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Evaluation of Soil Mineral Nitrogen under Different Organic and Inorganic Fertilization in Central Kenya

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Abstract

As part of an agricultural intensification strategy to increase livestock feed productivity, an agronomic trial was set up in Central, Kenya. The agronomic trial followed a Randomized Complete Block Design (RCBD) with three replicate plots measuring 4 meters by 2 meters per treatment. The treatments comprised of NPK fertilizer, Farmyard Manure (FYM), Farm Yard Manure + Biochar (FYM-BC), Bioslurry (all at 45 kg N·ha^{-1}), Lablab intercropping (Biological Nitrogen Fixation), and Control treatment (no fertilizer). GenStat Statistical analysis of variance among the treatment means significantly influenced ammonium (NH_4^+) and nitrate (NO_3^-) availability in the soil ($p < 0.001$). The highest NH_4^+ concentration was recorded under NPK (21.20 ± 27.01 μg·g^{-1} dry matter (D.M.), while the lowest NH_4^+ concentration was recorded under Lablab treatment (6.62 ± 8.02 μg·g^{-1} D.M.). Like NH_4^+, significantly higher (61.41 ± 38.83 μg·g^{-1} D.M.) NO_3^- concentration was observed under NPK plots, while the lowest concentration (37.09 ± 25.15 μg·g^{-1} D.M.) was recorded under Lablab. These findings indicate that NPK releases plant-available mineral N faster than organic fertilizers, which could lead to faster plant growth and higher N leaching losses compared to the slow-release organic fertilizers.

Subject Areas

Agricultural Science

Keywords

Nitrogen Fertilizers, Mineral N, Organic Fertilizers, Inorganic Fertilizers

1. Introduction

Nitrogen (N) is a soil nutrient essential for the development and nourishment of plants, especially vegetative development and is most frequently deficient in soils across the world. The population of the world is expected to hit 9 billion by 2050 (Haider *et al.* 2017) [1] meaning increased demand for food, freshwater, feed, and fiber (Haider *et al.,* 2017 [1]; Zabel *et al.* 2014 [2]). The use of excessive nitrogenous fertilizer poses serious issues to the soil and water ecosystems including soil acidification (Sheng *et al.,* 2016) [3], decrease in soil quality, and reduced nitrogen use efficiency (NUE) (Feng and Zhu, 2017) [4]. The poor NUE and continuous decline in soil quality are a threat to food security and agricultural especially in third world countries (Arif *et al.,* 2016 [5]; Jones *et al.,* 2013 [6]).

The increasing demand for livestock feeds and human food has led to an increase in N fertilizers in agricultural fields. Worldwide, approximately 103 to 112 million tonnes of artificial N fertilizers are applied annually to farms (Heffer and Prud'homme, 2010) [7], representing a potential hazard for ecosystem health when this reactive N is not taken up by plants but released to the environment. Due to the leaching attributes of nitrogen in humid conditions, excess application in the soil may lead to environmental degradation especially pollution of riparian and lacustrine ecosystems. The amount of added N found in the harvested crop products (the fertilizer N use efficiency, NUE) is was found to be only 33% in cereals (Raun and Johnson, 1999 [8]; Glass, 2003 [9]). Of the remaining 67%, apart from what remains in soils, much is lost through leaching or run-off, or as gaseous emissions such as N_2O, NH_3, and N_2 (Jambert *et al.*, 1997) [10]. This is indicative that excess addition of N to the soil is environmentally detrimental. Its implications are against the stipulations of the Kyoto Protocol and the UNFCCC provisions which encourage states to reduce greenhouse gas emissions to curb climate change.

As the costs of inorganic N fertilizers increase and as the demands for agricultural intensification picks up in East Africa, smallholder farmers are opting to use organic fertilization as alternative nutrient sources. Organic fertilization includes livestock by-products such as FYM, bioslurry, as well as recycled agricultural crop by-products. These fertilizers are applied either in raw forms or modified, such as composted materials or with the addition of biochar (B.C).

Organic fertilizers are generally low in nutrient supply, such as N concentrations ranging between 7 - 28 mg $N \cdot kg^{-1}$ on a D.M. basis (Quilty and Cattle, 2011) [11] compared with inorganic fertilizers of the same mass. They should therefore be applied at relatively high rates to meet plant nutrient demands. Also, N release from organic fertilizers relies on the qualities of mineralization and immobilization via soil microorganisms, which are hard to envisage when determining N supply to the crops precisely. Organic fertilizers with relatively higher labile C contents promote N losses through denitrification (Robertson *et al.*, 1988) [12]; while those with high C/N ratio lead to immobilization of N, which reduces the availability of N as it is taken up by soil microbes (Ramirez *et al.*, 2010 [13];

Bruun *et al.*, 2012 [14]). Therefore, this study evaluated the effects of various organic (FYM, FYM + 10% BC, Bioslurry) and inorganic (NPK) fertilizers, and Lablab intercrop on the soil mineral N availability in a Humic Nitisol soil planted with *Brachiaria brizantha cv. xaraes*.

