7 Improving the Nitrogen Cycling in Livestock Systems Through Silvopastoral Systems

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Abstract

Conventional livestock are monoculture systems where the major species are native grasses or African grasses, with biomass production being limited by seasonality of rainfall and low soil fertility. In animal production systems, the pasture degradation is associated with the nitrogen (N) cycle. Therefore, if farmer applied no subsequent fertilizer, milk production or live weight gains have been gradually reduced. As animals slowly gain weight, they produce more methane (CH_4) and nitrous oxide (N_20). This has led to the search for strategies to help minimize the impacts of livestock, and the excessive application of fertilizers, on the environment and natural resources. One strategy with promising results that has been developed in Latin America is the conversion of traditional livestock systems to silvopastoral systems (SPS), which include the establishment of shrub legumes at high densities and forage grasses aimed at increasing livestock profitability. With the association of legumes and forage grasses, forage quality can increase, more than 100%, compared to monoculture-based pastures and, consequently, production costs related to the purchase of imported cereal grains and nitrogen fertilizers are reduced. On the other hand, changes in climate and graz-

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ing pressure to increase stocking rate have resulted in extensive degradation of existing vulnerable pastures, which favour poorly palatable, perennial species, affecting directly livestock production and enhancing greenhouse gas (GHG) emissions and the loss of soil carbon and nitrogen stock severely affecting soil fertility. The importance of the association of species of legumes with grasses and *Leucaena* (*Leucaena leucocephala* L., (Lam.) de Wit) is an environmentally friendly proposal of positive interactions to improve soil fertility and animal productivity. Overall, improving forage quality and N efficiency of dietary nutrients is an effective way of decreasing GHG. Silvopastoral systems (SPS) are used successfully in many regions around the world, and there is considerable evidence that SPS can increase production efficiency, increase carbon sequestration and improve N cycling on land used for livestock production.

Keywords
Animal urine · Grass N uptake · Greenhouse gasses · Silvopastoral systems

Abbreviations

BNF	Biological nitrogen fixation
CH_4	Methane
CO_2	Carbon dioxide
CP	Crude protein
DE	Digestible energy
GHG	Greenhouse sasses
IFA	International Fertilizer Industry Association
ISPS	Intensive silvopastoral systems
N	Nitrogen
N_2	Atmospheric nitrogen
N_2O	Nitrous oxide
NDF	Neutral detergent Fibre
NH_4^+	Ammonium ion
NO_3^-	Nitrate
OM	Organic matter
SPS	Silvopastoral systems

7.1 Introduction

Global continuous increase of livestock production (milk, eggs and meat) demands more forage to feed the animals; consequently, more grazing areas would be necessary to reach the animal food intake; this could increase the deforestation, replacing forest areas for pastures, if the pastures are managed wrong, for example, overgrazing it enters in a process of degradation, so in a few years, more areas are necessary. Lately, overgrazing is one of the major causes of grassland degradation and represents the main cause of degradation among the major biomes. Steinfeld et al. (2006) estimated that approximately 73% of the pastures have been degraded; the same authors estimated that in the Amazon, the introduction of pastures is responsible for 70% of the deforestation.

It has been estimated that approximately 5% of soil organic carbon has been lost from overgrazing and during the dry season, ruminants are usually fed low-quality forages, which are characterized by their low concentrations of crude protein (CP), digestible energy (DE) and their high contents of neutral detergent fiber (NDF) and lignin, which induce a higher emission of methane (CH_4). Degradation of grazing biomes not only has a negative and direct effect on livestock production but also effects on the soil and the environment. Under tropical grassland conditions, cattle generally loses weight, and the milk production per cow is severely affected. Grass-based diet can lead to a daily weight gain of less than 300 g or a daily milk production of 4 kg/day (Ku et al. 2014; Meena and Meena 2017; Ashoka et al. 2017).

These grassland pastures are one of the ecosystems most vulnerable to climate change. In the tropics, livestock in extensive mixed systems suffer from permanent or seasonal nutritional stress (Ku et al. 2012; Yadav et al. 2018b). Poor nutrition is one of the major production constraints in small holder systems, particularly in tropical areas. Additionally, in the last decade, climate change and human population growth began to threaten the productivity of those grasslands due to changes in vegetation, mainly due to variability in rainfall along the year, frequently raising temperatures (IPCC 2007), including incorrect grazing management practices.

Two options to solve these problems have relied on the use of nitrogen-based fertilizer and the use of imported supplemental feed concentrates with social, economic and environmental negative effects. The dependence on grain as feed animal component has created a competition ground between humans and animals for the same source of food (Thornton 2009; Meena et al. 2015d; Kumar et al. 2017b; Meena and Lal 2018a, b). The abuse of chemical fertilizer, mainly those based on nitrogen, leads to environment and soil (nitrification and denitrification process) contamination. Both of these two options, however, have considerably increased animal production.

