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# Polymer-Coated Urea in Broadcast or Furrow Application in the Corn-Palisadegrass Intercropping System

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**Abstract**

Polymer coated urea (PCU) have the potential to increase nitrogen (N) use efficiency (NUE) by the release of N following crop demand while reducing losses by volatilization, leaching and denitrification. However, the NUE of PCU is still unclear especially in systems of corn-palisadegrass intercropping. Broadcast application of urea result in ammonia volatilization losses, new technologies must be adopted in order to allow broadcast application of urea. The aim of this research was to evaluate NUE from PCU in the corn-palisadegrass intercropping system and the viability of the broadcast application using PCU. Two field trials were carried out in a 4 × 2 factorial design including fertilization treatments and application forms. Fertilization treatments were: Conventional Urea topdressing (CUT); Conventional Urea at corn planting (CUP); PCU applied at planting to release in 30 days (PCU30); PCU mixture applied at planting to release in 30 and 60 days (PCU30+60); and application forms: broadcast placement and in furrow. $^{15}$N-urea was used for the determination of NUE. The corn yield and palisadegrass above-ground biomass were not affected by the fertilization treatments or application forms. PCU did not increase N uptake and the NUE by corn or palisadegrass in relation to urea. The N uptake from fertilizer by palisadegrass intercropped with corn is less than 1% of all N uptake on the intercropping system and at most 2% of the N fertilizer applied. The slow release urea does not enable the broadcast application and its efficiency depended upon the same climatic conditions as those of the conventional urea.

**Keywords:** *Brachiaria* spp., labeled nitrogen-$^{15}$N, sustainable cropping system, *Urochloa* spp.

## 1. Introduction

The Enhanced Efficiency Fertilizers (EEFs) come with the assertion of increased Nitrogen use efficiency (NUE) by reducing losses from leaching, volatilization and nitrous oxide emissions or by increasing plant uptake through gradual supply.

Urea (U) is the most widely N fertilizer used in Brazil, but broadcast application of U result in ammonia ($NH_3$) volatilization losses that average 30% (Silva et al., 2017). Incorporation of U is effective to reduce losses, but have the constraint to reduce operational throughput. New technologies must be adopted in order to allow broadcast application of urea without major losses.

Several studies reported reduction in denitrification losses following PCU when compared to conventional urea (Hadi et al., 2008; Halvorson et al., 2010; Hyatt et al., 2010; Asgedom et al., 2014). PCU also presented lower $NH_3$ volatilization losses when compared to urea (Zhao et al., 2013), but still higher when compared to ammonium nitrate and ammonium sulfate (Nascimento et al., 2013).

Effect of EEFs is controversial in relation to responses in yield and better NUE by crops. Positive effects have been reported (Nash et al., 2013; Ye et al., 2013; Zhao et al., 2013; Halvorson & Bartolo, 2014; Hatfield & Parkin, 2014). On the other hand, some studies have reported varied responses, that is, the best performance of the EEFs occurred in only a few situations of climate, soil or years evaluated (Noellsch et al., 2009; Malhi et al., 2010; Malhi et al., 2011; Gagnon et al., 2012; Hatfield & Venterea, 2014). There are also reports that the use of EEFs did not promote any benefit over conventional fertilizer (Hyatt et al., 2010; Grant et al., 2012; Halvorson & Del Grosso, 2013; Khakbazan et al., 2013; Asgedom et al., 2014). Such discrepancies and the high cost of EEFs have limited their usage in large areas of grain cultivation in Brazil.

Intercropping corn and palisadegrass allows simultaneously grain and straw biomass production for maintenance of the no-till system (Borghi et al., 2013; Crusciol et al., 2013). The N fertilization in this system must be made to ensure a competitive advantage to corn shade palisadegrass (Almeida et al., 2017a). In this case, this system can develop without corn yield reduction (Almeida et al., 2017a, b).

This research was conducted to evaluate the advantages of PCU, on corn and palisadegrass intercropping system, and the viability of broadcast application of PCU.

## 2. Material and Methods

### *2.1 Sites Characterization*

The experiments were carried out at two sites: in Taquarituba-São Paulo (Site 1) (23º35'23' S, 49°15'11" W, 654m alt.), and in Uberlândia-Minas Gerais (Site 2) (19º12′22″ S; 47°59′43″ W, 940 m asl.), both in the 2011-2012 season. The experimental design was a randomized block with four replications in a 4 × 2 factorial design: four fertilization treatments (F) and two application forms (A). The fertilization treatments were: 1) Conventional urea topdressing (corn at 4-leave stage) (CUT); 2) Conventional urea applied at corn planting (CUP); 3) PCU applied at planting to release in 30 days (PCU30); 4) A PCU mixture applied at planting to release in 30 and 60 days (PCU30+60); and two application forms: 1) broadcast and 2) in furrow.

