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Nitrogen fertilisation in tropical pastures: what are the impacts of this practice?

Antonio Leandro Chaves Gurgel[1*], Gelson dos Santos Difante[1], Denise Baptaglin Montagner[2], Alexandre Romeiro de Araújo[2], Alexandre Menezes Dias[1], Juliana Caroline Santos Santana[1], Jéssica Gomes Rodrigues[3], Marislayne de Gusmão Pereira[3]

[1]Faculty of Veterinary Medicine and Animal Science, Federal University of Mato Grosso do Sul, Avenida Senador Filinto Müller, 2,443, Campo Grande, CEP 79074-460, Mato Grosso do Sul, Brazil
[2]Embrapa Beef Cattle, Campo Grande, Brazil, Av. Rádio Maia, 830 - Vila Popular, CEP. 79106-550, Campo Grande, Mato Grosso do Sul, Brazil
[3]Academic Unit Specialized in Agricultural Sciences, Federal University of Rio Grande do Norte, Rodovia RN 160, Km 03, s/n - Distrito de Jundiaí, Macaíba - RN, CEP 59280-000, Rio Grande do Norte, Brazil

***Corresponding author: antonioleandro09@gmail.com**

Abstract

It is estimated that approximately 47% of the world's ruminant meat and milk is produced in tropical and subtropical regions, with pasture comprising the main food base of these animals. Nitrogen fertilisation is an essential practice for the maintenance of pasture productivity, considering that a deficiency of this nutrient is a primary factor in triggering pasture degradation. In addition to directly influencing the photochemical and biochemical phases of photosynthesis, nitrogen stimulates enzyme activity and the synthesis of enzymes responsible for fixing CO_2 (Rubisco in C_3 plants and phosphoenolpyruvate carboxylase in C_4 plants), thus increasing the efficiency of atmospheric CO_2 capture. All of these physiological processes are easily observed macroscopically in the characteristics of forage plants. This review examines the impact of nitrogen fertilisation in tropical pastures on the main components of production systems (soil, plants and animals), describes the results obtained in different situations and highlights the most efficient ways of producing meat without environmental impacts.

Keywords: animal; environment; nitrogen; plant, production system; soil.
Abbreviations: IBGE_Brazilian Institute of Geography and Statistics, FAO_United Nations Food and Agriculture Organization, N_nitrogen, C/N_carbon–nitrogen ratio, SD_soil density, PR_penetration resistance, UA_450 kg animal unit, LAI_leaf area index.

Introduction

The Brazilian beef cattle industry has undergone major changes in recent years. From 1995 to 2016, the national cattle herd grew from 153.1 to 220.9 million head (30.8%). One of the factors that has contributed to this advance is the opening of new agricultural frontiers, as evidenced by the growth in activity seen in the northern region of the country (Legal Amazon) in the last few years. The herd size in this region has grown faster than in other areas of the country; its proportion of the national herd size increased from 14% in 2010 to 22% in 2016 (IBGE, 2017).
The substantial increase in both cattle population and production efficiency seen in the last decade is a result of adopting and improving technological processes such as strategic supplementation, semi-confinement systems, multiple mixtures (Paula et al., 2011; Euclides et al., 2018) and breeding (Borba et al., 2016).
These practices have made it possible to reduce the production cycle; however, the particularity of livestock farming—that is, it is almost exclusively undertaken on pasture—is the predominant reason that beef cattle husbandry is a competitive activity worldwide. It is estimated that approximately 47% of the world's ruminant meat and milk originate from tropical and subtropical regions (FAO, 2013), and pasture comprises the main food base of these animals.
Brazil has a total pasture area of 158 million hectares (IBGE, 2017). In spite of the national herd size and all of the technological advances, Brazilian livestock production indices are still unsatisfactory, with lower values compared to its major competitors worldwide. This is mainly because neither pasture nor grazing management practices nor maintenance fertilisation have been widely adopted.
An alternative approach to optimising forage production, and consequently improving livestock production indices, is to associate pasture and soil management strategies. Nitrogen (N) fertilisation, along with maintenance

fertilisation, is essential to ensure pasture productivity (Liu et al., 2010; Świtek et al., 2019; Loide, 2019), and the low adoption of these tools is considered one of the main triggers of the degradation process. The influence of pasture management and N fertilisation on forage canopy characteristics and animal performance is well-known; investigating this association can therefore contribute to an understanding of every link in the pasture-based production system (soil, plants and animals).