In the tropical regions, environmental temperature and relative humidity are high, and frequently above the physiological capacity of livestock to dissipate body heat, causing enormous economic damages. Under these conditions, silvopastoral systems (SPS) are an important tool to increase livestock production and enhance resilience to drought and in reducing the contribution of cattle to climate change. Greenhouse gas (GHG) emissions are reduced due to fewer applications of nitrogen-based synthetic fertilizers that improved forage quality and production (CH_4 emission reductions estimated at 15–20% and nitrous oxide (N_2O) emission reduction at 25–30%). Given the prevalence of many leguminous species, closer integration of trees and shrub with grasses can rise to increased productivity and increased soil fertility (atmospheric nitrogen fixation) including animal welfare. Integrating local leguminous trees and shrubs species is usually well adapted to water stress of the tropical climate by storing nutrients and carbohydrates in perennial belowground organs, thus improving the capacity to store carbon in the soil and in the aboveground biomass due to trees and shrubs integrating with grass. The objective of this chapter is to discuss the role of SPS as a strategy to improve the N cycling in tropical and subtropical livestock systems.

7.2 Livestock and the Environment

Climate change is the result of the accumulation of GHG emissions in the atmosphere, caused mainly by human activities. The most important GHG directly emitted by humans include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since the Industrial Revolution, the amount of GHGs emitted exceeds the capture capacity of the biosphere, and the net result is the constant increase in GHG concentrations, which prevent heat from escaping the atmosphere (IPCC 2007). This global warming is the most obvious manifestation of climate change and refers to the rise in average surface temperatures.

Human activities such as agriculture and deforestation contribute to the rise of GHG emissions. Within this, the livestock sector is considered one of the main activities with the biggest impact on climate change through the emission of greenhouse gases (Herrero et al. 2013; Varma et al. 2017a; Buragohain et al. 2017). According to the FAO (2013), the livestock sector contributes 18% of the total gases emitted into the atmosphere. Large amounts of CO_2 are emitted from the burning of fossils fuels to make fertilizers which are used to grow grain to fed animals, including the deforestation to grassland expansion (Fig. 7.1).

Livestock activities contribute to global warming due to the large release of GHG into the atmosphere, originated from the enteric fermentation. Ruminant animals are the major emitters of CH_4, due to the digestive process in which microbes ferment the food consumed.

Fig. 7.1 Deforestation and soil preparation for grassland expansion in the Mexican tropics

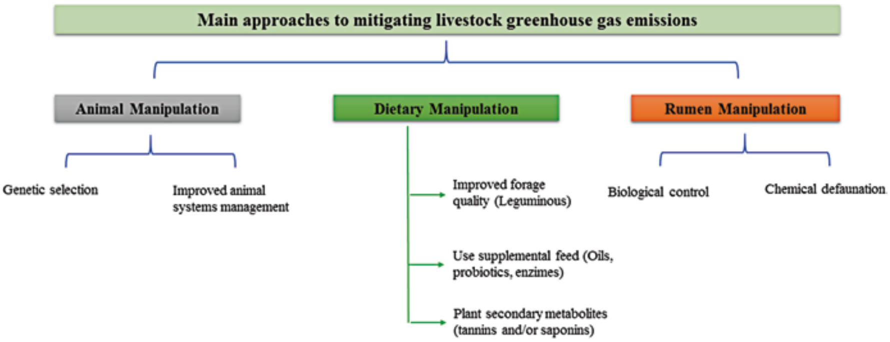

Fig. 7.2 Specific solutions for the mitigation of GHG emissions in the livestock sector

Ruminants grazing low-quality fodder increase CH_4 emissions, with a bigger negative impact on climate change. Excreted urine and faeces by ruminants significantly contributed to CH_4 and N_2O emissions. Although the amount of nitrogen (N) excreted depends on the feed quality ingested, low-quality feeds result in low N-excreted factors like temperature, and soil moisture can facilitate the release of GHG emissions on pastures based livestock production (Lessa et al. 2014; Meena and Yadav 2015; Dhakal et al. 2015; Datta et al. 2017b). Although GHG emissions have been increased markedly in the last five decades, many options exist that can mitigate GHG emissions from the livestock sector (Fig. 7.2).

7.3 Nitrogen Cycling in Livestock Systems

In the tropics and subtropics, millions of people have no food security; about 60% of rural communities are permanently affected by the decline in household food production, with sub-Saharan Africa and parts of Latin America, the Caribbean and Central Asia suffering worst (Stocking 2003; Meena et al. 2016a; Verma et al. 2015c). From 33 Latin American countries, Mexico occupies the second place in deforestation just below Brazil. Current estimates of deforestation rates in Mexico range from 400,000 to 1,500,000 hectares per year, the largest area located in the southern Mexico including the Peninsula of Yucatan (Cairns et al. 1995). The consequence of forest deforestation is the decline in soil productivity.

The progressive deterioration of natural resources in the tropics has led to the need of alternative methods to sustain crop production. Optimizing nutrient cycling and improving biological nitrogen fixation as a source of nitrogen have been proposed as the better strategy for achieving improved levels of production without further damage to the natural resource (Greenland 1975; Meena and Lal 2018a, b; Yadav et al. 2017c; Dadhich and Meena 2014; Kumar et al. 2018b). In the tropics, fast-growing trees, particularly nitrogen-fixing trees, are increasingly being recommended for land restoration where soil has been degraded (Franco and De Faria 1997; Dubeux et al. 2015; Varma et al. 2017b; Meena et al. 2015e), for fallow

