CHAPTER 3

Maintaining soil fertility and health for sustainable pastures

Maria Lucia Silveira and Marta Moura Kohmann
Range Cattle Research and Education Center, University of Florida, Ona, FL, United States

Soil fertility programs for pastures

> ***The ultimate goal of a pasture fertility program is animal feed for the most economical production of meat or milk. It is unwise to try a maximum fertility program on a large scale until the grower has had sufficient experience to know that he/she can efficiently utilize the quantity and quality of feed produced.***
>
> **W.G. Blue**

Importance

Soil fertility management is one of the most important decisions that can affect pasture productivity and sustainability. Most pastures in the Southeastern United States are established on marginal areas usually associated with poor soil fertility conditions (i.e., low nutrient availability, acidic pH, limited nutrient, and water holding capacity). These soils often contain insufficient amounts of one or more essential plant nutrients which results in decreased forage production and overall pasture performance. Therefore, sustainability of productive perennial forage systems in the Southeastern United States depends, to a major extent, on well-planned, environmentally and economically sound soil fertility programs. Ideally, pasture fertilization strategies should be aimed at balancing production (including the amount and nutritive value of the forage produced) and nutritional requirement of ruminant animals. However, in most circumstances, fertilization represents the costliest input and it is often absent or limited to N application. This "minimum input" approach may not supply adequate amounts of nutrients to replace those removed with harvested forage, and consequently, may result in inadequate forage performance, stand degradation through loss of desirable species coverage, weed encroachment, an increase in bare area, and an overall reduction in soil health conditions.

The combination of low soil nutrient availability, efficient nutrient uptake by most forage species, and relatively high-yield potential create favorable conditions for obtaining positive responses to pasture fertilization. However, the fate of nutrients

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applied through pasture fertilization is extremely complex and is affected by several factors including application rate and timing, fertilizer source, and soil and environmental conditions. The key is to consider all the factors that affect fertilizer efficiency to achieve sustainable forage production while protecting the environment.

Environmental concerns associated with pasture fertilization

Pasture fertilization is a vital component of modern agriculture; however, it has the potential to induce eutrophication in surface waters. As nutrients accumulate in soils in response to excessive fertilizer, animal manure, or municipal waste application, nutrients (particularly N and P) may become susceptible to transport via surface runoff and subsurface leaching. Pasture fertilization continues to be a controversial and a topic of agronomic and environmental importance in various agricultural production systems. For decades, pasture fertility management was focused primarily on the agronomic aspects of crop and livestock production. However, because of growing concerns over accelerated water degradation through excessive nutrient input, current pasture fertilization strategies are generally aimed at balancing agronomic requirements, economic returns, and the risks of nutrient transport to surface water and groundwater.

Repeated application of fertilizers or organic amendments can result in excess nutrient input in the soil and subsequent transport to surface waters. In most freshwater systems, primary productivity is limited by inadequate levels of nutrients, primarily N and P. External nutrient inputs from surface runoff and groundwater discharge can dramatically increase N and P status of natural waters; thus, stimulating biological productivity and causing a general degradation of water quality. This phenomenon of nutrient enrichment in the aquatic system, also known as *eutrophication*, has been identified as the major cause of surface water impairment in the United States [1]. In addition to drinking water quality issues, eutrophication can also negatively affect algae, aquatic plant diversity and productivity, and water use for recreation and fisheries.

As livestock production continues to modernize and intensify, public concerns will increase the impacts of plant nutrients and organic contaminants on environmental quality. Best management practices that mandate reduced nutrient inputs will continue to be the main focus of water restoration programs and regulatory agencies in the Southeastern United States. Thus, cost-effective nutrient management strategies that optimize yields while protecting water quality are critical for the success of sustainable beef cattle operations in this region.

In addition to potential environmental problems, the increasing cost of commercial fertilizers has also prompted the need to reexamine optimum fertilizer application levels, sources, and methods of application that can sustain economic pasture productivity. In many regions, pasture fertilization represents the most expensive cost in beef cattle production and is often not a priority for beef cattle producers. However, lack of proper soil fertility management can reduce forage yields and have important economic implications for the profitability of livestock production operations [2]. Inadequate soil fertility management can, for instance, increase the cost associated with extra animal feed needed to overcome the unsatisfactory forage yields and nutritive value. Although the target or goals of production vary depending on a number of factors such as forage utilization (hay vs stocking), desired stocking rate, and animal category (cow—calf and/or stocker), the choice and selection of fertilizer source, application level, and frequency are often governed by availability and cost of product. Fertilization strategies are therefore driven mainly by production for a targeted dry matter response and by the need to sustain the pasture system.

Fertility management for harvested versus grazed pastures

Fertility management of warm-season grasses depends on the goals and objectives of production and costs of fertilizer. Harvested forages including hay, green chop, silage, and grain crop residue have similar fertility management as row crops. Because the majority of the crop residue is exported with the harvested forage, large nutrient removal rates occur in these systems, and relatively high fertilizer inputs are often necessary to maintain forage productivity. Nutrient removal rates vary considerably depending on the soil nutrient availability, crop species, stage of maturity, harvest procedure, and the number of harvests.