This review examines the impact of N fertilisation of tropical pastures on the main components of production systems (soil, plants and animals), describes the results obtained in different situations and highlights the most efficient ways of producing meat without environmental impacts.

Nitrogen dynamics

Nitrogen is the most abundant element in the terrestrial atmosphere (70%). It constitutes a molecule of importance for life on earth, since the element is required in larger amounts by the majority of plants and has numerous functions. Specifically, in the plant, N is one of the most important components of amino acids, proteins, nucleic acids and enzymes. In addition, it promotes plant growth and is responsible for their green pigmentation (Taiz and Zeiguer, 2006).

This nutrient flows through the system via a pathway called the 'N cycle', which is considered an open system, subject to inputs and outputs, within the pasture ecosystem (Vestgarden et al., 2004). Nitrogen enters the system mainly through atmospheric deposition (Li et al., 2002), the biological fixation of atmospheric N gas (N_2) (Gaudin et al., 2014), chemical fertilisation (Loide, 2019) and recycling in the soil-plant-animal system (Arlauskienė et al., 2019).

Atmospheric deposition occurs when ammonia and other nitrogenous compounds (originating from soil, plants and the burning of petroleum) present in the atmosphere are incorporated into the soil through rainwater (Li et al., 2002). The quantity added by precipitation depends on proximity to animal management centres. Electrical discharge (lightning) can also convert atmospheric N_2 into oxide and subsequently nitrate (Li et al., 2002).

Biological N fixation is performed by cyanobacterial and bacterial species capable of transforming N_2 into ammonia (NH_3), which are hence termed 'N fixers'. This process is limited in C_4 plants and is much more common in leguminous species (Gaudin et al., 2014). Nitrogen is also incorporated through recycling (Lassaletta et al., 2014); that is, some of the N extracted and assimilated by plant cells is consumed by the animal and returned to the system through its faeces and urine. Recycling also occurs through the deposition of organic matter originating from decaying forage plants (Arlauskienė et al., 2019).

The majority of the N present in most tropical soils is incorporated naturally into the soil's organic fraction. The mineralisation of this fraction represents an important source of N for forage grasses. N mineralisation and immobilisation are considered sub-cycles within the N cycle. These processes occur simultaneously, though antagonistically (Buysse et al., 2013).

Mineralisation is understood as the transformation of organic N into inorganic forms (NH_4^+ or NH_3). Because the process is intermediated by heterotrophic microorganisms in the soil, the conditions necessary for organic N mineralisation to occur are those which favour microorganism activity: a pH of 6 to 7, aerobic conditions, moisture between 50% and 70% of the soil's water-holding capacity and a temperature between 40ºC and 60ºC (Buysse et al., 2013). Immobilisation is defined as the transformation of inorganic N into its organic form. This process is performed by microorganisms that incorporate into their cells inorganic N available in the soil (Buysse et al., 2013). Because these two processes are simultaneous and antagonistic, the prevalence of one over another depends on the carbon–nitrogen (C/N) ratio in the soil organic matter (Buysse et al., 2013; Arlauskienė et al., 2019). An equilibrium condition, in which mineralisation is approximately equal to immobilisation, is achieved when the C/N ratio in the organic matter is in the range of 20 to 30. In this case, N availability is not affected (Buysse et al., 2013).