2. Materials and Methods

The study was conducted at the International Livestock Research Institute (ILRI), Nairobi (**Figure 1**) which is physiographically an upland. The cumulative rainfall amount during the experimental period was about 802 mm with long rains (L.R.) lasting from April-June while the short rains (S.R.) were recorded in the months between October 2018 to January 2019, January 2019 to March 2019, and July 2019 to August 2019 (**Figure 2**).

2.1. Experimental Design and Plots Management

The study was conducted between October 2018 and August 2019 comprising of four harvest seasons of 10 weeks each: short rains (S.R., October 2018 to January 2019), Short rain season (SR, January 2019 to March 2019), long rains (L.R.,

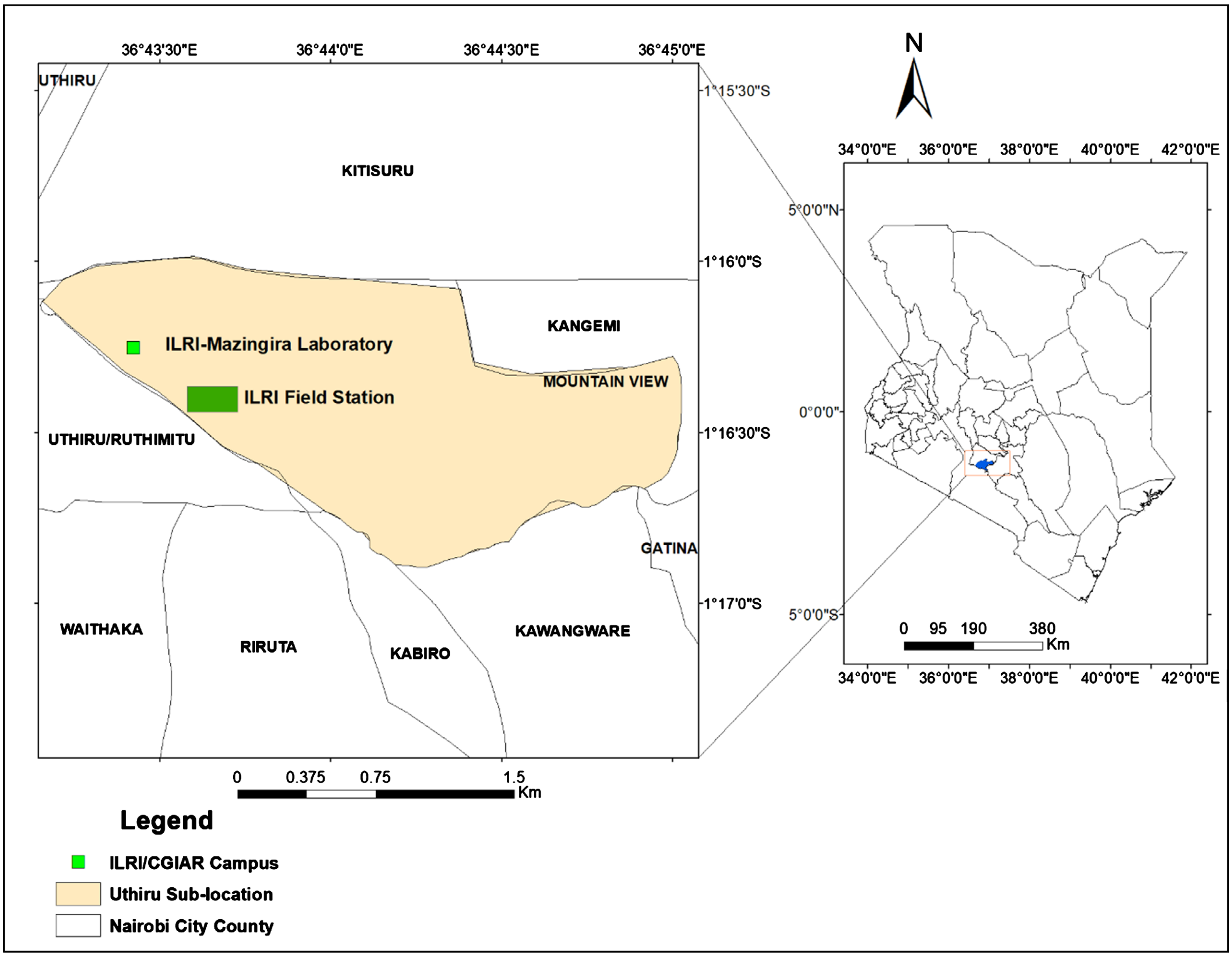


Figure 1. The study area (ILRI-Campus). Source: Mungoche 2020.