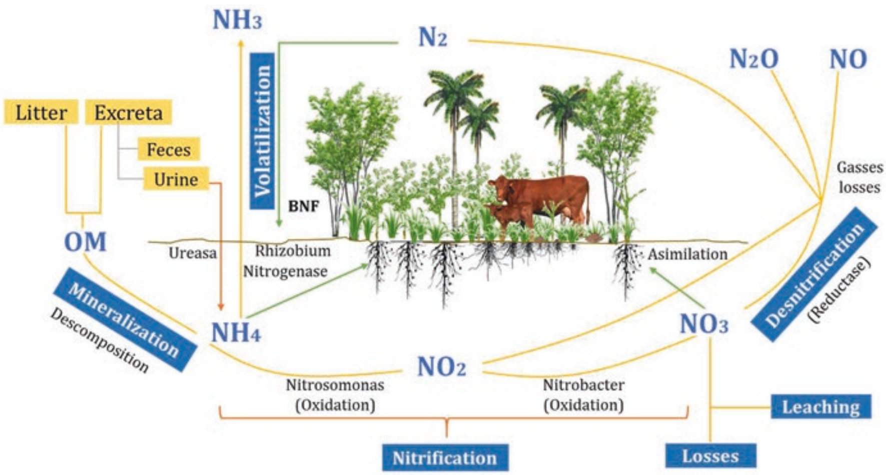

Fig. 7.3 Approach to outline for synthesizing understanding of N dynamics in livestock SPS

improvement and for erosion control; examples of benefits in soil improvement are well-documented by Kamara et al. (2000), Giller (2001) and Schroth and Sinclair (2003). In tropical agroecosystems, the leaf litter decomposition and subsequent nutrients released represent a good tool for the poor farmer in order to reduce external input and maintain or increase agricultural products (Mthembu et al. 2018; Kumar et al. 2018a). About 70–90% of the nutrients required for growing plants could be proportioned by leaf litter decomposition of a companion plants (Waring and Schlesinger 1985). Using this system, fodder trees, apart from being a source of foliage rich in nutrients to animal feed, could also be a very important source of nutrient to the soil (Fig. 7.3).

7.4 Agroecological Strategies to Improve N Cycling

In tropical countries the gap between food production and population growth is widening (Stocking 2003). This increased demand for more effective food production generally means increased application of industrially produced fertiliser nitrogen, because N is the most important nutrient for crop growth. Nevertheless, research has shown that biological nitrogen fixation by legumes is an efficient way to supply the large amounts of nitrogen needed to produce high-yielding crops with high protein content (Crews and Peoples 2004; Boddey et al. 2015; Meena et al. 2018a; Sihag et al. 2015). Introducing legumes into farming systems can provide a continuous supply of N for plant growth and provide good-quality organic matter to be incorporated into the soil; thus, legume species should play an important role in developing new strategies to increase food production (CGIAR 2004). Biological N_2 fixation contributes to enhanced production directly by increasing the yield of grain or other food crops for human or animal consumption or indirectly by contributing to the maintenance of soil fertility (Giller and Cadisch 1995; Graham and

Vance 2003; Meena et al. 2016b; Yadav et al. 2017b). In the latter case, N_2 fixation by leguminous trees is most likely to constitute a relevant input to farming systems when the soil is low in N and when N fertiliser is scarce (Schroth et al. 2001; Verma et al. 2015b). Additionally, trees or shrubs survive in most dry seasons and can contribute significantly to animal feed by providing nutritional foliage, in places where grassland productivity depends largely on the rainfall.

7.5 Silvopastoral Systems

At present, livestock production in tropical areas face serious problems related to climate change and the prevailing model of extensive production (FAO 2012). These problems are characterized by the transformation of natural ecosystems into large monoculture pastures, low productivity and with strong demand for fertilizers mainly nitrogen (Meena and Lal 2018a, b; Meena and Yadav 2014). This has a negative impact on agricultural production and plant biodiversity, which leads to a high dependence on external inputs and little integration between the agricultural, livestock and forestry sectors (Williams et al. 2017; Dadhich et al. 2015). In addition, extensive livestock systems have low levels of efficiency and profitability (Ku et al. 2014; Sofi et al. 2018) and are more vulnerable to extreme climatic conditions such as droughts or floods (Cuartas et al. 2014; Meena et al. 2015c).

The availability of nitrogen is one of the main constraints of tropical animal production (Ku et al. 2014). The application of nitrogenous inorganic fertilizers is a frequent practice, to correct the problem as well as to increase the productivity and quality of the pastures (Silveira et al. 2013; Yadav et al. 2018a). This causes considerable quantities of fertilizers to be imported annually to be applied to the soil (FAOSTAT 2014).

Additionally, the indiscriminate application of fertilizers causes irreversible damage to the environment by emissions of gases, mainly N_2O and contamination of groundwater (IFA 2002). In addition, the high costs of nitrogen N fertilizers increase the costs of livestock production (Pelletier and Tyedmers 2010; Verma et al. 2015a). In Mexico, for example, the price of agrochemicals doubled in recent years, to such a degree that in 1 year more than 60 million pesos were invested in their purchase; just to cite one example, urea has a cost of approximately $ 500 per ton (FAO 2008) and, 1 hectare of pasture requires approximately 120 kg of N/ha/year. This has led to the search for strategies to minimize the environmental impact of livestock production and the excessive application of fertilizers. Efforts have also been made with particular emphasis on increasing forage production and quality within these livestock production systems, which may contribute to a more efficient use of N throughout the production system.