In grazing systems, a large proportion of nutrients is returned to the soil via animal excreta. Therefore, grazing management can have significant impacts on soil fertility status. Significant amounts of N, P, K, Ca, Mg, and micronutrients can be recycled to the soil via animal feces and urine deposition. An estimated 60%—99% of the P and K ingested returns to the soil through animal excreta [3,4]. Similarly, only 5%—30% of ingested N is used by livestock for meat and milk production [5]. Therefore, fertilizer requirements of grazed pastures can be considerably lower than in harvested forage systems. However, because grazing animals tend to defecate and urinate near water, shade, and feeding areas, excreted minerals are not evenly distributed across the landscape which imposes a major challenge. The unequal distribution of nutrients is not only undesirable in terms of forage management, but it may also result in environmental problems due to high concentration of nutrients in small areas.

Grazing management is important for improving nutrient distribution and availability in grazed pastures [4,6]. Rotational stocking with short grazing intervals often results in more uniform nutrient distribution than continuously stocked pastures [7—9]. Research has also shown that intensifying pasture use by increasing stocking rates significantly affects excreta distribution, nutrient cycling, and redistribution of nutrients in the soil [4,6,10,11]. Nutrients are mineralized at a greater rate from animal excreta than from plant material [12]; thus, nutrient recycling is often accelerated at high stocking rates where greater forage use results in less plant litter deposition. Grazing management that promotes more uniform distribution of nutrients via excreta can potentially reduce fertilizer requirements while also reducing risks associated with nutrient buildup in the soil when adequate stocking rates are used [3,13].

Factors such as daily temperature and animal type may also affect animal grazing behavior, and consequently, nutrient redistribution in pastures. For example, nutrient distribution in a pasture may change with livestock tolerance to solar radiation, particularly in warm climates. Cattle breed and coat color may interact with environmental conditions and can affect pasture utilization and nutrient redistribution patterns [14,15]. Because there is a positive relationship between time spent in a particular pasture area and the number of excretions [16], it is likely that the more time cattle spend under shade, the greater the nutrient concentration will be in that area, and less excreta will be deposited on other pasture areas. These graze and rest behavioral traits also correlate with increasing air temperature or the temperature—humidity index [17].

Another important pathway for nutrients to be recycled in grazed pastures is through the plant material. Grazing animals and plant litter are not a source, but rather a pathway by which nutrient recycling is redistributed into the system. Senescent above- and belowground plant material is returned to the soil, forming part of the soil organic matter. The relative contribution of plant litter versus animal excreta in terms of nutrient cycling will depend on the stocking rate. Under high stocking rates, more nutrients are recycled through animal excreta, while at low stocking rates, nutrient turnover through plant litter may be favored [12,18].

Nutrient returns from senescent litter are more uniformly distributed than returns from animal excreta. However, only minimal amounts of nutrients are expected to derive from litter recycling in intensively -managed pastures relative to that of urine and dung [19]. Because of the chemical characteristics of tropical grasses (including high lignin content), litter of tropical grass pastures decomposes more slowly than that of temperate grasses. A major factor that affects litter decomposition is the carbon to nitrogen (C:N) ratio. Because warm-season grasses normally exhibit low tissue nitrogen concentrations, their C:N ratios tend to be greater than those of cool-season (temperate) species. Under high C:N ratios ($>30:1$), the microorganisms decomposing the litter "compete" with pasture plants for soil nutrients. This process is known as nutrient immobilization, and it is often associated with N deficiency and subsequent pasture degradation through reduced forage production, nutritive value, and, ultimately, pasture persistence. Pasture management strategies that improve litter quality, such as N fertilization or the use of legumes, can promote litter decomposition and increase nutrient availability to the forage [12].

Soil and tissue testing

From both agronomic and environmental perspectives, it is critical to understand the amounts and forms of nutrients present in the soil. The primary objectives of evaluating soil fertility levels are to: (1) determine the nutrient needs of the plant, with management strategies that meet dry matter production goals for hay or grazing; and (2) provide opportunities for efficient use and recycling of nutrients for economic and sustainable pasture production. Soil testing is the best management tool for monitoring soil fertility levels [20] and providing baseline information for cost-effective fertilization programs that meet forage nutrient requirements and minimize production costs. Routine soil tests can identify nutrient deficiencies and inadequate soil pH conditions that may negatively affect forage production. Soil tests also indicate which nutrients are present at adequate levels in the soil which provides an opportunity to avoid unnecessary addition of soil amendments. Applying only the required fertilizers results in cost savings and can also minimize off-site losses of nutrients and associated environmental problems.

A major limitation associated with soil testing is that it typically accounts for the plant available nutrient pool present in the surface (0–4 or 6 in.) soil layer. However, the subsoil can be an important source of water and nutrients, particularly in perennial forage systems, in which plant root systems can explore deeper soil depths. In addition, some nutrients are highly mobile in the soil and can easily leach into the subsoil resulting in nutrient accumulation in deep soil depths.

Plant tissue analysis is widely used as a diagnostic tool for assessing the nutrient requirement of crops [21–23]. This procedure involves the determination of nutrient concentrations from a particular part or portion of a crop, at a specific time and/or stage of development. Unlike soil analyses which relate soil-extracted nutrients to plant response, plant analyses usually give an indication of nutrient availability to the crop. Because of its extensive root system, plant analyses are believed to better assess the overall nutrient status of perennial forages while also revealing imbalances among nutrients that may affect crop production.

The application of plant tissue analysis to plant nutrition revolves around the concept of a critical nutrient concentration in the plant determined from calibration curves. The critical tissue nutrient concentration of a particular crop has been defined as the nutrient concentration corresponding to 90% of maximum yield [24]. Plants with tissue nutrient concentration above the critical concentration are adequately supplied with nutrients; whereas those with nutrient concentrations lower than the critical level are considered deficient and prone to respond to fertilization.

