role in adaptation and mitigation of climate change (Lal, 2008). Technical potential of C sequestration in global savannas, through land restoration and integrated management of livestock with crops and trees, can be as much as 2.55 Gt C/y (**Table 2**). Pertinent animal feeding strategies (e.g, use of flax seeds, protein-intensive forages) can reduce enteric CH_4 and NH_3 emissions (Yáñez-Ruiz et al., 2018). Above all, carbon sequestration in grass—by planting species with high biomass production and biological nitrogen fixation, such as trees like *Acacia albida* and *Leucaena leucocephala* in west Africa (Kang et al., 1990; Pieri and Gething, 1992; Soussana et al., 2010)—is an important option to reduce net emissions from the livestock sector. In addition, recycling of livestock manure in a whole-farm perspective (Petersen et al., 2007) can reduce the input of fertilizers in croplands.

Adaptation and mitigation of climate change in the livestock sector requires translating of science into action by policy interventions that remove barriers to implementing proven technologies (Smith et al., 2007). Appropriate policy interventions are especially important in developing countries for achieving sustainable management of rangeland because of ecologically fragile and climatologically harsh environments. In India, for example, total annual CH_4 emissions, estimated at 9–10 Tg (Tg = teragram = 1 million ton) from enteric fermentation and animal waste (Sirohi and Michaelowa, 2007), can be reduced by appropriate policy interventions such as payments for provisioning of ecosystem services.

The goal of enhancing and sustaining agricultural production for meeting the needs of the growing population while reducing the environmental footprint of agriculture necessitates local and site-specific integration of cropping with livestock systems. Soil C sequestration and decrease in gaseous emissions are in accord with SDG #13 of the U.N. Therefore, site-specific technologies for integrating livestock with crops and trees (**Table 1**) are needed to: (i) better moderate coupled biogeochemical cycles and reduce fluxes of pollutants into the atmosphere and the hydrosphere, (ii) create a more diversified and structured landscape mosaic that supports diverse habitats, and (iii) enhance capacity of the system to adapt to extreme events associated with climate change and alterations in the socio-economic and human dimensions (Lemaire et al., 2014). It is precisely in this context that management of grasslands can strengthen the coupled cycling of carbon (C) with those of H_2O, N, P, and S within vegetation, soil organic matter (SOM) stock and soil biota in general, but the soil microbial biomass in particular (Lemaire et al., 2014).

The schematic in **Figure 2** depicts the pathways of decreasing the environmental footprint of livestock products. Conceptually, choosing a livestock product with a lower emission footprint for a diet would reduce the overall negative impact on climate and the environment. The environmental footprint of a dietary product can be expressed in three ways (de Vries and de Boer, 2010): (i) per kg of product, (ii) per kg of protein, and (iii) per kg of average daily intake of each livestock product. Based on the lifecycle analysis (LCA) of 16 studies conducted in OECD (Organization for Economic Cooperation and Development) countries, de Vries and de Boer (2010) determined that the land and energy use and the GWP for 1 kg of product followed the order of beef > pork > poultry. This order was based on differences in feed efficiency, enteric CH_4 emission, and reproduction rates. Similar trends were reported by (Eshel et al., 2014).

Emissions of all gases (CO_2, CH_4, N_2O) are used to compute CO_2 equivalents (Lal, 2004). Direct emissions of CH_4 and N_2O in the livestock sector must be reduced. In this context, a multiple GHG perspective must be adopted (**Figure 3**) because CH_4 has a GWP of 21 and N_2O of 310. Because of the high GWP of CH_4 in both confined and grazing systems, steps must be taken to develop credible methods of measuring CH_4 emission by ruminants (Hill et al., 2016), and to reduce enteric fermentation by ruminants (Grossi et al., 2018). Precision feeding, matching feed intake with the need of the animal (Gerber et al., 2013a), and the choice of forages can also reduce the gaseous footprint. For example, the combination of highly digestible forages (Haque, 2018; van Gastelen et al., 2019) that contain secondary compounds such as tannins (Roca-Fernández et al., 2020) can also reuce methane emissions. The multiple GHG perspective is an important strategy that can address the potential pollution swapping—a reduction in one gas can lead to emission of another (Gerber et al., 2013a). Thus, a full accounting of all GHGs is required (Soussana et al., 2007).