One of the strategies with promising results that has arisen in Latin American tropical livestock is the reconversion of traditional monoculture systems with intensive silvopastoral systems (ISPS) (Murgueitio et al. 2011; Bacab et al. 2012; Solorio et al. 2012; Meena et al. 2015b), including shrub legumes at high densities associated with forage grasses which would increase both yield and quality of forage and

Fig. 7.4 Shrub forage legume for effective reconversion grassland to silvopastoral systems

promote the N atmospheric fixation and recycling nutrients (Fig. 7.4). With the association of legumes and forage grasses, forage quality could increase more than 100% in comparison to monoculture-based pastures (Sturludóttir 2011; Datta et al. 2017a), and, consequently, the production costs related to the purchase of nitrogen fertilizers and the use of feed concentrates will be reduced (Murgueitio et al. 2015; Meena et al. 2015a).

Intensive silvopastoral systems is an agroecological model of agricultural production, in which perennial woody trees (multipurpose trees and high-forage shrub densities) interact with pastures and animals under an integrated management system (Fig. 7.5). These systems have been designed and proposed based on research results, which have evaluated the yield and quality of forage (Murgueitio et al. 2015; Meena et al. 2014), animal productivity (e.g. production and quality of meat and milk) and carbon capture (Solorio et al. 2016; Dhakal et al. 2016), as well as improved the microclimate of grazing animals and biodiversity (Broom et al. 2013; Kakraliya et al. 2018).

With the implementation of SPS, it is feasible to reduce the environmental impact of traditional extensive livestock production systems (Murgueitio et al. 2011; Solorio et al. 2012; Ram and Meena 2014). Silvopastoral systems are developed as sustainable animal production strategies. The main structure of the SPS includes the association of grasses with shrub legumes and represents additional advantages, including legumes in the paddocks that obtain benefits in the production and quality

Fig. 7.5 ISPS with multipurpose trees, edible shrubs and the integration of animal-grass

of forage biomass, as a consequence of the biological fixation and transfer of N (Casanova et al. 2014). Several studies have demonstrated the potential benefits of silvopastoral systems and their effect on the profitability of livestock systems including environmental benefits, soil and their benefits in the productivity and sustainability of agroecosystems (Goh et al. 1996; Mercado et al. 2011; Alvarez et al. 2014; Meena et al. 2017c).

Other positive interactions among trees or shrub species may maximize above- and belowground resource utilization for growth (Cadisch et al. 2002; Yadav et al. 2017a; Kumar et al. 2017a). Intercropping legumes and nonlegumes increases the opportunity for complementary N use (van Kessel and Hartley 2000). Mixing species may also improve resilience, by improving nutrient cycling and enhancing resistance to pests or diseases. Additionally, mixing species can exploit interactions in which one species enhances the biological performance of another (Khanna 1997; Cadisch et al. 2002; Gathumbi et al. 2003; Meena et al. 2017a); perhaps the most important feature is the direct transfer of N from a N_2-fixing plant to a non-fixing plant, which can be better exploited in a mixed system.

7.6 Challenges in the Tropical Livestock Production Systems

Livestock activity has been associated with problems of deforestation, soil degradation, loss of biodiversity, environmental pollution and low productivity (Broom et al. 2013). These livestock systems often remove all the vegetation (as erroneous, considered competition for water and soil nutrients) in order to allow the growth of native or introduced forage grasses, (Grande et al. 2010; Jiménez et al. 2011).

Most Latin American beef cattle production systems use tropical grasses as the basal forage source. However, extensive livestock production that is mainly pasture-based results in lower yield (milk or beef) per unit of land and a negative environment impact (Ku et al. 2014). Its development and profitability are based on the extension of the grazing area with large areas that have been deforested for the production of milk and meat with dual-purpose cattle, specialized breeds and their crosses (Murgueitio et al. 2011). These problems can result in livestock weight losses and hence greatly restrict farmer's income. Fluctuations in forage availability, throughout the year, restrict the ability to achieve sustainable levels of animal production (Ku et al. 2014; Solorio et al. 2012), mainly due to the low quality of the grass which will consequently limit pasture intake and digestibility. Mismanagement of the grazing systems, the seasonality and low quality of forages, consequently, further decreases animal production (Murgueitio et al. 2011) and contributed to increase the CH_4 emissions from the digestive process of ruminants.

Mismanagement of the grazing systems has also contributed to the pasture degradation, due to overgrazing that has extracted nutrients from the soil without restitution (Murgueitio et al. 2013). The conservation and maintenance of ecosystems are currently under threat by the intensification of livestock systems. In order to reduce the deficiency of pasture-based animal production, farmers frequently rely on large quantities of imported concentrate feed (e.g. grains and cereals), and in the use of fertilizers, trying to increase livestock production, but highly dependent of external inputs and polluting the environment (Solorio et al. 2009).

In order to resolve the feed deficit in the dry season and meet the competing demands of increasing animal intensity while maintaining sustainable grain production, alternative forage sources need to be identified (Fig. 7.6). One of the options increasing the profitability of the livestock farmers includes the renovation of degraded pastures. The identification of the grass nutritional deficiencies can be reduced by improving livestock and grassland management with the incorporation of tropical forage legumes into their farming system. Figure 7.6 shows the effects of tropical forage legumes on the animal nutrition.