Critical nutrient level is affected by a number of factors including forage crop species, plant part used for the analysis, physiological growth stage [23,25], harvest or grazing management, mobility of that particular nutrient in the plant, soil moisture, temperature [26,27], and seasonality [28,29]. Since various factors can influence crop tissue concentrations, tissue testing should be used with caution and in conjunction with a routine soil testing program.

Recent reports from Florida have shown that when plant tissue analysis is used in combination with soil testing, it has the potential to be a useful diagnostic tool for developing nutrient management programs that predict when crops need additional nutrients while avoiding unintended impacts of excess fertilization on the environment [30]. Plant tissue analysis is currently being used in Florida in association with soil testing to guide P fertilization of established bahiagrass (*Paspalum notatum* Flügge) pastures.

Liming and fertilization of warm-season forage crops

> ***Soil acidity and fertility management are critical for grasses and legumes production on Coastal Plain soils of the southern and southeastern US. Acidity must be counteracted by limestone treatment of the soil to improve the environment for bacterial growth and activity, increase nutrient use efficiency, and reduce toxic levels of soil Al and possibly Mn.***
>
> **Vince Haby**

Essential nutrients

A total of 17 elements are considered essential for plant growth. These include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), iron (Fe), chlorine (Cl), and nickel (Ni). C, N, and O are obtained from the air and soil water, while the other 14 are supplied by the soil. N, P, and, K are considered primary nutrients because they are taken up by plants in the largest amounts. Ca, Mg, and S are considered secondary nutrients and are taken up in the next largest amounts. Fe, Mn, Zn, Cu, B, Mo, Cl, and Ni are required by the plants in very small amounts and are known as micronutrients. Regardless of the class to which they belong, all essential nutrients are equally important for plant growth.

Nitrogen is often a limiting nutrient in perennial pasture systems in the Southeastern United States. It can be supplied to pastures as commercial fertilizer, animal manure, or organic amendments. Biological fixation of atmospheric N by forage legumes can also provide adequate amounts of N to sustain forage and livestock production. P and K can be included in fertilizer blends and applied along with N. Sulfur is often associated with N and P fertilizers (i.e., ammonium sulfate and triple superphosphate), while Ca and Mg are usually supplied to forage crops through liming. Micronutrients are typically present in adequate amounts in the soil and are seldom applied to forage crops. However, under high soil pH conditions ($\mathrm{pH} > 7$), Fe and Zn may become limiting [31]. Conversely, under acidic conditions ($pH < 4.5$) some elements such as Al and Mn can become toxic to the plants.

Nutrients can be provided to pastures through different sources and application methods. This section of the chapter is intended to provide a brief summary overview of the most important aspects of soil fertilization management for perennial forage crops.

Managing soil acidity

Maintenance of adequate soil pH is an extremely important step in soil fertility programs for forage crops. Soil pH is one of the most important soil properties that controls nutrient availability to plants, root development, and fertilizer efficiency. Optimum soil pH promotes better root growth, which, in turn, results in more efficient fertilizer and water utilization by the plants [32,33].

> ***Coastal bermudagrass root weight per acre remained at a high level while nitrogen content of the roots and organic matter content of the soil increased slightly as fertilizer nitrogen rates increased from 0 to 1600 pounds per acre. Hay yields were greatly increased... from 1 to 11 tons per acre of dry forage... with the same treatments resulting in an 8-fold change in the root-top ratio.***
>
> **Ethan C. Holt and F. L. Fisher (1960)**

Coarse-textured Coastal Plain soils often exhibit low pH and are considered “acidic,” and lime or limestone is frequently applied to raise soil pH. Lime also serves as a primary source of Ca and Mg to pastures. Forage yield decline in response to soil acidity is commonly associated with toxicity of Al and Mn and low availability of essential nutrients. By raising the soil pH (desirable range of 5.5–6.5), macronutrient (i.e., N, P, and K) availability can also increase [34]. Conversely, at high soil pH (> 6.5) micronutrients become less available. With the exception of Mo, micronutrient availability decreases as soil pH increases [35,36]. Therefore, it is important that adequate amounts of lime are applied to the soil to increase the pH to a desirable range. Excessive lime application may cause nutrient imbalances and micronutrient deficiency. Excessively high or low soil pH can reduce root growth and crop ability to utilize nutrients and water, and consequently, impact forage production. Repeated applications of lime-containing soil amendments such as lime-stabilized biosolids can increase soil pH to excessively high levels that can reduce forage productivity.

Lime recommendations are based on soil test results and are specific to each soil type and forage species. For instance, cool-season legumes require higher soil pH levels than warm-season perennial grasses (Table 3.1). Forage grasses commonly cultivated in the Southeastern United States are relatively more tolerant of acidic soils than cool-season grasses. Recommended soil pH varies from 5.5 or greater for warm-season perennial grasses such as bahiagrass, bermudagrass, and limpograss [*Hemarthria altissima* (Poir.) Stapf & C.E. Hubbard] to 6.5 or greater for cool-season legumes or

Table 3.1 Target pH for different forage crops grown on mineral soils.