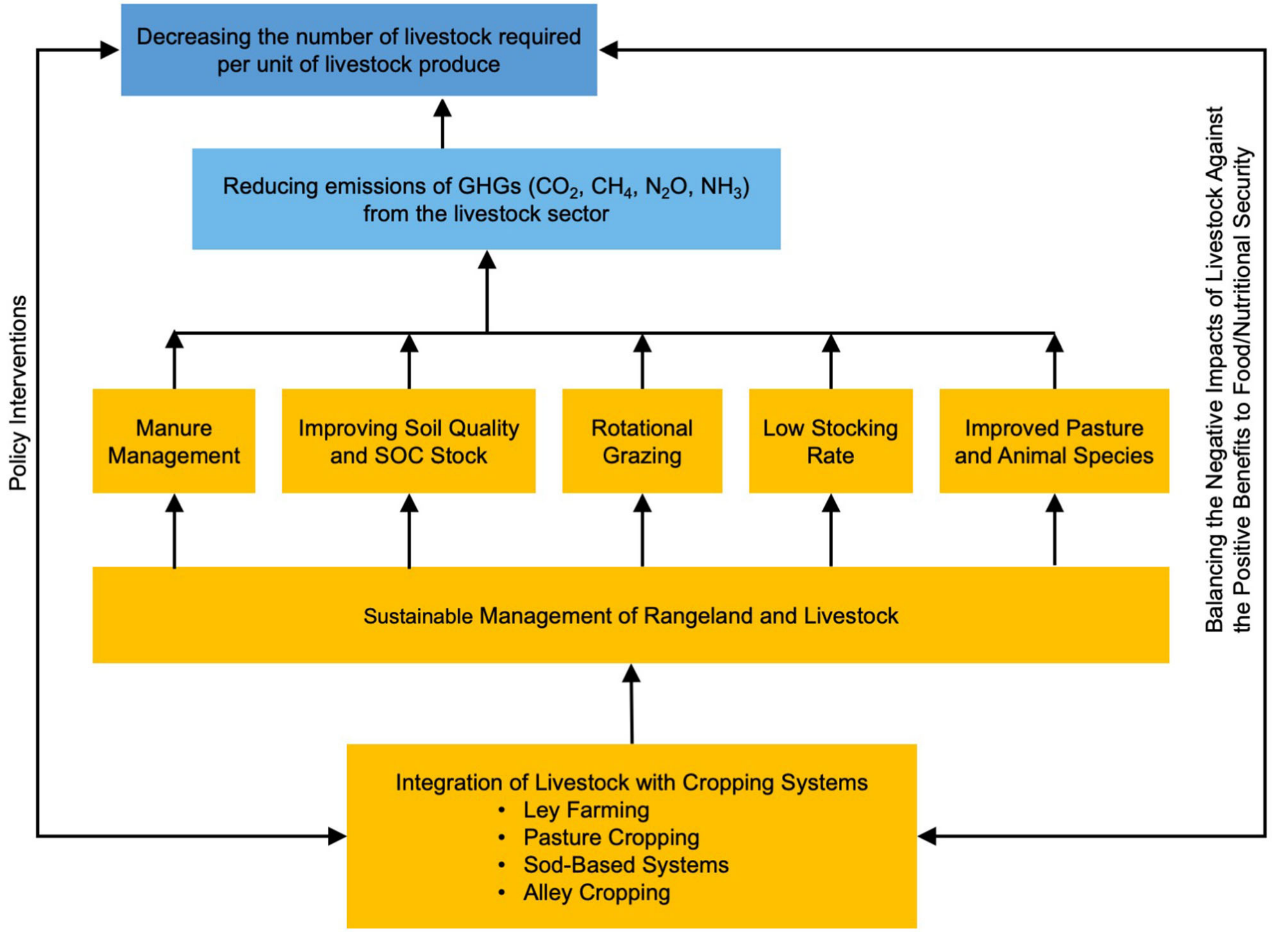

FIGURE 2 | A flow chart depicting the integration of livestock with arable land use for decreasing the number of livestock required (SOC, soil organic carbon; GHGs, greenhouse gases).