In tropical-grass residues, which have a high C/N ratio (50), microorganisms rely on inorganic N in the soil to support their population growth, which is promoted by the availability of carbon in the soil (Buysse et al., 2013). Thus, in pasture-based animal production systems, soil N is mostly immobilised.

Nitrification and denitrification are other important processes that affect N dynamics in soil. These two reactions produce nitrogen oxides (NO and N_2O). Nitrification produces relatively more NO, while denitrification is the dominant process in N_2O production (Kim et al., 2006), which is favoured under anaerobic soil conditions. Nitrification is favoured when NH_4^+ is present in soil that is adequately aerated and is cycling N at high rates (Arlauskienė et al., 2019).

It is noteworthy that N originating from natural processes (atmospheric deposition, biological fixation of atmospheric N_2) alone is insufficient to meet the nutritional needs of forage plants (Loide, 2019). For this reason, N is incorporated into the soil mainly via fertilisation with chemical sources.

In order for N found in the soil solution to be absorbed by the plant, it must make contact with the root system. This contact occurs mainly by mass flow, through the movement of ions in a mobile aqueous phase. After ion–root contact is established, absorption occurs passively; the element shifts from a region of higher concentration (the external solution) to a region of lower concentration (the cell wall, intercellular spaces and external surface of the plasmalemma [apparent free space]), with no energy expended by the plant cell. By contrast, during active absorption, the symplast is occupied, causing N to cross the plasmalemma's lipid barrier to reach the cytoplasm. For this, the cell must expend energy through respiration. The chemical source most widely used in pasture fertilisation is urea, since its high concentration of N (45%) reduces transport and application costs. In addition, it is highly soluble, less corrosive and easy to manipulate (Yano et al., 2005). Nevertheless, if urea is not incorporated into the soil through rainwater or irrigation, N may be lost by volatilisation (Wang et al., 2016; Kaneko et al., 2019).

Nitrogen leaves the system mainly through erosion, removal by plants and animals, leaching, denitrification and ammonia volatilisation (Wang et al., 2016). As previously mentioned, some of this N returns to the pasture ecosystem; however, the total balance is negative due to irreversible outputs such as extraction by plants and subsequent assimilation into animal tissue, leaching losses and erosion (Lou et al., 2004). Therefore, to maintain pasture productivity and longevity, it is crucial to understand how forage plants respond to N, as well as to identify management strategies that enable the most effective use of this nutrient.

Effect of nitrogen on forage production

Nitrogen is one of the main macroelements that limits plant growth in agrosystems. It is estimated that only 47% of the N added globally to soils is converted to and harvested in product form (Lassaletta et al., 2014). More than 50% of N is lost in the environment (Foyer et al., 2016), which leads to waste of forage resources, threats to biodiversity and bodies of water and increased emissions of polluting gases (Godinot et al., 2014). Given these facts, it is of paramount importance that current livestock systems adopt measures that utilise this nutrient with maximum efficiency.

In tropical regions, native pastures have been replaced with C_4 forage grasses of African origins with great forage accumulation potential, especially those of the genera *Brachiaria, Panicum* and *Cynodon* (Pontes et al., 2016a; Euclides et al., 2017; Euclides et al., 2019). These grasses are highly responsive to N fertilisation when compared to those of temperate climates. In Europe, linear responses have been described in herbage production by temperate forage grasses following N fertilisation at doses of up to 300 kg ha^{-1} yr^{-1} (Jarvis et al., 1995). In tropical grasses, linear responses have been observed following the application of annual N doses of 400 to 600 kg ha^{-1} (Campos et al., 2016; Bernadi et al., 2018).

In addition to directly influencing the photochemical and biochemical phases of photosynthesis, N stimulates enzymatic activity and the synthesis of enzymes responsible for fixing CO_2 (Rubisco in C_3 plants and phosphoenolpyruvate carboxylase in C_4 plants), thus improving atmospheric CO_2 capture efficiency. In the photochemical phase, N acts on the synthesis of chlorophyll a, which is responsible for light capture, an essential process for subsequent stages of photosynthesis. In the biochemical phase, in turn, N is associated with protein/enzyme biosynthesis, which is linked to photosynthesis (Taiz and Zeiguer, 2006).