Crop category	Crops included	Target pH
Warm-season perennial grasses	Bahiagrass, bermudagrass, stargrass (*Cynodon nlemfuensis*), limpograss (Hemarthria *altissima*), Rhodes grass (*Chloris gayana*), and digit grass (*Digitaria eriantha*)	5.5
Warm-season annual grasses	Corn (*Zea mays*), sorghum (*Sorghum bicolor*), sorghum-sudans, and millets *(Pennisetum glaucum)*	6.0
Warm-season legumes or legume–grass mixtures	Perennial peanut (*Arachis glabrata*), stylo (*Stylosanthes guianensis*), desmodiums (*Desmodium spp.*), aeschynomene (*Aeschynomene virginica*), alyceclover (*Alysicarpus vaginalis*), hairy indigo (*Indigofera hirsute*), and other tropical legumes	6.0
Cool-season annual grasses	Small grains and ryegrass (*Lolium spp.*)	6.0
Cool-season legumes or legume–grass mixtures	All true clovers (*Trifolium* spp.) (white, red, arrowleaf, crimson, subterranean), vetches (*Vicia sativa*), lupines (*Lupinus sp.*), and sweet clover (*Melilotus officinalis*)	6.5
Alfalfa	Alfalfa (*Medicago sativa*)	7.0

Adapted from R.S. Mylavarapu, D. Wright, D.G. Kidder, UF/IFAS standardized fertilization recommendations for agronomic crops. Florida Cooperative Extension Service, IFAS, University of Florida, SL 129. <http://edis.ifas.ufl.edu/ss163/>, 2015 (accessed 22.06.18).

legume–grass mixtures (Table 3.1). Rye (*Secale cereale* L.) is generally more tolerant of soil acidity and associated Al toxicity when compared to other small grain species [37]. Multiple genes condition resistance to Al toxicity in rye through mechanisms that include the release of organic anions from the roots [38].

Forage responses to lime application can vary considerably. While several studies showed positive bermudagrass yield response to lime application in acidic soils [39–41], others reported no effect [42,43]. Similar contrasting results have also been observed for other forage species. In a 4-year field study, Adjei and Rechcigl [31] observed a 30% decrease in bahiagrass yield when forages were fertilized in the absence of lime. Additionally, these authors observed that repeated N fertilizer applications in the absence of lime decreased root/stolon mass and created favorable conditions for mole cricket and weed infestations. However, in an earlier study [44], bahiagrass did not respond to the addition of calcitic lime, even when the initial pH was as low as 4.5.

Recommended lime application rates are also affected by soil chemical and physical properties. Soils with high buffering capacity (high clay and organic matter concentration) require more lime to reach the target pH than soils of similar pH and low buffering capacity. In general, sandy soils have lower buffering capacities than loamy soils, and thus require less lime to increase the pH. However, soils with lower buffering capacities require more frequent lime applications to maintain pH. Most soil testing laboratories include some type of estimate on soil buffering capacity when making a ground limestone recommendation.

The most common liming materials are dolomitic and calcitic limestone, calcium and magnesium oxide, slag, sludge, and wood ashes. Since the solubility of these materials is often very limited, they are typically applied 3−6 months prior to seeding or fertilization for the targeted production goals [45]. The reactions that take place in the soil when lime is applied will only occur in the presence of water and acidity. If soil moisture is not adequate, the positive effects of lime in neutralizing soil acidity will be very limited.

The quality of the lime material is expressed in terms of effective calcium carbonate equivalent (ECCE). The ECCE of lime materials is affected by two main factors: (1) fineness of the material or particle size, and (2) chemical purity. The physical composition of liming materials is defined by the percentage of the materials that pass through 10-, 60-, and 100-mesh sieves. Finely ground materials normally neutralize soil acidity faster than coarse liming materials [45]. Materials that contain a range of particles may be desirable when soil pH is not required to be increased in the short term. The moisture content should also be considered when selecting liming materials. Liming materials with greater moisture content may be more difficult to apply in the field.

In addition to the fineness of the material, the chemical composition and percentage of impurities will also impact the effectiveness of liming materials. The purity of the liming material is measured by the calcium carbonate equivalence (CCE). A material with CCE of 100% is equivalent to pure calcium carbonate. Some examples of CCE of various liming materials are shown in Table 3.2.

Lime recommendations vary from laboratory to laboratory based upon assumptions regarding ECCE and state lime laws. If a recommendation is made based on lime material that has 100% ECCE, the rate should be adjusted by dividing the recommended rate by the actual ECCE of the material.

Table 3.2 Calcium carbonate equivalence (CCE) of various liming materials.

Material	CCE (%)
Pure calcium carbonate	100
Calcitic lime	75−100
Dolomitic lime	75−109
Hydrated lime	120−136
Burned lime	179
Wood ash	30−70

Nitrogen fertilization

> ***Increasing the nitrogen rate from 0 to 900 pounds per acre annually increased hay yield, protein percentage, protein yield, stem length, leaf length, internode length and internode number in Coastal Bermudagrass; but decreased leaf percentage, seed-head frequency, and percentage nitrogen recovery.***
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> **Gordon M. Prine and Glenn W. Burton (1956)**

Nitrogen is a key nutrient that affects forage production, nutritive value, and sustainability of forage-based systems. Nitrogen application rates vary considerably depending on the region, forage species, management, and economic return, and are generally calculated based on expected yields. Crop removal (e.g., hay crops) and stocking rate are important variables that should be considered when choosing N fertilization levels.