IMPROVED MANAGEMENT OF LIVESTOCK IN THE TROPICS

Livestock are an important component of agroecosystems in the tropics and adopting innovative livestock/farming approaches can enhance production and reduce environmental footprints. Judiciously combining crops with livestock within the same landscape has numerous co-benefits (Gil et al., 2015). For example, ley farming (Carberry et al., 1996; McCown, 1996), involving light grazing of legumes grown in rotation with crops, is a pertinent strategy for integrating crops and livestock. Built on the concept of ley farming, pasture cropping is a farmer-initiated concept of sowing a winter-active cereal into a summer-active native perennial pasture (Millar and Badgery, 2009). Self-regenerating annual legume pastures (Puckridge and French, 1983) can enhance soil fertility and increase cereal yield, along with more forage for sheep and cattle production. Ley farming, developed in Southern Australia since the 1930s, is also relevant to similar regions in Sub-Saharan Africa, South/Central Asia, and the Caribbean. However, soil/site specific choices of legumes and grazing patterns/intensity must be identified.

The numerous benefits of ley farming include (Bell et al., 2010): (i) enhancing soil N for the next crop, (ii) sequestering SOC and off-setting emissions, (iii) controlling weeds and other pests, (iv) minimizing risks of runoff, soil erosion, and deep drainage, (v) increasing livestock production, and (vi) sustaining crop yield. However, several challenges exist. Successfully implementing ley farming includes a critical appraisal of the following (Bell et al., 2010): (i) addressing difficulties with pasture establishment, (ii) suppressing/removing pasture plants before seeding crops, and (iii) reducing competition for water and some plant nutrients. Site-specific choice of pasture species is critical.

Integrating livestock with cropland and forestland can also be a prudent complimentary strategy. For example, growing Acacia albida (*Faidherbia albida*) as a permanent tree crop on farmlands (cereals, vegetables, and livestock) is a traditional agroforestry system in Sub-Saharan Africa (Poschen, 1986; Weil and Mughogho, 1993; Wanyancha et al., 1994). *Faidherbia* sp. has been widely used for enhancing soil fertility and as a source of