All of these physiological processes are easily observed macroscopically in the characteristics of forage plants. Higher N availability in the soil and, consequently, in plant cells, potentiates all these processes, in particular altering tiller leaf structure (Pontes et al., 2016b) (e.g., size, weight, appearance rate [Basso et al., 2010] and population density [Pitman, 2012]). Such changes result in higher herbage accumulation rates (Hoeschl et al., 2007; Lopes et al., 2013), herbage mass (Canto et al., 2013) and leaf mass (Pontes et al., 2016b). These factors ultimately provide a quantitative and qualitative increase in the herbage allowance (Liu et al., 2011; Fontes et al., 2014). Increased herbage intake—the variable most closely related to animal performance—has been observed in response to increased herbage allowances (Euclides et al., 2017).

Forage plants are highly responsive to N, which can elicit a linear increase in yield up to a dose of 600 kg ha^{-1} (Campos et al., 2016; Bernadi et al., 2018). As the N dose is increased, the opposite behaviour is seen in relation to fertilisation efficiency (Quaresma et al., 2011; Rowlings et al., 2016). A quadratic response may also be observed, whereby efficiency increases (Castagnara et al., 2011). In general, to achieve non-limiting N nutrition conditions, tropical grasses must be fertilised with 300 kg of N ha^{-1} yr^{-1} (Carvalho et al., 2013).

Nitrogen supply usually has little direct or indirect effect on the nutritional value of forage. Some studies have shown that increasing N fertiliser doses has little to no effect (Pitman, 2012), while others have observed an increase (Bartl et al., 2009; Pontes et al., 2016a) or reduction (Lima et al., 1999; Johnson et al., 2001) in the nutritional value of forage plants. These diverging results are linked to the plant's ability to absorb and accumulate N in its tissues (Pontes et al., 2016a; Pontes et al., 2016a) and the availability of the element in the soil (Luo et al., 2002).

Effect of nitrogen on animal production

In the presence of environmental resources, forage is produced (primary production), and this forage is consumed by the animal through grazing and converted into animal product (secondary production). This process is influenced by the animal's behavioural traits and by the nutritional and structural characteristics of the plant community (Carvalho et al., 2013). Nitrogen changes the plant community and leads to alterations in plant–animal interaction.

Stocking rates in tropical regions are generally higher or lower than pasture carrying capacity, which negatively affects forage production and animal performance (Carvalho et al., 2010). Intense or overly lenient grazing for long periods results in degradation, demonstrating the low sustainability of these systems (Lemaire et al., 2013; Euclides et al., 2019). To achieve maximum efficiency of primary and secondary production, it is essential to understand the complex interactions between plants and animals in intensive production systems.

Pasture productivity is the result of a combination of individual animal performance and stocking rate employed (Euclides et al., 2017). Individual performance, in turn, depends on the genetic potential of the animal, as well as the quality of the herbage and how it is supplied to the animal (Euclides et al., 2017; Euclides et al., 2018). Nitrogen fertilisation increases primary production (Bernadi et al., 2018) and changes grazing dynamics (Moreira et al., 2011), with a direct impact on individual secondary production and production per area (Pontes et al., 2016a).

Moreira et al. (2011), who investigated the production of cattle grazed continuously in *Brachiaria decumbens* pastures fertilised with N, reported no effects of N fertilisation on the average daily gain of beef steers. However, when the N fertilisation dose was increased from 75 to 300 kg ha^{-1}, the stocking rate rose by 32% and 28%, respectively, in the first and second years. A similar outcome was reported by Lupatini et al. (2013), who evaluated the performance of cattle in black-oat and ryegrass pastures fertilised with three N doses (0, 150 and 300 kg ha^{-1}) and found that stocking rate and live weight gain responded linearly to N levels.