The labeled PCUs (30 and 60 days) used were developed by the technology of coating urea granules with polyurethane polymer. To release at 30 and 60 days, respectively, 3.7% and 4.55% polymer relative to the mass of urea were added. The labeled PCUs were analyzed and was found 42.26% and 41.03% of N for PCU 30 and 60 days, respectively.

The soil was classified as Typic Hapludalf in site 1 and Typic Hapludox in site 2 (Soil Survey Staff, 2014), with 590 and 802 g $kg^{-1}$ clay in the subsurface horizon, respectively. A soil sampling was performed in the 0-0.2 m soil depth before installation in both sites and chemical analysis performed according to Raij et al. (2001). Chemical analysis revealed pH of 6.3 and 6.1 ($CaCl_2$); P of 61 and 61 mg $dm^{-3}$ (resin); K, Ca, Mg and potential acidity (H+Al) of 0.2, 5.2, 3.0, 1.6 and 0.2, 3.9, 1.0, 2.2 $cmol_c$ $dm^{-3}$, with a base saturation of 84% and 70%, for site 1 and 2 respectively.

The climate in site 1 is classified as Cfa, subtropical with well-distributed rainfall and hot summers, and an average annual temperature of 20 ºC. The climate of site 2 is classified as Cwa, highland tropical, with summer rainfall, mild winters and dry, hot summers, with an average annual temperature of 22 ºC. The rainfall data and water balance are presented in Figure 1.

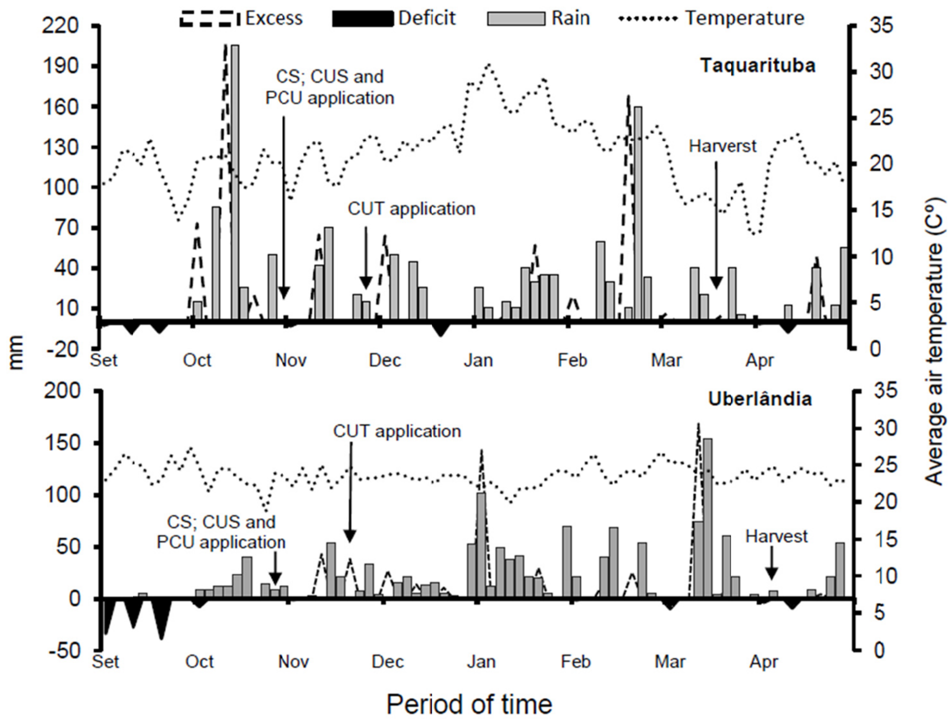


Figure 1. Precipitation, temperature and sequential water balance in Taquarituba-SP (Site 1) and Uberlândia-MG (Site 2) during 2011/2012 crop season. CS = corn sown; CUP = Conventional urea at corn planting; PCU = Polymer coated urea; CUT = Conventional urea topdressing

In site 1, the fertilization at planting was made with 30 kg $ha^{-1}$ of N, 120 kg $ha^{-1}$ of $P_2O_5$ and 60 kg $ha^{-1}$ $K_2O$. The remaining N fertilization (120 kg $ha^{-1}$) was applied in 01 Nov. or 26 Nov. (Figure 1). The total N applied on the corn-palisadegrass intercrop was 150 kg $ha^{-1}$. In site 1, corn was sown in a no-tillage system in early Nov. 2011, with a population of 60,000 plants $ha^{-1}$. Each plot consisted of eight rows, 10-m-long, spaced at 0.9 m, in a total area of 72 $m^2$. In late Mar. 2012, the corn ears in the five meters of the four central rows of the plot were harvested.