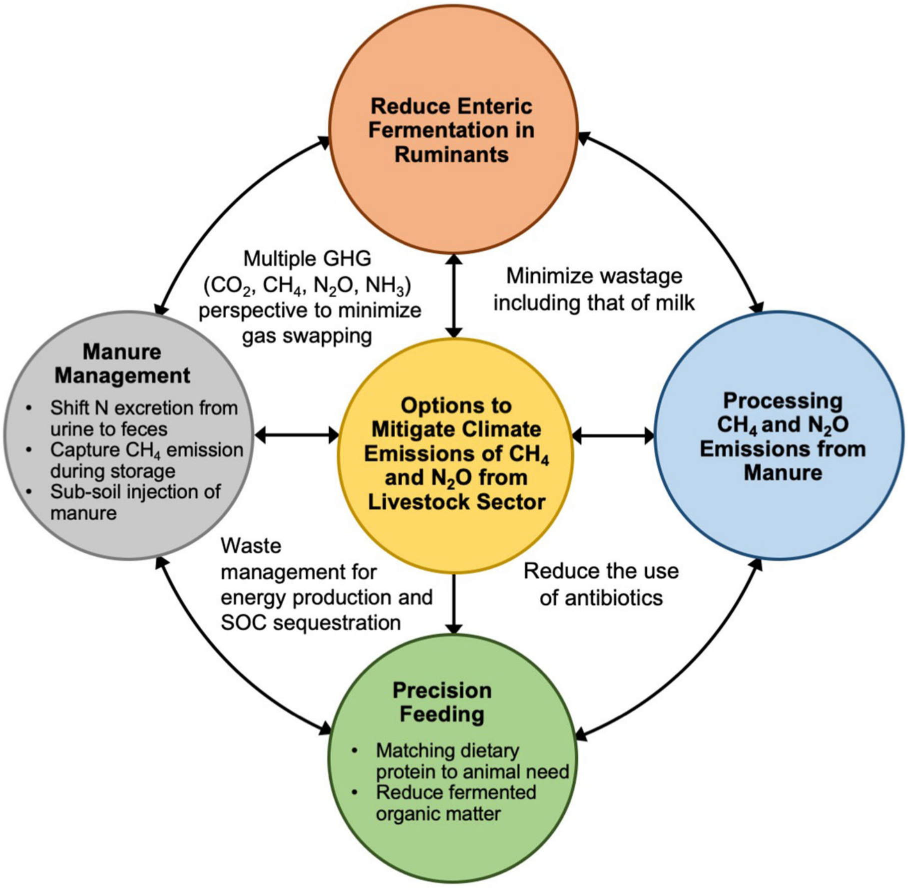

FIGURE 3 | Measures to reduce emissions of greenhouse gases (GHGs) from the livestock sector (SOC, soil organic carbon).

shade and shelter for livestock in Sub-Saharan Africa (Pieri and Gething, 1992).

Widespread adoption of integrated systems can reduce the risks of rangeland degradation, as seen in China (Hou et al., 2008). India provides an example of how integrated systems can reduce land area under pasture. With 2.3% of the global land area, India supports 18% of the human and 11% of the world's livestock population: the latter consists of 536 million animals and 740 million poultry in 2019, which are raised on only 12.3 M ha of land under permanent pastures and grazing land (TAAS, 2019).

Successfully integrating crops with livestock has numerous economic, ecological, and other benefits (**Figure 4**), especially in developing countries of the tropics (Herrero et al., 2013). Important among these are: (i) creating another income stream for farmers and alleviating rural poverty (De Haan et al., 2001), (ii) developing a safety net for the poor and especially women farmers, (iii) enhancing assets for farmers, and (iv) alleviating malnourishment (**Figure 4**). However, livestock need additional land, water, nutrients, and forage resources. Therefore, judicious management of the growth of this sector is critical, especially for reducing environmental footprints. These technical dimensions must be objectively considered within the context of institutional support (market) and the human dimensions (Tarawali et al., 2011).

CONCLUSIONS

Intensive farming, which is designed to produce large amounts of economic food to meet the demands of the growing and increasingly affluent human population by using high inputs on small areas, has its merits and demerits. Intensification of crops and livestock systems have drastically increased per capita food production since the 1960s. However, the environmental footprint of livestock sector must be reduced by decreasing soil degradation, increasing water and nutrient use efficiency, reducing eutrophication of water, decreasing pollution of air, and minimizing the risks to global warming. Despite the successes in food production, there are 820 M people vulnerable to undernourishment and more than 2 B to malnourishment caused by the deficiency of protein, micro-nutrients and vitamins. The proportion of vulnerable population may increase as a result of the COVID-19 pandemic. Thus, the objective of sustainable agriculture is