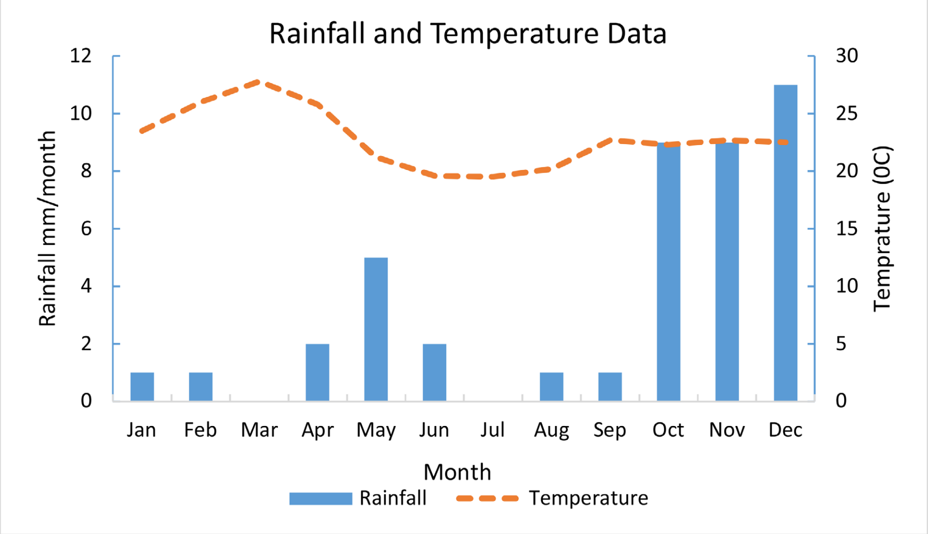


Figure 2. Rainfall and temperature trends for January to December 2019.

March 2019 to June 2019), and cold, dry season (CD, June 2019 to August 2019).

The experiment followed a Randomized Complete Block Design (RCBD) replicated three times. The treatments applied were Control (no fertilizer), farmyard cattle manure (FYM), FYM + 10% biochar (FYM-BC), and FYM digested in a bio digester (Bioslurry), mineral fertilizer (NPK), and legume intercrop (Lablab). FYM was collected from the ILRI farm. Bioslurry was produced in two biogas digesters located at ILRI's Mazingira Centre. Before application, FYM and bioslurry were homogenized manually and analyzed for N content to adjust the applied quantity. Part of the FYM was mixed with 10% (w/w) of chopped biochar. Fertilization was applied at 45 kg $N \cdot ha^{-1}$ for all the organic and inorganic fertilizer treatments after every harvest except for Lablab intercrop, of which biological N fixation (BNF) was measured at the end of the agronomic trial. All the agronomic management practices emulated those commonly found on smallholder farms in Kenya (**Figure 3**).

The agronomic trial followed a complete randomized block design with three replications. Each plot measured 4 m × 2 m. The treatments comprised of NPK fertilizer, FYM, FYM-BC, Bioslurry (all at 45 kg $N \cdot ha^{-1}$), Lablab intercrop (biological N fixation to be determined), and Control treatment (no fertilizer). Each block consisted of 18 plots (3 forage grass species and six fertilizer types), giving a total of 54 plots (4 m × 2 m) (**Table 1**)

2.2. Soil Sampling

Soil sampling for mineral nitrogen was done at a depth of 0 to 15 cm at planting (N0). Fertilization was done after two weeks of planting (N1) and repeated two weeks after first fertilization (N2). It was done again after at harvest (N3), and again two weeks after harvest (N4). Subsequently, sampling at N3 and N4 were repeated during the study period across seasons. The soil was sieved (0.5 mm), extracted using 1 M KCl, and NO_3^- and NH_4^+ were determined calorimetrically.