Early reports in the literature suggest that Coastal bermudagrass may respond to N application at rates up to 1000 lb N/acre per year [46], with a linear yield response to N up to ~550–620 lb N/acre per year [47]. In the early 1950s, research demonstrated that application of 400–800 lb N/acre per year resulted in Coastal bermudagrass yields of ~9.8 and 10.7 tons/acre, respectively [48]. Similarly, Wilkinson and Langdale [49] demonstrated that Pensacola bahiagrass responded to as much as 600 lb N/acre per year. Blue [50] showed that bahiagrass yield increased as N increased to 360 lb N/acre per year. Research in Florida reported stargrass yield responses to N application of 180–360 lb N/acre per year [51]. Although yields may increase at increased N rates, high levels of N application are neither economical nor environmentally sustainable in most forage-based animal production systems. At present, levels of ~60–80 lb N/acre are typically applied to established grass swards in Florida [52]. Higher N levels (up to 80 lb N/acre per harvest) are often associated with intensive hay production systems [53]. These high N rates do not take into consideration N recycling in pasture through animal excreta or litter decomposition.

Management of inorganic and organic nitrogen fertilizer sources

Ammonium nitrate has been the predominant N fertilizer source used on pastures in the United States. It typically contains between 33% and 34% N, and despite its relatively high solubility in water, is stable under adequate storage conditions. When applied at agronomic rates, ammonium nitrate does not produce as much acidity as other N fertilizer sources (i.e., ammonium sulfate). In addition, the salt index (a measure of the salt concentration that the fertilizer produces in the soil after its application) of ammonium nitrate is 2.99, indicating that there is limited probability of ammonium nitrate to cause burning problems in the pastures.

Ammonium sulfate is another common N fertilizer source used in pastures in the Southeastern United States. It contains between 20% and 21% N and approximately

24% sulfur. Repeated application of ammonium sulfate can significantly increase soil acidity [54]; therefore, it is important to monitor soil pH after repeated applications of ammonium sulfate. An advantage of ammonium sulfate is that in addition to providing N, this fertilizer can also provide adequate amounts of S, which is an essential nutrient for forage grasses. Ammonium sulfate has a salt index of 3.25, which may result in temporary forage damage due to burning when applied at extremely high rates. However, when applied at adequate rates, the potential of ammonium sulfate to cause injury in forages is negligible.

Urea has become a popular N source due to the high N concentration ($\sim 46\%$) and consequent lower cost associated with transport. Urea can be applied to pastures as a solid or as a solution via foliar spray. After application to the soil, urea first reacts with water and is converted to ammonium bicarbonate (NH_4HCO_3). In soils that exhibit high pH (> 6.5), ammonium bicarbonate can be further converted to ammonia gas (NH_3). Under these circumstances, significant amounts of N can be lost via ammonia volatilization. Compared to ammonium nitrate and ammonium sulfate, urea produces less acidity and typically does not affect soil pH significantly.

While plants may benefit from soluble nutrients present in inorganic fertilizer sources, a significant fraction of these nutrients may be lost before the plants have a chance to utilize them. Most commercial inorganic fertilizers should be applied when the forage is actively growing, preferably at the beginning of the season (early spring). Mid-season or late fertilizer application normally occurs for stockpiled forage production. For the establishment of new plantings, fertilizer is not recommended to be applied until plants have emerged. In harvested foraged systems, N and K are typically applied after each cutting according to soil type and soil test recommendations.

Different fertilizer technologies have been developed recently to increase crop nutrient uptake. These include slow-release fertilizers and fertilizer materials that contain urease or nitrification inhibitors [55–57]. Slow-release N fertilizers can be classified into two categories: (1) chemical compounds with inherently slow rates of dissolution; and (2) N fertilizers provided with a coating that acts as a moisture barrier. Sulfur-coated urea, urea form, and polymer-coated fertilizers are examples of slow-release N fertilizers. Only a small proportion of the pastures in the Southeastern United States receive slow-release fertilizers; however, there has been an increasing interest in these fertilizer forms because of their potential to reduce the environmental impacts of N fertilization. Although slow-release N fertilizers are believed to increase the synchrony between N release from the fertilizer and crop requirements, limited science-based data on how forage crops respond to these N sources are currently available.

Organic fertilizer sources such as biosolids and animal manure represent important sources of N that can be used in pastures, but the majority of N present in organic sources is not readily available to plants. As the organic compounds mineralize, N and other essential nutrients become available. Therefore, time and rate of application are critical factors that can impact the effectiveness of organic sources for providing N to pastures. In addition, organic sources typically contain excessive P concentrations than is required by the forage when application is based on N due to the lesser ratio of N:P in the manure compared to crop demand [58]. In general most manures have an approximate N:P_2O_5 ratio of 1:1, while plants generally take up at least five times more N than P_2O_5. Therefore, supplying N to the plants via organic sources often results in excessive phosphorus application rates. While manure application based on crop P requirements may reduce excess P accumulation in the soil, it results in smaller manure application rates and larger land area required for manure disposal [59], as well as the need for supplemental N application via commercial fertilizer.

Total nitrogen is often a poor indicator of N availability from organic amendments. For example, nitrogen availability of beef cattle manure has been shown to be about 40% of the total manure N applied in the first year, compared to 90% for swine manure, 50% for dairy manure, and 75% for poultry manure [60]. These differences are often related to the amount of total N present as ammonium N, urea N, or organic N in the manure. In addition to nutrient availability, factors such as source, time and rate of application, and environmental conditions can impact the effectiveness of organic materials in providing N to pastures.