Ribeiro et al. (2011) evaluated the effect of increasing N doses (75, 150 and 225 kg ha^{-1} N) on *Panicum maximum* cv. Tanzania (Tanzania grass) pastures in a continuous grazing system and did not detect changes in individual cattle performance. However, the researchers observed that stocking rate and gain per area were highest at the N dose of 225 kg ha^{-1}. Other authors have also reported positive results in the performance of cattle in response to N fertilisation (Canto et al., 2009; Pinheiro et al., 2014). It should be stressed that, in all of the above-mentioned cases, pastures were managed under the same grazing-target condition: 50% reduction in canopy height as defined by 95% light interception, which potentiates the effect of N.

Nitrogen and soil physics

The presence in the soil of essential nutrients in balanced quantities (fertile soil), coupled with biological characteristics, is fundamental for the development of any agrosystem. However, for soil to be considered productive, not only must its chemistry and biology be taken into account, but also the physical characteristics that indicate its degree of compaction (Haynes & Graham, 2004). Given the direct influence of animal trampling, the study of soil's physical attributes may be considered a key factor in the evaluation of soil quality in livestock systems (Stavi et al., 2012).

Soil density (SD) and the soil's mechanical resistance to penetration (penetration resistance, or PR) are the parameters most commonly used to evaluate soil's physical characteristics and degree of compaction (Torres et al., 2013). Soil structure is modified by animal trampling, which is influenced by interference with the pasture ecosystem (e.g., through pasture management and fertilisation) and time of year (Conte et al., 2011; Stavi et al., 2012). These changes affect primary and secondary production. When applying different management strategies in a production system, information about SD and PR is essential, since these variables are directly linked to pasture production and perenniality (Stavi et al., 2012).

Soil PR allows for inferences to be made about soil compaction at different depths. Among the physical variables of soil that can be evaluated, PR is admittedly the easiest to measure in terms of time and labour.

Furthermore, Chanasky and Naeth (1995) and Torres et al. (2013) reported that PR in livestock systems is more sensitive to animal trampling than other correlated variables and can thus be used to draw inferences about the soil compaction profile. A PR value of 2 MPa has been established as a criterion for plant development (Lapen et al., 2004), while a PR of 3 MPa has been used in forest soils (Zou et al., 2000). For soils planted with pasture, a PR of 2.5 MPa has been adopted as the limiting value for plant development (Leão et al., 2004).

SD is the property most widely used to quantify the physical quality of the soil of grazed pastures (Lanzanova et al., 2007; Fidalski et al., 2008; Torres et al., 2013). An SD of 1.40 g cm^{-3} in the soil of grazed pastures is considered restrictive to root growth and water infiltration (Souza et al., 2005). In such a system, PR and SD are closely related to animal trampling (Stavi et al., 2009). These effects are normally observed in the uppermost soil layers. During grazing, the pressure exerted by cattle weighing 500 kg can reach 0.50 MPa (Proffitt et al., 1993).

Studies of pasture-based animal production systems always seek ways of increasing yield in order to optimise financial and environmental resources. Recurrent practices used to attain these goals include intensifying production systems through management practices, using supplementation strategically, choosing more productive cultivars and using maintenance and N fertilisation. Nitrogen application both intensifies the production system and increases the probabilities of PR and SD being altered.

Sarmento et al. (2008a) evaluated the PR of an Argisol cultivated with *Panicum maximum* Jacq. cv. IPR-86 Milênio under intermittent grazing conditions as a function of different N doses (0, 150, 300 and 450 kg ha^{-1}). A higher PR was observed in soil fertilised with 300 and 450 kg ha^{-1} of the element. The authors attributed this finding to the higher stocking rate observed at those doses (Sarmento et al.; 2008a). Likewise, Bertol et al. (2000) reported that SD in the 0 to 5 cm layer increased from 1.1 to 1.4 kg dm^{-3} after the animal stocking rate was increased from 2.7 animals weighing 450 kg (AU) to 5 AU ha^{-1}.