Another very important issue related to animal production is water. Water is a scarce and valuable resource essential to human and animal life. Water for livestock

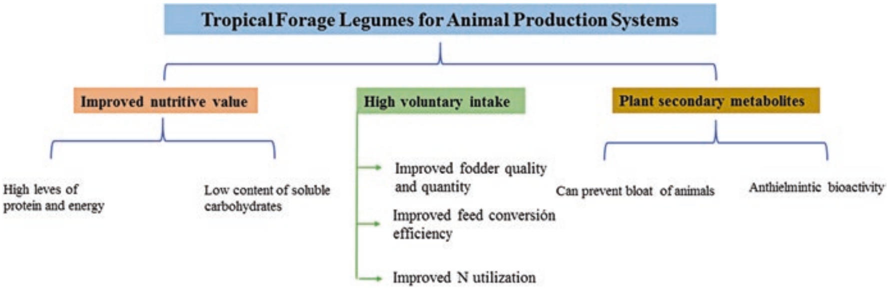

Fig. 7.6 Forage legumes for animal production and the GHG mitigation

production is used for drinking, irrigation and growing crops/pasture. The water required to produce feed is the major factor behind the water footprint of animal products (Mekonnen and Hoekstra 2012). Animals can negatively affect water quality by having free access to water sources where animals can excrete faeces. Waste from animals can be dangerous because it carries harmful bacteria. Bacteria can enter water sources during heavy rainfalls that might result in an overflow of the manure catchment basin or from manure that has been put on fields as fertilizer (McAllister et al. 2012).

The challenge for livestock production therefore is to improve environmental sustainability and reduce greenhouse gas emissions. Challenges remain to reverse the economic losses from grassland degradation while accommodating growing demand and simultaneously avoiding the conversion of ecosystems.

7.7 Fertilizers and Livestock

Livestock production, as mentioned previously, is constrained by many factors. However, feed shortages during the dry season constitute the greatest challenge in terms of quantity and quality given by the seasonality of rainfall. Other factors include low soil fertility for forage production. Of the 17 chemical elements that are essential for plant growth, N is the nutrient that most often limits grass growth. N is very mobile in the soil and can become limiting in areas with high rainfall or irrigation, in coarse or shallow soils and in soils with low organic matter.

Climate change together with inadequate grassland management and the soil's low fertility is the main constraint to increasing livestock productivity. The lack of good-quality livestock feed, produced at a competitive cost, in the dry season, can jeopardize food security. Improvements in forage production through improved soil fertility practices have the potential to increase income and reduce livestock production costs. As pasture soil do not usually contain sufficient amounts of N for high and sustained fodder production, frequently farmers rely on the use of chemical fertilizer. The most common sources of commercial fertilizer N are urea. However, urea application is highly susceptible to volatilization (leaching to the atmosphere and water pollution).

The purpose of using of inorganic chemical fertilizers is to increase livestock productivity, but it also leads to environmental problems and contamination of natural resources (water, soil and air). Nitrogen is the main element for the growth of plants and agricultural crops in general; this element forms part of 46% of urea, the most widely used fertilizer in the world (Liu et al. 2015). In pastures and forages, doses of 140 to 325 kg/ha/year of this chemical fertilizer are used (González Torres et al. 2009). In 2007, urea production increased by 6.6%, reaching 144 million tons. For 2009, world consumption of 184.3 million tons was estimated, with approximate applications of 140 to 200 kg of N/ha/year for pastures and up to 325 kg of N/ha/year in crops such as forage maize (González Torres et al. 2009).

A common problem with the indiscriminate use of chemical fertilizers is related to the infiltration and consequent contamination of aquifers (approximately 10% of the fertilizer applied to the soil is infiltrated) and emissions of gases to the atmosphere (approximately 5% of the applied fertilizer is lost as a gas) (Vendramini et al. 2007). In addition, livestock contribute approximately 40% of global ammonia emissions mainly from animal excreta and from the use of fertilizers in pastures (IFA 2002). According to the International Fertilizer Industry Association (IFA), between 2002 and 2007, there was an increasing trend in world fertilizer production. The global supply grew by 3.4%, reaching an average of 165.3 million tons of nutrients: nitrogen, phosphorus and potassium, mainly (FAO 2008).

However, agroecological opportunities for improving the nutrition of livestock do exist, for instance, multipurpose legume trees can provide high-quality feed and improve soil fertility (Lenné and Thomas 2006). Intercropping legumes with grasses, which are an excellent source of N, improves forage quality. In Queensland, Australia, *Leucaena* (*Leucaena leucocephala* L., -Lam- de Wit)-grass mixes had higher live weight gain. A steer must consume a diet containing 35–40% *Leucaena* (4 kg/day for a 450 kg steer) to gain more than 1 kg/day (Dalzell et al. 2006). The main value of *Leucaena* is as a much-needed protein supplement to cattle grazing tropical grass pastures. Cattle require about 13% CP in their diets to produce good weight gains; they cannot get this from grass alone. When cattle are allowed to graze in *Leucaena* paddocks, their intake of protein immediately increases.

Intercropping *Leucaena* pastures can also enhance the environment by revitalizing the fertility of degraded soils by contributing biologically fixed nitrogen (BNF). *Leucaena* pastures offer the opportunity to intensify production in an environmentally sustainable manner. *Leucaena*-grass pastures are persistent and productive at higher stocking rates. Beef production is 4–6 times higher than from the best native pastures. Most crop-livestock production relies directly on rainfall, and adverse changes in quantity and temporal patterns of rainfall are a major risk to production. The drought tolerance of deep-rooted *Leucaena* can protect the land against the worst effects of drought. Also these may increase soil organic matter (OM), aggregation, nutrient availability, plant resistance to stresses and yield.