Management of organic fertilizer sources such as animal manure, broiler litter, or biosolids is more complex than that of inorganic fertilizers, primarily because the nutrient composition of organic sources is extremely variable, and not all nutrients are available immediately for plant uptake. Organic fertilizer strategies that synchronize rate of nutrient mineralization and crop demand result in greater manure utilization by plants and reduce losses of nutrients to the environment [61]. However, predicting and achieving this goal for organic fertilizer sources has proved elusive. Choice of fertilizer source will ultimately rely on goals in production, environmental and regulatory constraints, cost, and availability of materials.

Nitrogen inputs through forage legumes

While N fertilizer is a costly energy input and a potential source of environmental contamination when improperly managed, atmospheric N_2 may be efficiently fixed by legume species and may be a reasonable economic and environmental alternative for providing N to grass pastures [62]. In addition, while synthesis, storage, transfer, and application of N fertilizers result in considerable emissions of CO_2 primarily from fossil fuels, N derived from biological fixation is C neutral [63,64]. Nitrogen fixed by legumes can be efficiently transferred to companion or succeeding grasses through animal excreta and legume plant decomposition [65]. Nitrogen-fixing legumes provide adequate N supply for pasture growth [66–68], increase forage nutritive value [69,70], extend the stocking period [65], and enhance animal performance compared to grass monoculture [65,71,72]. Pasture systems using N-fixing legumes can also produce forage with high cumulative nutritive value and is often an economically viable management option to livestock producers in the United States [73,74]. Application of N fertilizer to swards containing over 50% legumes is rarely considered because of the cost and potentially detrimental impacts on legume persistence [75,76].

The amounts of legume N transferred to the forage grass and the predominant pathway of this transfer are variable (<18–180 lb N/acre per year) and depend on the species, cultivar, soil fertility conditions, and proportion of legume if cultivated with non-N-fixing species [65]. Dubeux et al. [77] reported that rhizoma peanut (*Arachis glabrata* Benth.) cultivars in monocultures fixed between 100 and 250 lb N/acre per year. When cultivated in mixtures with bahiagrass, Santos et al. [78] found that rhizoma peanut fixed an average of 12 lb N/acre per harvest (~36 lb N/acre per year) compared with 27 lb N/acre per harvest (~81 lb N/acre per year) in monoculture. Nyfeler et al. [79] reported that in legume (red clover [*Trifolium pratense* L. cv. Merviot] and white clover [*Trifolium repens* L. cv. Milo])–grass (perennial ryegrass [*Lolium perenne* L. cv. Lacerta] and orchardgrass [*Dactylis glomerata* L. cv. Accord]) mixtures fertilized with 45, 134, or 400 lb N/acre, N fixation activity was reduced when legume proportion was above 40% or at the higher N fertilization level. They also reported that the presence of grasses increased atmospheric N uptake through symbiosis in the legume, with N yields equal to that of legume monocultures when legume proportion was between 40% and 65% in mixtures with grasses. Evaluating similar treatments, Nyfeler et al. [80] also showed that forage mass in grass–legume mixtures with 50%–70% legumes was equivalent to that of grass monocultures fertilized with 450 lb N/acre. Nyfeler et al. [79] reported that perennial ryegrass and orchardgrass root density and N acquisition were greater in grass–legume mixtures compared with grass monocultures. The authors suggested the positive effects of the mixture were the result of mutual stimulatory effects on N acquisition of the grass and legume component of the mixture. Morris et al. [67] reported that active transfer from arrowleaf clover (*Trifolium vesiculosum* Savi.) to annual ryegrass was less than 5 lb N/acre as measured by isotope dilution using ^{15}N-depleted ammonium nitrate. In mixtures of alfalfa (*Medicago sativa* L.) and bermudagrass, the active transfer from legume to grass was about 16 lb N/acre [81].

The predominant pathways of N transfer from legumes to grasses are through decomposition of legume plant residue, excreta from grazing animals, and subsequent N mineralization. Decomposition of belowground biomass from legumes is a significant N input source. Dubach and Russelle [82] demonstrated that while decomposing nodules are the main source of belowground N transfer in birdsfoot trefoil (*Lotus corniculatus* L.), alfalfa inputs to soil N come mainly from fine root decomposition. In an experiment conducted in pots with stylosanthes (*Stylosanthes guianensis* cv. Mineirão) and brachiaria mixtures (*Brachiaria decumbens* cv. Basilisk), transfer of legume N from belowground biomass to grass was significant only after aboveground biomass was removed, but not while both plants were growing concomitantly [83].

Potassium and phosphorus fertilization

Potassium is an essential nutrient for forage production required by plants in greater amounts than any other nutrient except N. Despite its important roles, however, pasture K fertilization has received much less attention than N. In most forage production systems in the Southeastern United States, K is not supplied at adequate levels to replace that which is removed with harvested forage. Intensively managed hay production systems are particularly prone to K deficiency because of the relatively high amount of K removed with harvested forage. Several studies reported significant bermudagrass yield increases in response to K fertilization. For instance, Slaton et al. [84] observed a ~20% bermudagrass yield increase in response to K application (at annual levels of 89 lb K_2O/acre) compared to control (no K application) treatments. In a 4-year study in Texas, Haby et al. [85] observed a 22% bermudagrass yield increase when K was applied at 134 lb K_2O/acre compared to zero K application. Nelson et al. [86] observed a 50% yield increase of bermudagrass when K was annually applied at 170 lb K_2O/acre on a fine sandy loam soil in east Texas. Similarly, Snyder and Kretschmer [87] demonstrated that limpograss and bermudagrass forage accumulation decreased linearly as K fertilization level decreased. In addition to yield increases, many studies have demonstrated that adequate levels of soil K reduce bermudagrass winter injury and increase survival after freezing temperatures [88,89].