The larger herbage accumulation in the pasture resulting from increasing N doses (Hoeschl et al., 2007; Campos et al., 2016; Bernadi et al., 2018) is responsible for this increase in the stocking rate, which in turn increases trampling. The effects of trampling on PR and SD can be minimised by adopting a rest period, which allows normal soil conditions to be re-established. In this regard, Lanzanova et al. (2007) investigated the effect of two rest periods (14 and 28 days) without animal grazing on an intercropped pasture of black oat and ryegrass. When a 14-day rest period was used, a 36.4% increase in the ungrazed system was observed. When the pasture was rested for 28 days, the increase was only 30%.

Gurgel (2019) examined the residual effect of N fertilisation on the SD and PR of soil in pastures planted with *Panicum maximum* cv. Mombasa (Mombasa grass) and grazed by beef cattle. Higher SD and PR values were observed in the uppermost layers (0 to 10 cm and 10 to 20 cm), regardless of the residual N dose. Although the stocking rate was 33% higher at the highest residual dose (300 kg ha^{-1}) as compared to the lowest residual dose (100 kg ha^{-1}), the authors observed no effect of residual N concentration on the soil's physical characteristics. This response was attributed to the pasture rest period of 25 days, which was sufficient to decompress the soil. These results demonstrate that, even in intensive production systems, adequate pasture management allows the soil to re-establish physical conditions that are ideal for the forage plant's development.

Effect of nitrogen on the root system

Forage grasses have a fasciculate root, which plays a primary role in functions related to plant development such as structural support and nutrient absorption. Root development is directly affected by nutrient availability, moisture (Sarmento et al., 2008b), physical characteristics of the soil and pasture management (Beloni et al., 2016).

Plant shoot responses to N are widely known; however, the same is not true for the grass root system. Moreover, results have been conflicting. Giacomini et al. (2005) evaluated the root growth of *Panicum maximum* cv. Aruana (Aruana grass) and Tanzania grass when subjected to two N doses (150 and 300 kg ha^{-1}). A larger root mass was found in Tanzania grass when it was fertilised with 300 kg ha^{-1} N compared to 150kg ha^{-1}; this difference was not observed for Aruana grass. A lack of response to fertilisation with increasing N doses was also reported by Soares-Filho et al. (2013) for Tanzania grass and by Beloni et al. (2016) for Mombasa grass. On the other hand, Sarmento et al. (2008b) observed a quadratic effect for variables related to the root system of *Panicum maximum* cv. Milênio fertilised with four N doses (0, 150, 300 and 450 kg ha^{-1}).

These inconsistent results have led to diverging discussions, which makes it difficult to understand root system dynamics as a function of N fertilisation. More sudden changes in the root system of forage grasses may be attributed to changes in pasture management practices that affect the leaf area index (LAI). When the LAI is substantially changed due to defoliation by animals, alterations are observed in the roots of forage plants (Bertol et al., 2000).

Because forage grasses have a root type that cannot reach great depths, their roots are concentrated in the uppermost layers of the soil (Beloni et al., 2016). The greatest root density is limited to a depth of 20 cm, where 50% of forage grass roots are found, regardless of pasture management practices or the chemical and physical characteristics of the soil (Sarmento et al., 2008b; Soares-Filho et al., 2013; Beloni et al., 2016; Barros et al., 2017).

Conclusion

Nitrogen fertilisation of tropical pastures promotes a considerable increase in primary and secondary production. Input of N into the system must be accompanied by other technologies that allow for maximum utilisation efficiency, such as pasture management practices that adjust for the stocking rate and suitable occupation and rest periods. In this way, SD and PR can be maintained at levels that allow for adequate water infiltration and root penetration into the soil. Pasture management is therefore a primary factor in controlling the physical characteristics of the soil and the root system of forage grasses, thus potentiating the positive effect of N.

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