According to Ku et al. (2014), for improving meat and milk production and quality in tropical regions, different options have been created for manipulating the energy metabolism of ruminants. Silvopastoral systems, based on *Leucaena* and Tanzania grass *(Megathyrsus maximus (jacq) B.K. Simon & S.W.L. Jacobs)* association, can provide live weight gains of 770 g/d in growing cattle. For milk, it is possible to increase the concentration of unsaturated fatty acids from tannins in foliage that are beneficial effect on human health. This addition could provide aggregate value to the cow's milk. Improved feeding practices are required to decrease CH_4 emissions from the rumen. This can be done by feeding animals with foliage and fruits which contain secondary metabolites which are capable of affecting ruminal fermentation.

7.8 Silvopastoral Systems Benefits

7.8.1 Environmental Issue

The benefits of ISPS are associated with the integration of the multipurpose trees and shrubs. The leguminous component viz; *Leucaena*, *Gliricidia sepium (Jacq.) Kunth ex Walp.*, *Sesbania grandiflora L. Pers.*, *Cratylia argentea*, (*Desv*.) O. Kuntze, of these species has the capacity to fix atmospheric nitrogen through symbiotic association with bacteria of the genus Rhizobium (Peoples and Herridge 1999; Peoples et al. 2009). For example, *Leucaena* has the capacity to fix between 70 and > 285 kg atmospheric N/ha/year (Goh et al. 1996; Giller 2001; Sarabia 2013; Meena et al. 2017b). Therefore, the leguminous component contributes to the reduction of the excessive use of nitrogen fertilizers required by grasses in monocultures to improve the production and quality (Sierra et al. 2007; Peoples et al. 2009; Layek et al. 2018).

In addition, this type of shrub legume species presents greater tolerance to droughts, besides having a wide range of adaptation to diverse climatic conditions (climate change mitigation) and a great capacity to regrow in short periods or to resist frequent defoliations. SPS also integrates multipurpose trees that contribute to improving environmental conditions, reducing temperatures, improving animal behaviour and generating other products (e.g. wood, fruits, fodder, etc.). In addition, the inclusion of trees in association with pastures helps carbon sequestration, reduce water loss through evaporation and increase OM content in soils (Don 2012; Casanova Lugo et al. 2014).

7.8.2 Production and Quality of Forage

Silvopastoral systems are characterized by the diversity of species that can be incorporated into the system to increase animal production (Solorio et al. 2016). It highlights the importance of the association between shrub legumes, such as *Leucaena*, with grasses, since a variety of positive interactions occur, such as increased nitrogen availability, reduced solar radiation impact and temperature, improves animal comfort, shrubs also improve forage quality (increase protein content of the whole grassed forage), which contributes to improved animal productivity (Solorio et al. 2016). An important aspect of these interactions is the fixation and transfer of N, of which the associated pastures are directly benefited (Tessema and Baars 2006). Due to the high production of forage of high nutritional value, shrub legumes contribute significantly to animal feed, increasing the production and quality of the ingested forage.

Leguminous shrubs can continuously fix nitrogen and due to their deep rooting system act as a 'pumps'; they can also bring up nutrients from lower soil horizons and return them to the surface in the litter (Young 1997). Proper management of trees will ensure that the foliage is available for animal feeding during the critical period of food scarcity. For example, the association of leguminous with non-leguminous trees in a mixture may increase rates of N cycling. On nitrogen-deficient sites, mixed stands present an ecological opportunity for increasing both total stand growth and the growth of non-fixing trees (Binkley et al. 1992; Dakora and Keya 1997; Parrota 1999).

Evidence suggests that in addition to the positive advantages to agriculture from the leguminous species, they also play a major role in the growth of non-leguminous plants if they are planted in close contact with them (Parrota 1999; Rothe and Binkley 2001; Forrester et al. 2004). Reports on mixtures of leguminous trees with non-leguminous trees or annual crops show that the N concentration tends to increase in the leaves of the non-leguminous species in comparison to that of monocrop stands of the non-fixing plants (Khanna 1997; Chirwa et al. 2003). New evidence suggests that non-leguminous crops benefit from the direct transfer of N fixed by the plants (Fagbola et al. 1998; Graham and Vance 2000). The roots of nitrogen-fixing species have more nodules when they grow in close contact with roots of non-nitrogen-fixing plants (Van Noordwijk and Dommergues 1990; Sanchez 1995; Young 1997). This increased nodulation may lead to the direct transfer of nitrogen to the non-nodulating plant. Symbiotic activity in some intercropped legume species can be stimulated if the associated plants in the mixture exert intense competition for soil N, forcing the legume to rely more on symbiosis for its N nutrition (Eaglesham et al. 1981; Rerkasem et al. 1988). Since legumes usually do not have to compete with non-leguminous plants for soil N uptake, legumes grown in mixture with non-leguminous plants usually derive a higher percentage of their N from symbiosis (Graham and Vance 2000).

7.8.3 Importance of N_2 Fixation

Nitrogen is a key element in soil fertility and in the development of food production systems, being one of the most important elements for plant growth (Mafongoya et al. 2004). The N content of the soil is maintained thanks to natural processes, such as the BNF and the application of organic fertilizers and mineral fertilizers (Giller et al. 1997). However, BNF is the most important source for sustaining soil fertility (Stockdale et al. 2001; Unkovich et al. 2008; Meena et al. 2018b).