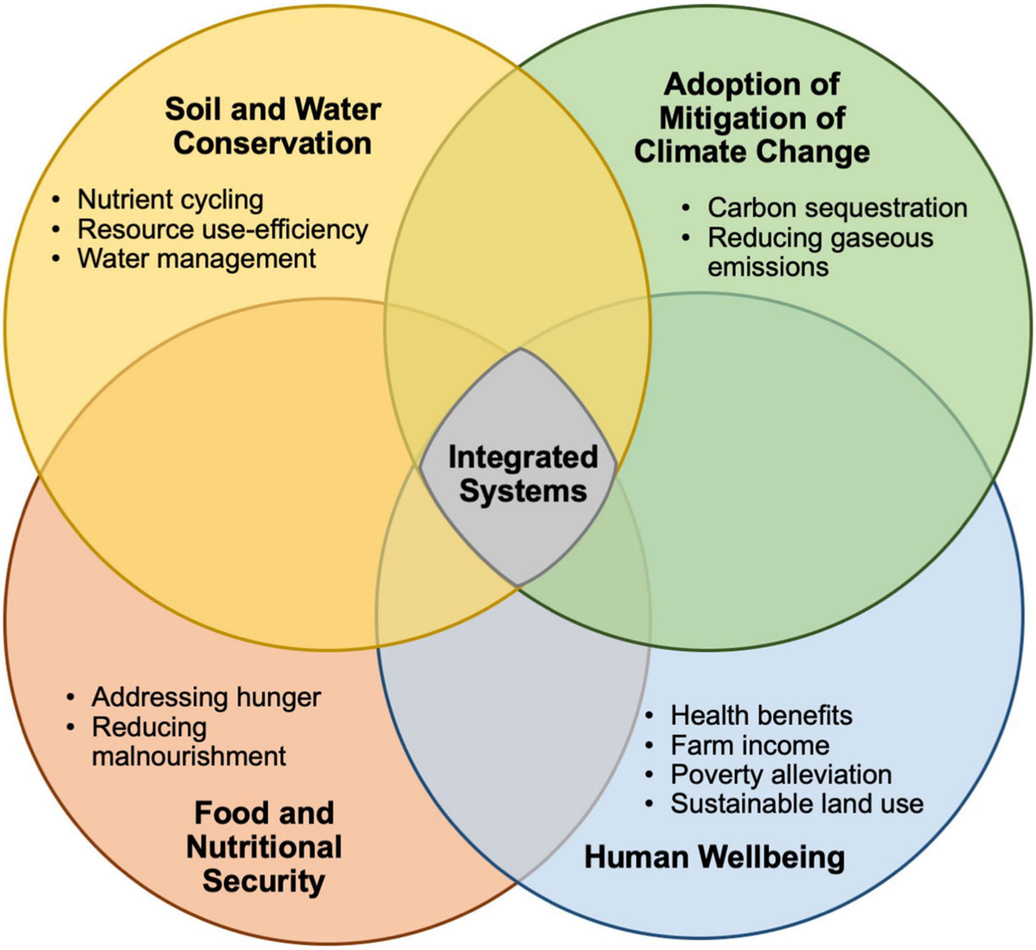

FIGURE 4 | Ecological and socio-economic benefits of integrating livestock with crops and trees.

to adopt technologies that increase production, reduce the environmental footprint of food production systems (IPBES, 2019; IPCC, 2019; UNEP, 2019), and also minimize any risks of diseases and infections through intensive livestock farming (Sigsgaard and Balmes, 2017; Smit and Heederik, 2017).

A feasible option to produce the required amount of nutritious food while restoring and sustaining the environment is through site-specific integration of livestock with crops and trees. Such an approach of eco-intensification would simultaneously achieve several overlapping and interconnected SDGs including #2 (Zero Hunger), #3 (Good Health and Wellbeing), #6 (Clean Water and Sanitation), #13 (Climate Action) and #15 (Life on Land). Ignoring such an option would aggravate risks of environmental pollution, exacerbate perpetuation of natural ecosystems, increase harmful interactions between humans and the wildlife, and even aggravate the frequency and intensity of tragedies such as the COVID-19 pandemic (Lal, 2020b). Some recommendations of the Conference of Parties (COP) of the United Nations Framework Convention to Combat Climate Change (UNFCCC) are also in accord with the strategies of integrating livestock with crops and trees. Examples of these are the "4 Per 1,000" initiative launched at COP21 in Paris in 2015 and "Adapting African Agriculture"of COP 22 in Marrakech (Lal, 2019, 2020a). The scientific community and land managers should seize the opportunity to adopt innovative options such as those outlined in this article and promote sustainable agricultural practices which reconcile the need for producing more and nutritious food with the absolute necessity of improving the environment. Integrating livestock with crops and trees can reduce direct non-CO_2 emissions and achieve the COP21 mitigation goal of limiting global warming to 2°C.

These efforts can be enhanced through research priorities identified by The Committee on Consideration for the Future of Animal Science Research (NAS, 2015). They include: (1) identifying appropriate mixes of intensification and extensification required to simultaneously increase production and reduce environmental footprints in different regions throughout the world, (2) enhancing sustainability of medium- and smaller-scale producers, (3) developing policy interventions to optimize demand for animal products, and (4) evaluating environmental impacts of diverse livestock-based production systems.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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