In addition to the negative impacts on forage production, K deficiency has also been linked to reductions in stand integrity and increases in pest and disease incidences [90,91]. Several studies have demonstrated the important role of K fertilization on rhizome production, root development, stand persistence, and plant resistance to disease and pest injury [92–94]. These reports suggested that first visual signs of stand decline due to K limitation were more frequently observed in the initial spring regrowth.

Because of the sandy nature and low cation exchange capacity of most coastal soils of the Southern and Southeastern United States, these soils often exhibit limited ability to retain K even after receiving K fertilization. Therefore, the repeated application of K is often required to meet plant requirements. Potassium application rate, frequency, and time of application are important considerations for pasture production in the Southeastern United States. Soil test along with tissue analysis can provide a good estimate of K status. Reports in the early 1970s suggested that Coastal bermudagrass required between 200 and 400 lb K_2O/acre per year. Corroborating these early studies, Robinson et al. [95] observed maximum bermudagrass yields at the 300 lb K_2O/acre rate. However, despite the positive impacts on bermudagrass production, these relatively high K application rates are likely not economical in many production systems. Similarly, maintaining soil test K at medium or higher levels can be expensive and difficult to achieve in coastal plain soils in the Southeastern United States. On the other hand, extremely low K supply may also represent an economic risk, and efforts should be focused on replacing K removed with harvested forage.

Although forage response to P fertilization is typically less than that of N and K because of the lower crop P requirement as compared to the other primary macronutrients [96], adequate supply of P is critical for establishment and maintenance of productive warm-season grass stands. Reduction in forage accumulation due to low P supply has been documented in several previous studies. For instance, Adjei et al. [97] reported a linear decrease in limpograss herbage accumulation as P fertilization levels decreased. However, the extent of warm-season grass responses to P fertilization varies considerably depending on the forage species, soil type, and management history [97]. Because N fertilization has the greatest potential to increase herbage accumulation, greater levels of N fertilization can also increase P requirements of forage crops [96,98]. As soil P reserves become more depleted, marginal crop responses to added N (or any other nutrient) are expected to occur [96]. Similarly, although P fertilization is not expected to have direct impacts on forage nutritive value, reduced N use efficiency due to P deficiency may, in turn, decrease forage nutritive value.

Organic fertilizers such as animal manure and biosolids can be used to provide P and K to forages. Immediately after application, N availability in organic fertilizers is between 40% and 90% of total N. The remaining N requires a mineralization process to become available to plants; however, K and P are typically more readily available for plant uptake at the time of application. The P availability is about 82% of the total P in applied beef cattle manure [60], and this relatively high availability is due to a large portion of total P (60%–90%) being in the inorganic form [99]. Availability of K is close to 100% for manure of several animal species [60] and similar to that of K fertilizer because K is rarely tied up as inorganic or organic compounds in the plant cells. Similar to N fertilization, the concentration and availability of P and K present in the amendment should be taken into consideration when planning organic fertilizer application to maximize nutrient use efficiency by plants as well to avoid detrimental effects to the environment.

Managing soil health for pasture sustainability

Definition

In the past 50 years, significant scientific effort toward improving crop productivity was directed to soil and nutrient management based on standardized soil testing procedures to predict the availability of essential nutrients to the plants. Routine soil testing, for instance, was designed to estimate plant nutrient availability for optimal forage production, and to diagnose potential nutrient deficiencies and suboptimal soil pH conditions that may negatively affect crop production. Soil testing was also intended to determine nutrients that were present at adequate levels in the soil; thus, providing an opportunity to eliminate unnecessary soil amendment applications. For decades, soil test reports have been used to predict the likelihood of obtaining a positive crop response from the application of the nutrients tested. However, recent evidence suggests that in certain circumstances, a standard predictive soil test alone may be a poor predictor of nutrient requirements and particularly for perennial pasture systems where the root system can extend beyond the top 4–6 in. of soil that are typically tested. Similarly, assessment based on routine soil test indices often poorly reflects the impact of grazing and nutrient management on soil properties.

Maintaining a healthy and productive soil is the foundation of sustainable agriculture. To address the concerns and limitations associated with routine soil testing, scientists and land managers in recent years have looked for new tools that can provide an overall assessment of soil's ability to sustain crop production. In this context, the concept of "soil health" was developed to provide a more holistic view of soil management. The term soil health refers to the ability of soils to support specific functions such as nutrient cycling, regulating water, filtering and buffering potential pollutants, and so forth. According to the USDA Natural Resource and Conservation Service, soil health is defined as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans." Soil health has also been defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental health, and promote plant and animal health [100].

Soil health also influences crop resilience to extreme climatic events, and it can directly impact local jobs and the economic stability of rural communities. Soils can also support other important functions such as environmental protection, biodiversity habitat, water relations, and waste recycling. Additionally, soils mediate many ecological processes that can have important and direct impacts on the global water cycle and climate. Although economic factors may limit the extent to which soil health concepts can be adopted at a farm scale, there is a growing recognition that agriculture, and more specifically soil management, can provide much more than food, fuel, and fiber. Critically important ecosystem services offer a potential for society to recognize farmers and land managers for the true value they provide.