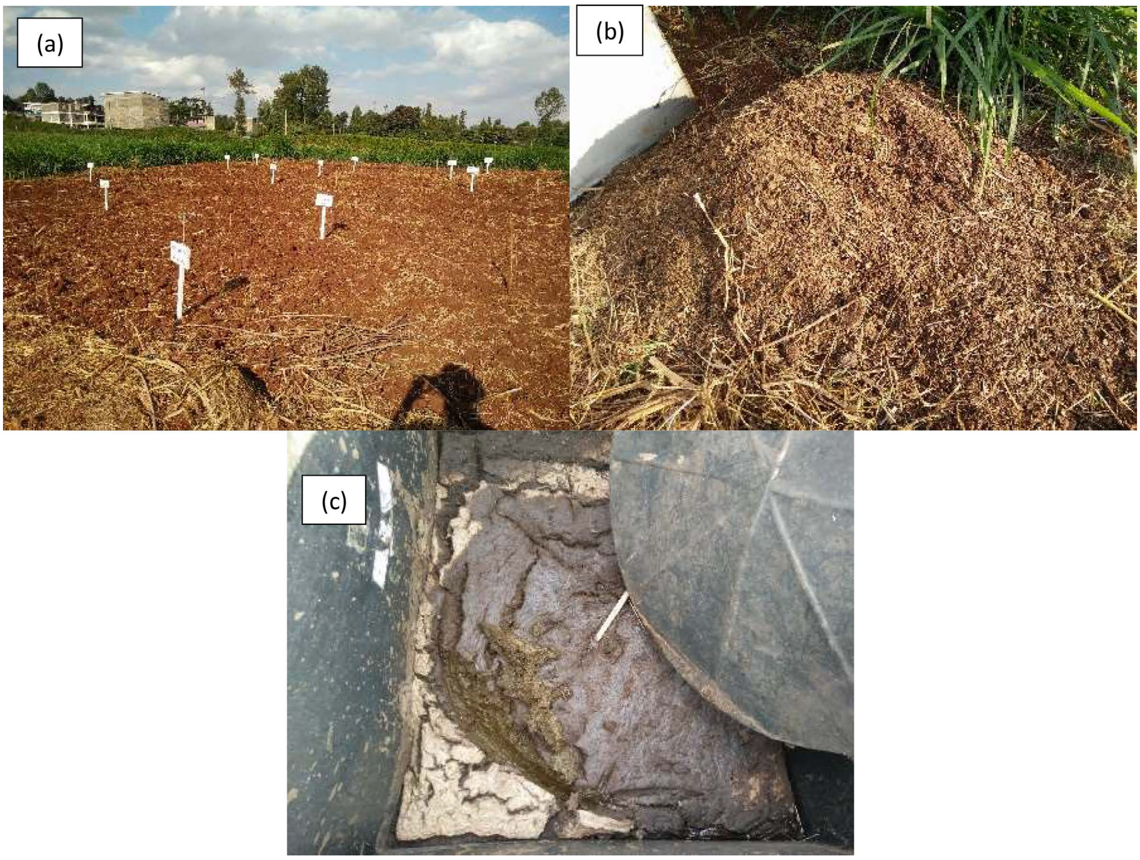


Figure 3. (a) The field layout at ILRI farm after plowing and before planting in September 2018. (b) Homogenized farmyard manure ready for application (c) Bioslurry collected from the biogas digesters at Mazingira Centre.

Table 1. Experimental set up for the agronomic forage grass fertilizer trial.

Forage grass species	Fertilizer type	Fertilizer rate per harvest (kg N·ha^{-1})
Brachiaria brizantha cv. Xaraes	Control (Control)	0
	Legume intercropping (Lablab)	-
	Farmyard manure (FYM)	45
	Farmyard manure + 10% biochar (FYM-BC)	45
	Manure bioslurry (Bioslurry)	45
	Mineral NPK fertilizer (NPK)	45

2.3. Soil Analysis

Composite soil samples were taken at 0 to 15 cm depth after transplanting and fertilization, harvesting, and then after 15 days of each harvest using a soil auger. Fresh soil samples were put in labelled bags and immediately taken to the Mazingira Centre for analyses. In the laboratory, the soil samples were sieved using a 0.5 mm sieve, after which extraction of the field-moist soil (8 g) with 40 ml of 1 *M* KCl for calorimetrically determined mineral nitrogen (NH_4^+ and NO_3^-) was done. Samples were put on an orbital shaker for 60 min and afterward filtered on ash-free filter paper (What man No. 42), calorimetrically to determine NO_3^--N and NH_4^+-N (Hood-Nowotny, *et al.*, 2010) [15].

2.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was done to determine if the measured soil NO_3^- and NH_4^+ pools were significantly different among the fertilizer treatments. Significant differences in the analysis of variance were accepted at $p \leq 0.05$. Tukey's HSD *post hoc* test was used to separate means of the measured soil attributes under the influence of fertilizer treatments. All soil data parameters were analyzed statistically using excel and GenStat Discovery 15th edition statistical software package for Windows. Significant differences were confirmed using a two-way ANOVA at $p \leq 0.05$.

3. Results

3.1. Effects of Treatments on Soil Ammonium and Nitrate Availability

Treatments significantly influenced NH_4^+ and NO_3^- availability in the soil ($p < 0.001$). A Higher NH_4^+ concentration was recorded under *Brachiaria* NPK (21.20 ± 27.01 μg·g^{-1} soil) while the lowest NH_4^+ concentration was recorded under *Brachiaria brizantha cv. xaraes* Lablab (6.62 ± 8.02 μg·g^{-1} D.M.) (**Figure 4**). Generally, the temporal patterns of NH_4^+ concentration were similar across all the treatments during the study period except under NPK, which exhibited higher NH_4^+ concentration two weeks after 2nd and 3rd fertilization, respectively (**Figure 5**).