In site 2, corn was sown in a no-tillage system in late Oct 2011 spaced 0.7 m between rows with a population of 70,000 plants $ha^{-1}$. The fertilization at planting was 34 kg $ha^{-1}$ of N, 122 kg $ha^{-1}$ of $P_2O_5$ and 34 kg $ha^{-1}$ of $K_2O$. The remaining N (116 kg $ha^{-1}$) was applied in 27 Oct. or 20 Nov. (Figure 1). The total N applied on corn palisadegrass intercrop was 150 kg $ha^{-1}$. In site 2, each plot consisted of seven rows, 10-m long, spaced at 0.7 m, in a total area of 49 $m^2$. In early Apr. 2012, the corn ears in the five meters of each of the three central rows of the plot were harvested.

Intercropped corn and palisadegrass was implemented in both sites using *Urochloa ruziziensis* (*Brachiaria ruziziensis* synonymous) planting in furrow between rows of corn at the 4-leave stage of corn. The amount of seed used was 7 kg $ha^{-1}$. The NUE was determined by the isotopic technique with labeled urea with 2.53% of atoms $^{15}N$ excess. In the center of the plots, microplots were installed with dimensions of 1.0 m length and three rows of corn. The labeled urea was applied only to the centerline of microplot at a rate of 120 kg $ha^{-1}$ of N in site 1 and 116 kg $ha^{-1}$ of N in site 2.

*2.2 Analysis*

When the corn plants flowered, leaves were collected for foliar diagnosis of the N concentration (N-leave), according to the methods of Malavolta et al. (1997). The yield was obtained by the average weight of seeds per plant harvested and then measured in kg $ha^{-1}$ with a moisture correction of 130 grams of water per kilogram of seed.

Corn plants on the center of the microplots were collected for isotopic analyses. To collect corn roots, trenches 0.4 m deep were dug in the center of the microplots. Roots were extracted from the soil by washing with water and separated using a 2 mm mesh sieve. Plants were divided into shoots (S), grains (G), and roots (R) to determine the dry matter (DM). Shoots of the palisadegrass (P) in the microplots were collected for the determination of DM and sent for isotopic analysis.

In the microplots, soil in layers 0.2 m to 1.2 m depth was also collected for total N and the recovery of $^{15}N$. For this purpose, samples at up to 0.4m were taken from homogenized soil in trenches dug for root sampling and a sampling probe with 0.025 m inner diameter and 0.8 m length was used to Soil samples from 0.4 up to 1.2m.

The plant material collected was dried for 72 hours in a forced-air oven at 60ºC to measure dry mass. The ground material was used to measure the total amount of N and $^{15}N$ concentrations (% atoms) in an automated mass spectrometer coupled to an ANCA-GSL N analyzer (Sercon Co., UK). The total N concentrations and $^{15}N/^{14}N$ isotope ratio were calculated according to the method of Barrier and Prosser (1996).

Nitrogen from fertilizer (NFF) in the plants, soil and the total system (kg ha$^{-1}$), nitrogen use efficiency (NUE) by plants (% of applied N), and nitrogen recovery in the soil (NRS) were obtained using the following equations:

$$\text{NFF} = \frac{^{15}\text{N\%} - {}^{15}\text{Nnat}_1}{^{15}\text{Nfert} - {}^{15}\text{Nnat}_2} \times \text{Ntot} \quad (1)$$

where, NFF corresponds to nitrogen from the fertilizer in each sample (kg ha$^{-1}$); $^{15}$N% is the abundance of $^{15}$N atoms (%) in the labeled sample; $^{15}\text{Nnat}_1$ is the natural abundance of $^{15}$N atoms (no labeled material); $^{15}$Nfert is the abundance of $^{15}$N atoms in the labeled fertilizer (2.53%); $^{15}\text{Nnat}_2$ is the natural abundance of $^{15}$N atoms in the fertilizer; Ntot (kg ha$^{-1}$) is the total N of each sample.