Soil health indicators

Indicators of soil health provide information about how the soil is functioning with respect to a particular management goal or ecological role. Since a specific soil function may involve several processes, and each process may be associated with a combination of soil chemical, physical, and biological properties, the exact number of properties measured to assess soil health may, therefore, vary considerably. Similarly, because many soil properties that contribute to soil health are interrelated, no single soil attribute can be used as a measure of soil health.

Significant efforts are currently being placed on identifying soil properties for the determination of soil health. Researchers have developed a wide range of soil health assessment methodologies. These often include a combination of physical, chemical, and biological properties such as soil organic matter, texture, water holding capacity, and extractable essential nutrient concentrations. Ideal soil health indicators should: (1) be easy to measure; (2) measure changes in soil functions; (3) encompass chemical, biological, and physical properties; (4) be accessible to many users and applicable to field conditions; and (5) be sensitive to variations in climate and management.

Universal calibration of soil health indicators is not possible; therefore, interpretation of soil health assessments must rely on comparative data. Similarly, soil health indicators will vary depending on the soil type, management goal, region, and cropping system; therefore it is critical that soil health indicators be developed at a local/regional scale so that they are relevant to the area of interest. Likewise it is expected that soil health indicators for perennial pastures will likely be different than those commonly used for grain crops in the Midwestern United States. In addition, the coarse texture of most coastal plain soils and their intrinsic limited nutrient holding capacity associated with low organic matter levels suggest that sensitive soil attributes that can distinguish differences in soil health under different pasture management scenarios will likely be unique to the Southeastern United States. Research is needed to develop and validate a soil quality framework for guiding pasture management decisions and monitoring their outcomes.

Soil organic matter

A number of soil properties may serve as indicators of soil health. Some of these properties are descriptive and can be measured directly in the field. Others must be measured using laboratory analyses. Because some properties such as soil texture and depth are inherent of a particular soil type, they are not affected by soil management. Others, however, can be reversed and/or improved through the adoption of proper soil management strategies. Soil organic matter has been long recognized as an important indicator of soil productivity and ecosystem sustainability. Soil organic matter is essential to diverse soil functions and ecosystem services and plays an important role in improving soil physical, chemical, and biological properties. Maintenance of adequate levels of organic matter in the soil have been linked to reductions in soil degradation [101] and overall improved soil health conditions [102]. Likewise, soil organic matter has been suggested as the single best integrator of inherent soil productivity and a useful indicator of soil health. Although there is no threshold level of soil organic matter below which crop productivity can be negatively impacted, soil organic matter loss is of concern because it may also adversely affect other important soil properties.

Until recently, the importance of maintaining (or preferably increasing) soil organic matter in pastures was underestimated compared with the use of fertilizers and lime. Therefore, knowledge of soil organic matter levels in perennial pasture systems and the impacts of management on soil organic carbon dynamics is limited. Although pasture management strategies (e.g., fertilization strategy and grazing management) are generally aimed at increasing forage production to match animal stocking rates or forage demand for hay, a significant body of the literature demonstrated that pasture management can also promote soil organic matter accumulation [103–106]. In fact, most techniques used to improve forage production promote carbon inputs to the soil and increase soil organic matter accumulation. For instance, fertilization, irrigation, grazing management, fire regimen, introduction of legumes, and use of improved grass species can boost plant productivity while promoting soil carbon sequestration. Studies have shown that when low-fertility soils receive fertilizer or lime, forage productivity and soil carbon levels generally increase [105,107]. Research also shows that grazing intensity can have major impacts on soil carbon accumulation. Although overgrazing is often associated with reductions in soil carbon concentrations, proper grazing management can result in greater soil carbon concentrations than nongrazed systems. Well-managed grazing lands generally maintain or even increase soil carbon accumulation compared with native ecosystems. Also, livestock benefit from well-managed lands because the grass usually has higher nutrient concentrations due to proper fertilization. Opportunities for increasing soil organic matter accumulation in response to management practices vary in intensity and are specific to each ecosystem.

Conclusion

The sustainability of productive perennial forage systems in the Southeastern United States depends, to a major extent, on well-planned, environmentally and economically sound soil fertility programs. Soil pH controls nutrient availability to plants, root development, and fertilizer efficiency; thus, maintenance of adequate soil pH should be the first strategy to improve soil fertility conditions. Fertilizer recommendations vary considerably depending on the production system, forage species, soil type, and climatic conditions. The choice of fertilizer application rate and source should be based on both the production goals and routine soil and tissue testing.

The recycling of nutrients and harvest management can have significant impacts on soil fertility status. Mechanically harvested forage systems including hay, green chop, silage, and grain crop residue have similar fertility management as row crops; however, because a large proportion of nutrients in grazing systems is returned to the soil via animal excreta, the use of fertilizer can be reduced. Grazing management that promotes more uniform distribution of nutrients via excreta can potentially reduce fertilizer requirements while also reducing risks associated with nutrient buildup in the soil.

In addition to increasing forage herbage accumulation and nutritive value, soil fertility strategies can also affect soil chemical, physical, and biological properties; therefore, pasture fertilization decisions should include both production and conservation goals. Currently new technologies and assessment tools are being developed to identify soil properties that affect pasture productivity and resilience as well as to guide pasture management strategies and monitor their outcomes.

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