Significantly higher NO_3^- concentration (61.41 ± 38.83 μg·g^{-1} soil) was observed under NPK plots, while the lowest concentration (37.09 ± 25.15 μg·g^{-1} soil) was found in Lablab (**Figure 4**, **Figure 5**). However, the NO_3^- concentration in the Control (50.86 ± 29.66 μg·g^{-1} soil) treatment was higher than NO_3^-

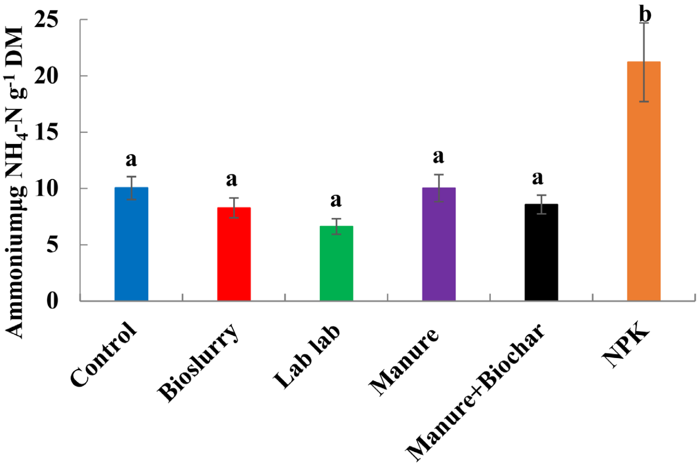
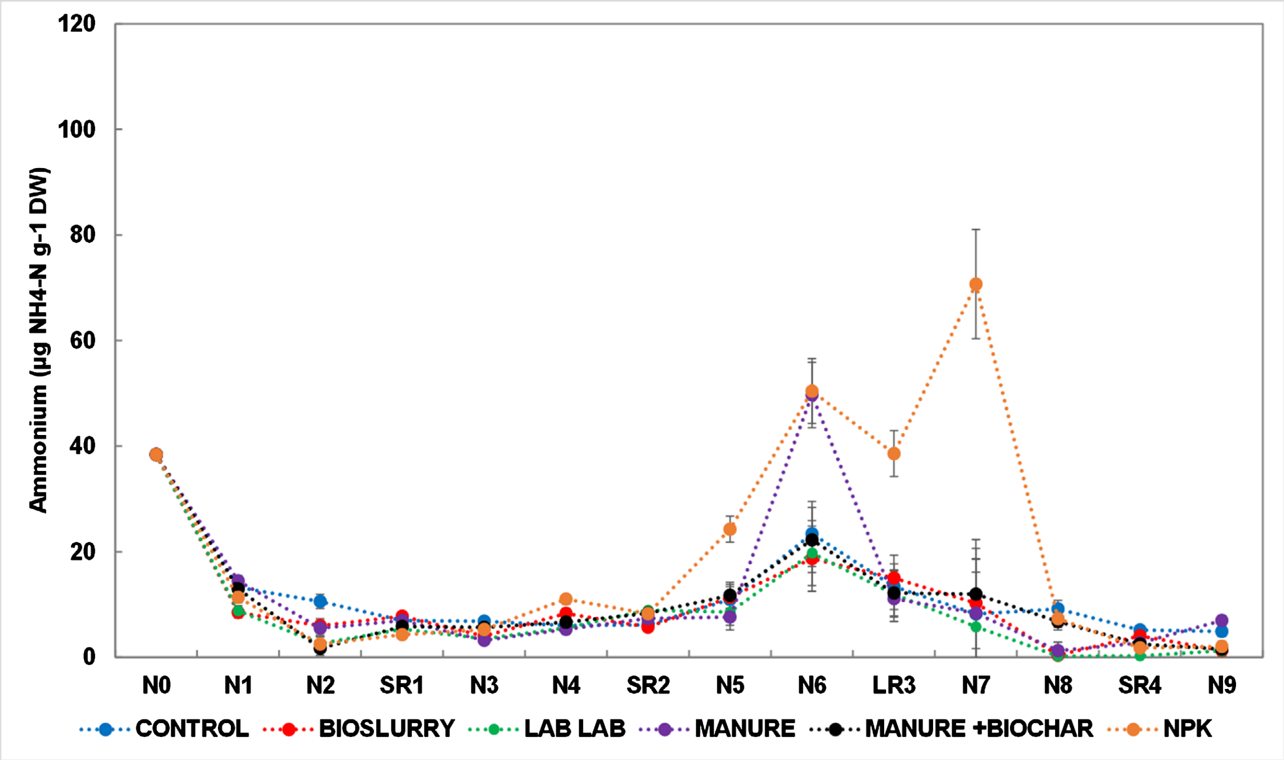


Figure 4. Effect of treatments on the availability of ammonium in soil under *Brachiaria brizantha* cv. xaraes in central Kenya. Bars with different letters represent a significant difference between treatments.