The nitrogen in the corn plants from the fertilizer (NFFC-kg ha$^{-1}$) was obtained by summing NFF in S, G and R. The nitrogen from the fertilizer in the soil (NFFS-kg ha$^{-1}$) up to 1.2 m depth was obtained by summing the NFF of all soil layers.

Nitrogen from fertilizer in the soil-plant system (NFFSP-kg ha$^{-1}$) was calculated as the sum of all evaluated compartments (nitrogen in the palisadegrass from fertilizer (NFFP)+NFFC+NFFS), and nitrogen not recovered in the soil-plant system ($\text{NNRSP}_1$-kg ha$^{-1}$) was calculated as the difference between the rate of $^{15}$N and NFFSP.

$$\text{NUE or NRS} = \frac{\text{NFF}}{\text{RN}} \times 100 \quad (3)$$

where, NUE is the nitrogen use efficiency of sample (% of applied N); NRS is nitrogen recovery in soil (% of applied N); NFF is the nitrogen derived from fertilizer in each sample (kg ha$^{-1}$) Equation (1); RN is the rate of $^{15}$N applied at each study site.

The nitrogen use efficiency in corn plants (NUEC) was determined by summing the NUE in S, G and R. The nitrogen recovery in soil (NRS) to a depth of 1.2 m was obtained by summing the NUE in all soil layers.

The nitrogen use efficiency in the soil-plant system (NUESP-%) was obtained by calculating the sum of recovery in all evaluated compartments (Nitrogen use efficiency in palisadegrass plants (NUEP+NUEC+NRS), and the percentage of nitrogen not recovered by soil-plant system ($\text{NNRSP}_2$-%) is the value corresponding to the difference between the total (100%) and NUESP.

### *2.3 Statistical Analyses*

The results were submitted to normality and variance homogeneity tests, as well as an analysis of variance (ANOVA) by the F-test at 5% probability statistical procedures were conducted using PROC NLIN in SAS (Statistical Analysis System, version 9.2). The two experimental sites were analyzed together for the response variables if the division of the mean squared error of the ANOVA, for each site had a quotient less than or equal to 7, as proposed by Banzato and Kronka (2006). If the null hypothesis was rejected, Fisher's least significant difference (LSD) test at $p \leq 0.05$ was performed to compare the means for the fertilization treatments and the application forms for each site.

## 3. Results

### *3.1 Palisadegrass Dry Mass, Corn Yield and N-Leave*

The dry mass of palisadegrass and corn yield did not change with fertilization treatments or with the application forms in both sites. The palisadegrass dry mass was 751 kg ha$^{-1}$ in site 1 and 815 kg ha$^{-1}$ in site 2. The corn yield in site 2 was 10,603 kg ha$^{-1}$, higher than site 1 with 7,916 kg ha$^{-1}$ (Tables 1 and 2).

The N-leave was 31.5 g kg$^{-1}$ and was not affected by the fertilization treatments and application forms in site 1 (Table 2); this result was lower than that found it in site 2 (Table 1), where the N-leave was not influenced by the application forms, but the PCU30+60 resulted in higher N-leave, 6.6% more than other treatments.

Table 1. Combined analysis of variance between sites, fertilization and application forms of N fertilizer for: Palisadegrass dry mass, corn yield, N concentration in corn leave (N-leave), Total N Palisadegrass (NtotP), Total N Corn (NtotC), N From Fertilizer palisadegrass (NFFP), N From Fertilizer Corn (NFFC), N Use Efficiency palisadegrass (NUEP) and N Use Efficiency Corn (NUEC)