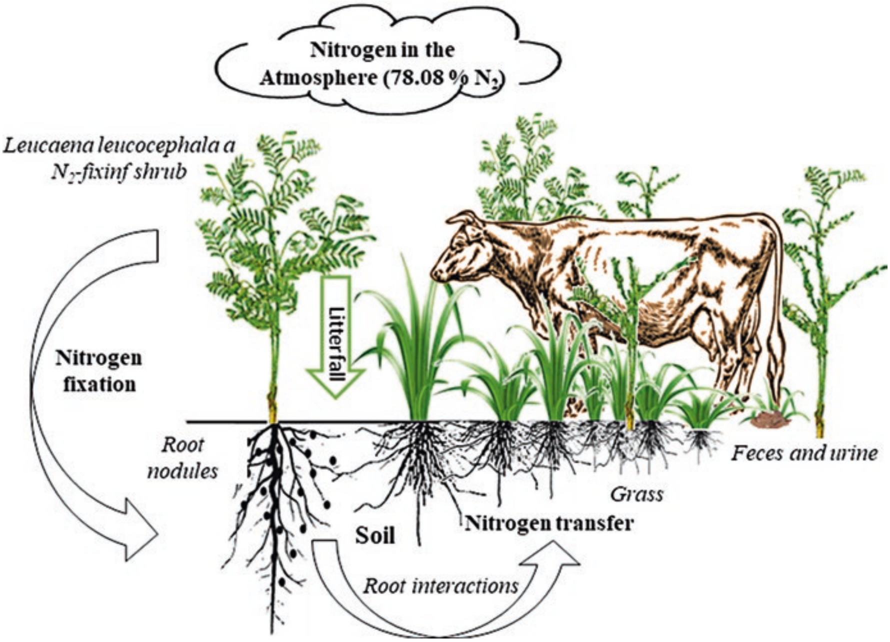

Fig. 7.7 The proposed model of the N fixation in SPS for animal production

Generally, the N absorbed by the plants comes from the soil, which must be mineralized in the form of nitrate (NO_3^-) or ammonium (NH_4^+). On the other hand, 78% of the air in the atmosphere is nitrogen gas (N_2), which is not readily available to plants; only some species are able to directly use N_2 by symbiosis with soil bacteria that are N_2-binding agents (Fig. 7.7). In this case, there are different genera of N_2-fixing bacteria. The genus *Rhizobium* is one of the most important for leguminous plants, since they play a very important role in some N transformations through the biological fixation process.

The amount of nitrogen required by the plants may be greater than that provided by the soil; in most crops, N fertilization is necessary, since the nitrogen cycle has been altered by the removal of trees (particularly legumes) from the system and the excessive use of grassland in monoculture.

Introducing legumes into livestock farming systems can provide a continuous supply of N for animals and for plant growth (Fig. 7.7). Also, providing OM of good quality to be incorporated in the soil, legume species should play an important role in developing new strategies to increase animal production. Biological N_2 fixation contributes to enhanced production directly by increasing forage biomass and quality or indirectly by contributing to the maintenance of soil fertility (Giller and Cadisch 1995; Murgueitio et al. 2015). In the latter case, N_2 fixation by leguminous trees is most likely to constitute a relevant input to farming systems when the soil is low in N and when N fertilizer is scarce (Schroth et al. 2001; Meena et al. 2018c). Additionally, trees or shrubs usually survive dry seasons and can contribute significantly to animal feed by providing nutritional foliage, in places where grassland productivity depends largely on the rainfall.

7.8.4 BNF and N Transfer

Positive interactions among trees or shrub species in SPS may maximize above- and belowground resource utilization for growth (Cadisch et al. 2002). Intercropping legumes and non-legumes increases the opportunity for complementary N use (van Kessel and Hartley 2000). Mixing different species may also improve resilience, by improving nutrient cycling and enhancing resistance to pests or diseases. Additionally, mixing species can exploit interactions in which one species enhances the biological performance of another (Cadisch et al. 2002; Gathumbi et al. 2003). Perhaps the most important feature is the direct transfer of N from a N_2-fixing plant to a non-fixing plant, which can be better exploited in a mixed system.

Evidence suggests that in addition to the positive advantages to agriculture from the leguminous species, they also play a major role in the growth of non-leguminous plants if they are planted in close contact with them (Sierra et al. 2007). Reports on mixtures of leguminous trees with non-leguminous trees or annual crops show that the N concentration tends to increase in the leaves of the non-leguminous species in comparison to that of monocrop stands of the non-fixing plants (Khanna 1997; Chirwa et al. 2003). New evidence suggests that non-leguminous crops benefit from the direct transfer of N fixed by the plants (Thilakarathna et al. 2016). The roots of nitrogen-fixing species have more nodules when they grow in close contact with roots of non-nitrogen-fixing plants (Van Noordwijk and Dommergues 1990; Sanchez 1995; Young 1997). This increased nodulation may lead to the direct transfer of nitrogen to the non-nodulating plant. Symbiotic activity in some intercropped legume species can be stimulated if the associated plants in the mixture exert intense competition for soil N, forcing the legume to rely more on symbiosis for its N nutrition (Eaglesham et al. 1981; Rerkasem et al. 1988). Since legumes usually do not have to compete with non-leguminous plants for soil N uptake, legumes grown together with non-leguminous plants usually derive a higher percentage of their N from symbiosis (Graham and Vance 2000).