Key: N0 (planting and), N1 (1st fertilization), N2 (2 weeks after planting), SR1 (Short rains 1-October 2018-January 2019), N3 (fertilization after 1st harvest) N4 (2 weeks after fertilization) SR2 (short rains 2- January 2019-March 2019) N5 (fertilization after 2nd harvest), N6 (2 weeks after fertilization), LR3 (Long rains-March 2019-June 2019), N7 (fertilization after 3rd harvest), N8 (2 weeks after fertilization), SR4 (short rains 4-June-August 2019), N9 (fertilization after 4th harvest).

Figure 5. Variations of soil ammonium concentration during the experiment period under *Brachiaria brizantha* cv. xaraes in central Kenya.

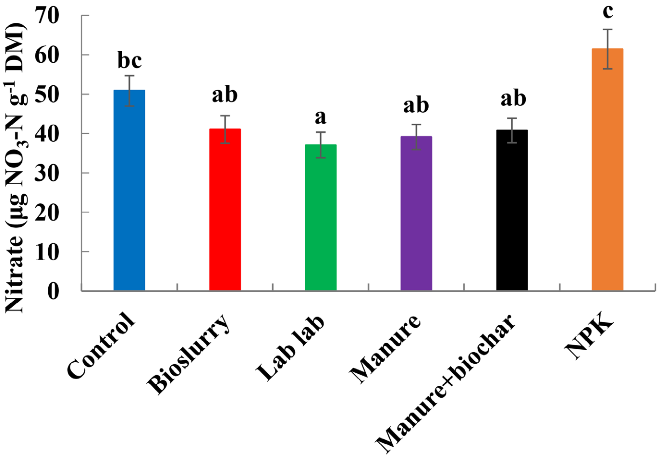


Figure 6. Effect of treatments on the availability of nitrate in soil under *Brachiaria brizantha* cv. xaraes in central Kenya. Bars with different letters represent a significant difference between treatments.

concentration in Lablab (37.09 ± 25.15 $\mu g \cdot g^{-1}$ soil), FYM (39.10 ± 21.38 $\mu g \cdot g^{-1}$ soil), FYM + 10% B.C. (40.78 ± 22.26 $\mu g \cdot g^{-1}$ soil), and Bioslurry (41.04 ± 25.81 $\mu g \cdot g^{-1}$ soil) (Figure 6, Figure 7).