| | Palisadegrass dry mass | Corn Yield | N-leave |
|---|---|---|---|
| | Pr>F | | |
| Site (S) | $0.5590^{ns}$ | <0.0001*** | <0.0001*** |
| Fertilization (F) | $0.5839^{ns}$ | $0.1519^{ns}$ | $0.2549^{ns}$ |
| Application (A) | $0.8139^{ns}$ | $0.8665^{ns}$ | $0.2456^{ns}$ |
| S × F | $0.8588^{ns}$ | $0.5752^{ns}$ | $0.0541^{ns}$ |
| S × A | $0.2167^{ns}$ | $0.6599^{ns}$ | $0.7713^{ns}$ |
| F × A | $0.9039^{ns}$ | $0.8060^{ns}$ | $0.5815^{ns}$ |
| S × F × A | $0.0170^{*}$ | $0.3401^{ns}$ | $0.7553^{ns}$ |
| CV% | 27.84 | 6.19 | 5.67 |
| | NtotP | NtotC | NFFP |
| | Pr>F | | |
| Site (S) | $0.1217^{ns}$ | $0.0602^{ns}$ | $0.2891^{ns}$ |
| Fertilization (F) | $0.5486^{ns}$ | $0.2601^{ns}$ | $0.7688^{ns}$ |
| Application (A) | $0.9062^{ns}$ | $0.5998^{ns}$ | $0.0820^{ns}$ |
| S × F | $0.8065^{ns}$ | $0.2494^{ns}$ | $0.9096^{ns}$ |
| S × A | $0.1395^{ns}$ | $0.0647^{ns}$ | $0.0130^{*}$ |
| F × A | $0.9244^{ns}$ | $0.3952^{ns}$ | $0.7794^{ns}$ |
| S × F × A | $0.0622^{ns}$ | $0.5720^{ns}$ | $0.4770^{ns}$ |
| CV% | 43.50 | 3.45 | 18.67 |
| | NFFC | NUEP | NUEC |
| | Pr>F | | |
| Site (S) | <0.0001*** | $0.3678^{ns}$ | <0.0001*** |
| Fertilization (F) | <0.0001*** | $0.7689^{ns}$ | <0.0001*** |
| Application (A) | $0.0630^{ns}$ | $0.0804^{ns}$ | $0.0575^{ns}$ |
| S × F | $0.2589^{ns}$ | $0.9097^{ns}$ | $0.2740^{ns}$ |
| S × A | <0.0001*** | 0.0128* | <0.0001*** |
| F × A | $0.3013^{ns}$ | $0.7821^{ns}$ | $0.2957^{ns}$ |
| S × F × A | $0.1882^{ns}$ | $0.4791^{ns}$ | $0.1844^{ns}$ |
| CV% | 8.39 | 18.67 | 8.39 |

*Note.* $^{ns}$ not significant; $^{*}$ significant at 5% probability; $^{***}$ significant at less than 0.1% probability of error by the F test.

Table 2. Analysis of variance between fertilization and applications forms for site 1 and site 2 for: Palisadegrass dry mass, corn yield, N concentration in corn leave (N-leave), Total N Palisadegrass (NtotP) and Total N Corn (NtotC)

| Fertilization † | Site 1 | | | Site 2 | | |
|---|---|---|---|---|---|---|
| | Broadcast | In furrow | Mean(F) | Broadcast | In furrow | Mean(F) |
| *Palisadegrass dry mass (kg ha$^{-1}$)* | | | | | | |
| CUT | 518 | 876 | 697 | 918 | 383 | 651 |
| CUP | 1,021 | 555 | 788 | 772 | 1,069 | 920 |
| PCU30 | 788 | 615 | 702 | 600 | 1,020 | 810 |
| PCU30+60 | 968 | 664 | 816 | 731 | 1,029 | 880 |
| Mean (A) | 824 | 678 | | 755 | 875 | |
| Fertilization(F) | 0.9441$^{ns}$ | | | 0.5289$^{ns}$ | | |
| Application(A) | 0.3325$^{ns}$ | | | 0.3880$^{ns}$ | | |
| F × A | 0.2925$^{ns}$ | | | 0.0779$^{ns}$ | | |
| CV % | 30.22 | | | 47.23 | | |
| *Corn yield (kg ha$^{-1}$)* | | | | | | |
| CUT | 8,344 | 7,941 | 8,143 | 10,764 | 11,110 | 10,937 |
| CUP | 7,492 | 7,924 | 7,708 | 10,554 | 10,377 | 10,466 |
| PCU30 | 7,991 | 7,560 | 7,776 | 10,598 | 10,665 | 10,632 |
| PCU30+60 | 7,914 | 8,159 | 8,037 | 10,319 | 10,435 | 10,377 |
| Mean (A) | 7,935 | 7,896 | | 10,559 | 10,647 | |
| Fertilization(F) | 0.2438$^{ns}$ | | | 0.3572$^{ns}$ | | |
| Application(A) | 0.8187$^{ns}$ | | | 0.7083$^{ns}$ | | |
| F ×A | 0.1941$^{ns}$ | | | 0.8847$^{ns}$ | | |
| CV % | 6.05 | | | 6.17 | | |
| *N-leave (g kg$^{-1}$)* | | | | | | |
| CUT | 31.89 | 32.28 | 32.09 | 34.04 | 34.81 | 34.4 b |
| CUP | 31.87 | 31.53 | 31.70 | 35.78 | 35.76 | 35.8 ab |
| PCU30 | 30.72 | 31.58 | 31.15 | 35.03 | 34.63 | 34.8 b |
| PCU30+60 | 30.80 | 31.59 | 31.20 | 36.12 | 38.57 | 37.3 a |
| Mean (A) | 31.32 | 31.74 | | 35.24 | 35.94 | |
| Fertilization(F) | 0.7109$^{ns}$ | | | 0.0478* | | |
| Application(A) | 0.5275$^{ns}$ | | | 0.3349$^{ns}$ | | |
| F × A | 0.9098$^{ns}$ | | | 0.5781$^{ns}$ | | |
| CV % | 5.87 | | | 8.15 | | |
| *NtotP and NtotC* | NtotP | NtotC | | NtotP | NtotC | |
| Fertilization(F) | 0.9358$^{ns}$ | 0.2424$^{ns}$ | | 0.2992$^{ns}$ | 0.3433$^{ns}$ | |
| Application(A) | 0.3331$^{ns}$ | 0.1512$^{ns}$ | | 0.2388$^{ns}$ | 0.1456$^{ns}$ | |
| F × A | 0.5752$^{ns}$ | 0.5839$^{ns}$ | | 0.0607$^{ns}$ | 0.4754$^{ns}$ | |
| CV % | 46.46 | 9.81 | | 38.5 | 17.21 | |