N_2 fixation is made by N-fixing bacteria, which require a source of chemical energy from the plant. Therefore, this process has been identified as Rhizobium – leguminous symbiosis. This association contributes between 30 and 50% of biological N_2 fixation and is based on the exchange of carbon by nitrogen between both symbionts (symbiotically associated organisms), also helping to reverse the low fertility of the soil. Therein lays the importance of proper inoculation with Rhizobium, since it is possible to considerably increase the atmospheric fixation of N_2 in agricultural systems (Rodrigues et al. 2013).

The capacity of N_2 fixation is an important characteristic of the Rhizobium bacteria, which infects and colonizes the roots of the legumes causing the deformations that are known as nodules; it is in these where the transformation of N_2 to mineral nitrogen is carried out. The N_2 fixation process has a high energy cost, because the

Table 7.1 Milk and meat production under ISPS and grass monoculture

System	Milk production (kg animal^{-1} día^{-1})	References
ISPS + concentrated feed (1,5 kg)	9.20	Bacab and Solorio (2011)
Grass-based only + concentrated feed (8 kg)	10.4	
	Meat production (kg animal^{-1} día^{-1})	
ISPS	0.770	Mayo et al. (2013)
Grass-based only	0.28-0.62	Ku et al. (2012)

triple bond linking the two nitrogen atoms is difficult to break. The great advantages that they obtain from this symbiosis are multiple; among the most important, we can cite the following ones: (a) the plant can self-supply of N, increasing considerably the content of protein in its tissues; (b) the legume transfers N to other associated crops (Kurppa et al. 2010); (c) the legume helps to prevent loss of soil fertility by incorporating and leaving available nitrogen in the soil for the next crop in the rotation; and (d) there is a greater efficiency of the use of atmospheric nitrogen by crops compared to the application of nitrogen fertilizers, because the applications of the latter are lost leaching fractions, which then become pollutants of soils, waters, animals and even humans (Parsons 2004).

Several studies (Solorio 2005; Sierra et al. 2007; Burchill et al. 2014; Mitran et al. 2018) show that in agroforestry systems, crops associated with legumes can increase their N content, since in the roots of trees and shrubs when interacting closely with the roots of crops, the N fixed by the legumes is transferred directly and is used by the grasses and is expressed through the increase in the protein content of the grasses. In this sense, the importance of nitrogen transfer is oriented to the ability of legumes to transfer nitrogen directly to grazing animals including the pastures associated with it (Table 7.1). Therefore, they have the capacity to increase the protein content in forage, which is reflected in higher weight gain in grazing animals and higher milk yield compared to monoculture pastures (Table 7.1).

Recent studies with SPS established with *Leucaena*, which evaluated the fixation and transfer of atmospheric nitrogen, indicate the ability of *Leucaena* to fix high amounts of N up to 285 kg N ha-^{1} (Solorio 2005; Sarabia 2013), having greater potential of fixation and transference when they have high densities of *Leucaena*. In recent studies with *Leucaena* established at high densities, N transference to pastures greater than 50% has been found (Sarabia 2013). Despite the great importance of atmospheric N fixation for agricultural systems, there are few studies to evaluate the effect of climatic and edaphic conditions on the influence of legumes to incorporate nitrogen into the associated crops (Dreyfus et al. 1988).

7.9 Challenges

Despite the research evidence showing the advantages of SPS and the large interest in soil fertility maintenance in tropical agroecosystems, few reliable estimates and data of N cycling in SPS are available. Most of the research involving woody plants has been focused on grassland monoculture, while other research on more than one species relates only to their growth in a rotation system. Strategies for improving N use in livestock systems are becoming critically important, and today one of the most promising strategies for the GHG mitigation relies on the improvement of the fodder quality. Tropical soils have not enough N soil to crops, improving the overall use efficiency of available N, through intercropping systems where non-N_2-fixing plants are grown in close contact with N_2-fixing legumes (van Kessel and Hartley 2000; Graham and Vance 2003; Gogoi et al. 2018).

Silvopastoral systems adoption by farmers are still limited; livestock producers are reluctant to integrate the SPS into their farming systems. Research should be addressed to identify specific barrier (Dagang and Nair 2003). Long-term investment return and high costs for initial implementation could be another barrier for their adoption. Inefficient support of state policies, a national programme should be orientated to the implementation and to give a long-term support for the livestock producers.

7.10 Conclusions

Extensive livestock systems have resulted in degradation of natural resources and loss of productivity. In order to counter this effect, farmer uses the acquisition of inputs which results in a vicious circle of low productivity and environmental pollution. Silvopastoral systems have been increasingly adopted in different eco-regions of Latin America. They represent a viable alternative to contribute to providing excellent quality forage for tropical livestock. Additionally, they have several advantages over traditional monoculture-based livestock systems. The inclusion of legumes into animal production systems can incorporate significant amounts of N into the soil and transfer much of it directly or indirectly to the animal, soil and the associated grasses.

Silvopastoral systems can play also a major role in the rehabilitation of fragmented ecosystems, contributing towards mitigating the impacts of climate change on livestock and reducing GHG emissions, mainly N_2O, CO_2 and CH_4.Grass pastures can be restored by improving the carbon sequestration and increasing atmospheric N fixation in the soil through the integrations of leguminous shrubs and trees. Livestock feeding with leguminous species rich in N, tannins and saponins would be one of the best strategies for methane mitigation and reduce gaseous N losses from manure.

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