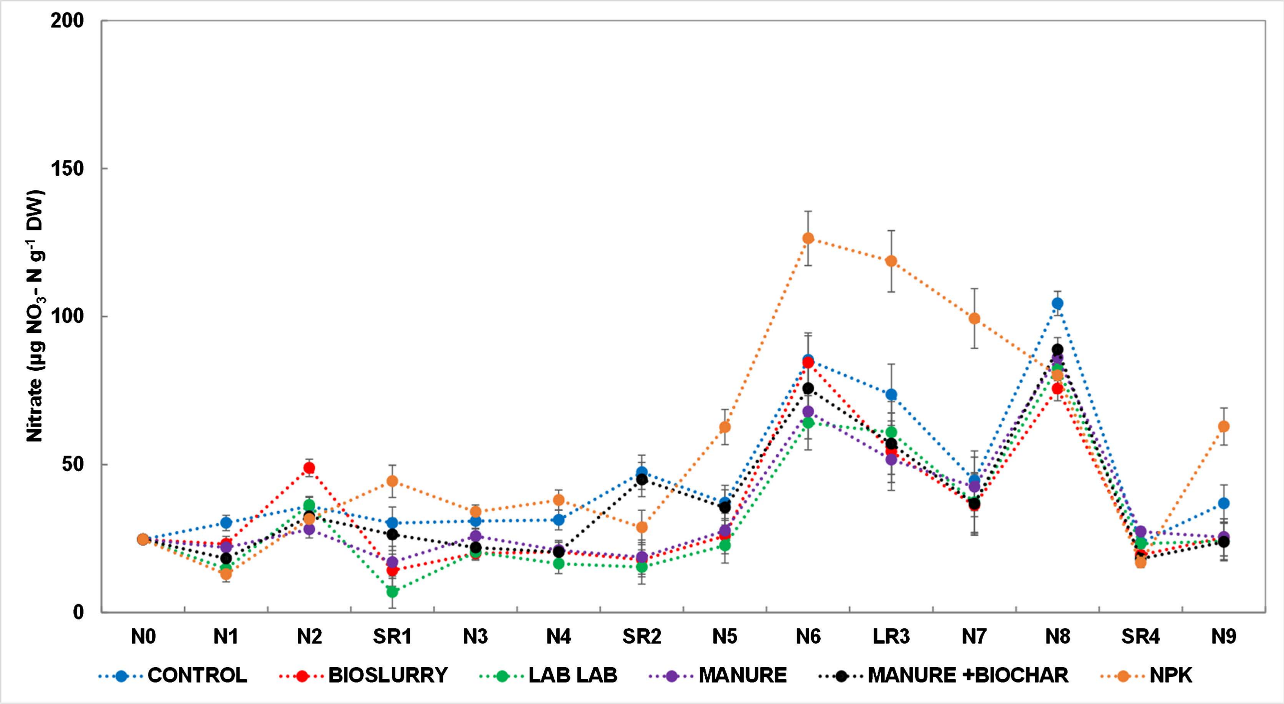


Figure 7. Variations of soil nitrate during the experiment period under *Brachiaria brizantha* cv. xaraes in central Kenya.

3.2. Correlations between Soil Mineral Nitrogen and Other Selected Parameters

Total carbon positively correlated with total nitrogen ($r = 0.937$, $p = 0.006$) at the 0.01 level of significance. Ammonia negatively correlated with total nitrogen ($r = -0.835$, $p = 0.039$) at the 0.05 level. Ammonia also negatively correlated with total carbon ($r = -0.895$, $p = 0.016$) at the same level. Gravimetric water content correlated with ammonia ($r = 0.826$, $p = 0.043$) and also with NO_3 ($r = 0.864$, $p = 0.027$; $p = 0.001$) all at the 0.05 level. NO_3 correlated positively with NH_4^+ ($r = 0.969$) at the 0.05 level (Table 2).

4. Discussion

This study observed an increased mineral N concentration at the beginning of the seasons, after the fertilization events. The mineral N concentration dropped afterward, potentially due to increased crop N-uptake, leaching below the root surface, possible immobilization and/or volatilization to the atmosphere. The increased concentrations of NH_4-N in the soil relative to the Control can be attributed to increased release under NPK treatments. The nitrification process has long term management implications as it results into the release of hydrogen ions which lowers the soil reaction.

Nitrogen response is affected by soil moisture (Agehara and Warncke, 2005) [16]. When soil moisture is adequate, N response is expected. NH_4-N can be fixed by soil organic matter and clay minerals as they are negatively charged, resulting in adsorption on NH_4^+ and slower release (Kissel, *et al.*, 2008) [17]. On the other hand, NO_3^--N, which is negatively charged, is not well retained by the

Table 2. Correlations table.

Parameter	r & p- value	Soil temp	Soil mois.	Total N	Total C	Grav. wc	NH_4^+	NO_3^-
Soil temp	Correl. Coe	1						
	Sig. (2-tailed)							
Soil mois.	Correl. Coe	0.059	1					
	Sig. (2-tailed)	0.911						
Total N	Correl. Coe	0.067	0.377	1				
	Sig. (2-tailed)	0.9	0.461					
Total C	Correl. Coe	0.101	0.06	0.937**	1			
	Sig. (2-tailed)	0.849	0.91	0.006				
Grav. wc	Correl. Coe	0.495	0.39	−0.494	−0.632	1		
	Sig. (2-tailed)	0.318	0.444	0.32	0.178			
NH_4^+	Correl. Coe	0.094	0	−0.835*	−0.895*	0.826*	1	
	Sig. (2-tailed)	0.86	1	0.039	0.016	0.043		
NO_3^-	Correl. Coe	0.189	0.035	−0.714	−0.761	0.864*	0.969**	1
	Sig. (2-tailed)	0.719	0.948	0.111	0.079	0.027	0.001	

*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed). Where: Soil tem*p* = Soil temperature, Soil mois. = soil moisture, Grav. Wc = Gravimetric water content.

soil and can be leached more easily, representing a potential hazard because NO_3^- is a groundwater pollutant (Lodhi, 1979) [18]. In respect to this, when high rainfall is experienced, NH_4-N gives a better yield response compared to NO_3^--N in the soil (Gallardo, *et al.,* 2006) [19]. The differences in bioavailability of NO_3^--N and NH_4-N have been studied and reported that NH_4-N can be directly assimilated into amino acids, whereas NO_3^--N has to be reduced first into NH_4-N before the assimilation process (Carey, and Migliaccio, 2009 [20]; Fernandes, and Rossiello, 1995 [21]). Whenever the proteins present in inorganic fertilizers are depolymerized and decomposed to NH_4-N, the soil's NH_4-N concentrations will increase (Li *et al.*, 2018 [22]; Chantigny, *et al.*, 2010 [23]; Noll, *et al.*, 2019 [24]). This phenomenon also explains why ammonium fertilizers are more suited in wetland ecosystems compared to nitrate fertilizers because they can benefit crops without the risk of leaching owing to their ready solubility. Furthermore, the nitrification process can only produce NO_3^--N in the presence of enough NO_3^--N to stimulate the denitrification process to release N_2O and N_2 (Azam, *et al.,* 2002) [25]. The long-term implication of the link between soil moisture and soil nitrogen is the possibility of leaching especially under humid climates. Long term nitrogen resource to the soil could be maintained by use of biological nitrogen fixation by intercropping or rotating legumes with other crops. It could also be done through seed treatment with rhizobium inoculant strains at planting to ensure long term, environmentally friendly soil nitrogen resource. This suggestion agrees with the findings of Kahindi *et al.* (2009) [26] who elucidated the importance of BNF in the ecosystem management.