*Note.* † CUT = Conventional urea topdressing; CUP = Conventional urea at corn planting; PCU30 = PCU to release in 30 days applied at corn planting; PCU30+60 = Mixing of PCU to release in 30 and 60 days applied at corn planting. $^{ns}$ not significant, * significant at 5% probability of error by the F test; values followed by the same lowercase letters in columns are not significantly different at $p \leq 0.05$ according LSD test.

### *3.2 N Extraction and N Derivate from the Fertilizer*

The fertilization treatments and the application forms did not affect the NtotP and NtotC, and were similar in both sites (Table 2). NtotP was 19 kg ha$^{-1}$ in site 1 and 16 kg ha$^{-1}$ in site 2. The NtotC was 223 kg ha$^{-1}$ in site 1 and 210 kg ha$^{-1}$ in site 2. The N uptake in the corn plus palisadegrass was 242 kg ha$^{-1}$ in site 1 and 226 kg ha$^{-1}$ in site 2. NtotP in this total is only 8% in site 1 and 7% in site 2. Figure 2 shows the cumulative amount of N in the palisadegrass and corn.

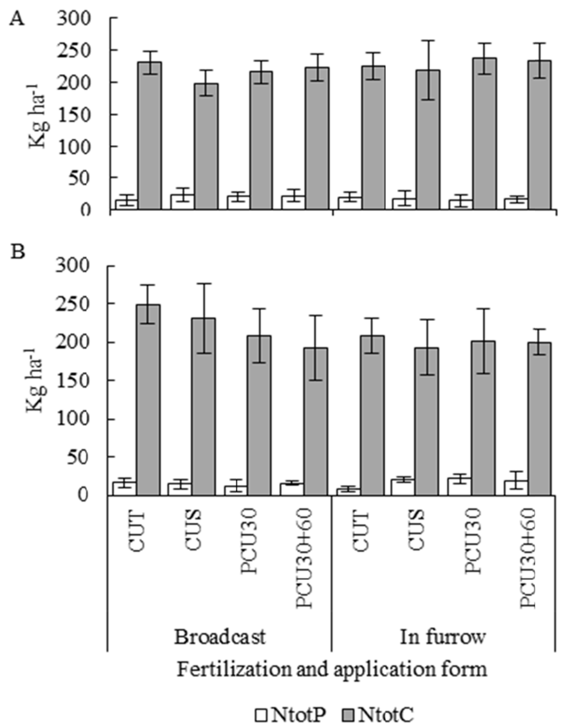


Figure 2. Total N Palisadegrass (NtotP) and Total N Corn (NtotC) obtained with Conventional urea topdressing (CUT), Conventional urea at corn planting (CUP), PCU to release in 30 days applied at corn planting (PCU30) and mixing of PCU to release in 30 and 60 days applied at corn planting (PCU30+60) applied broadcasted and in furrow in site 1 (A) e site 2 (B)

Nitrogen from fertilizer palisadegrass (NFFP) had S × A interaction (Table 1), because the broadcast application was better than in furrow in site 1, which did not occur in the site 2, where the application forms promoted a similar amount of NFFP (Table 3). In the site 1, NFFP was 57% lower for in furrow application than for the broadcast application.