NH_4^+ and NO_3^- are more rapidly taken up by plants when applied during growth stage before maturity (Steiner *et al.*, 2007) [27]. During this time, water availability is critical for nutrient fluxes from the soil to plant roots (Christophe, *et al.*, 2011) [28]. Without N fertilizers, the inorganic N concentration of the grounds planted with forage grasses becomes low throughout the whole year (Sommer, *et al.,* 2004) [29]. Obtained values for NH_4^+ concentrations (21.20 ± 27.01 $\mu g \cdot g^{-1}$ for NPK and 6.62 ± 8.02 $\mu g \cdot g^{-1}$ for Lablab were consistent with the numbers reported previously in Kenya (Sommer, *et al.,* 2004) [29]. However, in this study, the NO_3^- concentrations were higher at 61.41 ± 38.83 $\mu g \cdot g^{-1}$ for NPK and 50.86 ± 25.15 $\mu g \cdot g^{-1}$ in Lablab intercrop. Soil NH_4^+ and NO_3^- were lower in FYM, FYM-BC, which could be attributed to low mineralization rates of organic materials. This might have slowed soil microbial action and maintained a mineralization process that allows for the gradual release of C and N in soils over time (Kemmitt, *et al.*, 2006) [30]. A study by (Prasad, & Singh, 1980) [31] noted that when applying FYM and NPK in a maize plantation, there was a 55% increase in NH_4^+ concentrations over the Control treatment, which are higher values than those recorded in this study (40%). Similarly, high NO_3^- concentrations in treatment containing FYM in this study has been previously reported by (N'Dayegamiye, *et al.*, 1997) [32].

The positive relationship between total carbon and total nitrogen is indicative of the role of carbon in maintaining nitrogen resources in the soil. This finding is consistent with observations of Lelago and Buraka (2019) [33] and Mwendwa *et al.* (2020) [34] who observed a positive correlation and attributed it to the ability of carbon to bind nitrogen. It has a management implication of the role of organic inputs including well decomposed manure which is usually rich in carbon. Increasing ammonia seems to reduce the availability of total carbon and nitrogen in the soil which can be attributed to immobilization by soil bacteria.

Increasing mineral N in the soil after harvest is indicative of potential leaching to ground water. Previous research has indicated that over half of the Nitrogen applied to the soil is lost through leaching down the soil profile with less than half available for plant uptake (Liu *et al.,* 2013) [35]. This is suggestive that organic manure is the best bet nitrogen supplier to the soil in long term management. The finding is consistent to findings of Dunjana *et al.* (2012) [36] who observed that manure maintains stable N, P and soil organic matter contents in the topsoil for up to four years. There is evidence that soil quality and fertility simultaneously improve as soil organic matter content increases as the organic matrix provides a solid foundation for sustainable soil productivity (Hou *et al.,* (2012) [37]. This happens by preventing soil nutrients from leaching and maintaining residual compounds in the topsoil after rapid mineralization. This opinion is consistent with findings of Pinitpaitoon *et al.* (2011) [38]. All these arguments point to the choice of organic materials despite their slow release of mineral N. This point should, however, be taken with caveats as it may be invalid for short term crops especially in leased land systems.

5. Conclusions and Recommendations

In conclusion, we found out that organic fertilizer releases the minerals faster to release NH_4^+ and NO_3^- in the soil unlike FYM, Bioslurry, FYM-BC (organic fertilizers) which are slow-release fertilizers for mineral N and can stay in the soil for more extended periods as their mineralization is gradual. Added inorganic N fertilizer is more effective in low soil N conditions to maximize forage grass production yields. However, the gradual mineralization of organic fertilizers, particularly FYM and FYM-BC, which eventually have a long-term residual effect in the soil, is a promising strategy for improving forage grass production in sub-tropical Africa (SSA) overtime.

When discussing the effects of organic and inorganic fertilizers on mineral N, besides quantifying N concentrations, escape pathways such as leaching should be evaluated. This could provide insights into understanding the exact quantities of mineral N utilized from various organic fertilizers by forage grasses for improved yields. This could also form a basis for the calculation of nutrient balances in forage grass fields. It can also help to understand the nutrient uptake by forage grasses and measure the contribution of organic and inorganic fertilizers to forage grass biomass yield.

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Conflicts of Interest

The authors declare no conflicts of interest.

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