Table 3. Analysis of variance between fertilization and applications forms for site 1 and site 2 for: N from fertilizer palisadegrass (NFFP), N from fertilizer Corn (NFFC), N use efficiency palisadegrass (NUEP)

| Fertilization † | Site 1 | | | Site 2 | | |
|---|---|---|---|---|---|---|
| | Broadcast | In furrow | Mean(F) | Broadcast | In furrow | Mean(F) |
| *NFFP (kg ha$^{-1}$)* | | | | | | |
| CUT | 1.7 | 0.8 | 1.3 | 1.8 | 1.1 | 1.5 |
| CUP | 2.7 | 1.2 | 2.0 | 1.1 | 1.5 | 1.3 |
| PCU30 | 2.2 | 1.3 | 1.8 | 0.7 | 2.6 | 1.7 |
| PCU30+60 | 3.8 | 1.0 | 2.4 | 1.1 | 2.4 | 1.8 |
| Mean (A) | 2.6 A | 1.1 B | | 1.2 | 1.9 | |
| Fertilization(F) | 0.7727$^{ns}$ | | | 0.8222$^{ns}$ | | |
| Application(A) | 0.0062$^{**}$ | | | 0.5663$^{ns}$ | | |
| F × A | 0.9405$^{ns}$ | | | 0.3592$^{ns}$ | | |
| CV % | 19.26 | | | 17.97 | | |
| *NFFC (kg ha$^{-1}$)* | | | | | | |
| CUT | 85.2 | 76.1 | 80.7 a | 41.9 | 44.5 | 43.2 a |
| CUP | 65.9 | 51.9 | 58.9 b | 27.5 | 48.1 | 37.8 ab |
| PCU30 | 57.3 | 53.3 | 55.3 b | 26.6 | 39.2 | 32.9 b |
| PCU30+60 | 65.4 | 61.4 | 63.4 b | 28.3 | 43.8 | 36.1 b |
| Mean (A) | 68.5 A | 60.7 B | | 31.1 B | 43.9 A | |
| Fertilization(F) | 0.0003** | | | 0.0326* | | |
| Application(A) | 0.0409* | | | <0.0001*** | | |
| F × A | 0.7184$^{ns}$ | | | 0.0691$^{ns}$ | | |
| CV % | 15.7 | | | 17.25 | | |
| *NUEP (%)* | | | | | | |
| CUT | 1.44 | 0.68 | 1.06 | 1.56 | 0.95 | 1.26 |
| CUP | 2.26 | 1.00 | 1.63 | 0.93 | 1.28 | 1.11 |
| PCU30 | 1.84 | 1.11 | 1.48 | 0.61 | 2.22 | 1.42 |
| PCU30+60 | 3.16 | 0.84 | 2.00 | 0.91 | 2.08 | 1.50 |
| Mean (A) | 2.18 A | 0.91 B | | 1.00 | 1.63 | |
| Fertilization(F) | 0.7727$^{ns}$ | | | 0.8222$^{ns}$ | | |
| Application(A) | 0.0062** | | | 0.5663$^{ns}$ | | |
| F × A | 0.9405$^{ns}$ | | | 0.3592$^{ns}$ | | |
| CV % | 19.26 | | | 17.97 | | |

*Note.* † CUT = Conventional urea topdressing; CUP = Conventional urea at corn planting; PCU30 = PCU to release in 30 days applied at corn planting; PCU30+60 = Mixing of PCU to release in 30 and 60 days applied at corn planting. $^{ns}$ not significant, * significant at 5%, ** significant at 1%, *** significant at less than 0.1% probability of error by the F test; values followed by the same lowercase letters in columns and uppercase letters in rows are not significantly different at $p \leq 0.05$ according LSD test.

Fertilization with PCU did not improve NFFP (Table 3). For the broadcast application, the NFFP represented 13% of NtotP and 6% in the in-furrow in site 1. In site 2, there is no difference, and NFFP represented 10% of NtotP.

Difference between sites and applications forms was observed for NFFC (Table 1). In site 1, the best form was the broadcast application, which resulted in a NFFC 1.1-fold higher than the in-furrow form (Table 3). On the other hand, the in-furrow form resulted in 1.4 times more NFFC than the broadcast application in site 2 (Table 3). In site 1, the NFFC with CUT was 1.36 times higher than other fertilization treatments, and in site 2, CUT provided better performance than the others, however, with no difference from CUP (Table 3). In site 1, NFFC was 35% of the NtotC with CUT, and 27% of the average of other fertilization treatments. In site 2.1% of NtotC was derived from fertilizer with CUT and 17% in average for other fertilization treatments.

### *3.3 Nitrogen Use Efficiency and Nitrogen Recovery in Soil*

NUEP was different between application forms between sites, as shown by the S × A interaction presented in Table 1; this occurs because the broadcast application was better than the in-furrow application in site 1; in site 2, both application forms promoted the same NUEP (Table 3).

Broadcast application promotes 2.1% of NUEP in site 1 and 0.91% of the in-furrow application. In site 2 NUEP was 1.3% of the N-fertilizer applied. PCU did not improve NUEP (Table 3).

There was a significant sites and application forms interaction for NUEC. The application forms were different in each site. In site 1, the best form was the broadcast application, with 6.4% more NUEC than the in-furrow application (Table 4); on the other hand, the in-furrow application in site 2 resulted in 11% higher NUEC than the broadcast application. In site 1, NUEC with CUT was 17.8% higher than the other fertilization treatments, and in site 2, CUT also promoted greater NUEC but without differing from CUP (Table 4).

Table 4. Analysis of variance between fertilization and applications forms for site 1 and site 2 for: N Use Efficiency Corn (NUEC), N from the fertilizer in the soil (NFFS) and N recovery in soil (NRS)

| Fertilization † | Site 1 | | | Site 2 | | |
|---|---|---|---|---|---|---|
| | Broadcast | In furrow | Mean(F) | Broadcast | In furrow | Mean(F) |
| *NUEC (%)* | | | | | | |
| CUT | 70.9 | 63.4 | 67.2 a | 36.0 | 38.2 | 37.1 a |
| CUP | 54.9 | 43.2 | 49.1 b | 23.6 | 41.3 | 32.5 ab |
| PCU30 | 47.8 | 44.4 | 46.1 b | 22.9 | 33.7 | 28.3 b |
| PCU30+60 | 54.5 | 51.2 | 52.9 b | 24.3 | 37.7 | 31.0 b |
| Mean (A) | 57.0 A | 50.6 B | | 26.7 B | 37.7 A | |
| Fertilization(F) | 0.0003** | | | 0.0326* | | |
| Application(A) | 0.0409* | | | <0.0001*** | | |
| F × A | 0.7184$^{ns}$ | | | 0.0691$^{ns}$ | | |
| CV % | 15.7 | | | 17.25 | | |
| *NFFS (kg ha$^{-1}$)* | | | | | | |
| CUT | 41.2 | 12.0 | 26.6 | 31.6 Aa | 6.0 Ba | 18.8 |
| CUP | 33.6 | 15.6 | 24.6 | 14.0 Ab | 11.7 Aa | 12.9 |
| PCU30 | 39.4 | 16.8 | 28.1 | 18.6 Aab | 9.3 Ba | 14.0 |
| PCU30+60 | 31.0 | 13.2 | 22.1 | 21.8 Aab | 7.7 Ba | 14.8 |
| Mean (A) | 36.3 A | 14.4 B | | 21.5 | 8.7 | |
| Fertilization(F) | 0.3649$^{ns}$ | | | 0.9345$^{ns}$ | | |
| Application(A) | <0.0001*** | | | <0.0001*** | | |
| F × A | 0.5138 | | | 0.0080** | | |
| CV % | 10.91 | | | 8.92 | | |
| *NRS (%)* | | | | | | |
| CUT | 34.6 | 9.8 | 22.2 | 27.1 Aa | 5.1 Ba | 16.1 |
| CUP | 28.0 | 13.0 | 20.5 | 12.0 Ab | 10.0 Aa | 11.0 |
| PCU30 | 32.8 | 14.0 | 23.4 | 16.0 Aab | 8.0 Ba | 12.0 |
| PCU30+60 | 25.8 | 11.0 | 18.4 | 18.7 Aab | 6.7 Ba | 12.7 |
| Mean (A) | 30.3 A | 12.0 B | | 18.5 | 7.5 | |
| Fertilization(F) | 0.3649$^{ns}$ | | | 0.9345$^{ns}$ | | |
| Application(A) | <0.0001*** | | | <0.0001*** | | |
| F × A | 0.5138 | | | 0.0080** | | |
| CV % | 10.91 | | | 8.91 | | |

*Note.* † CUT = Conventional urea topdressing; CUP = Conventional urea at corn planting; PCU30 = PCU to release in 30 days applied at corn planting; PCU30+60 = Mixing of PCU to release in 30 and 60 days applied at corn planting. $^{ns}$ not significant, * significant at 5%, ** significant at 1%, *** significant at less than 0.1% probability of error by the F test; values followed by the same lowercase letters in columns and uppercase letters in rows are not significantly different at $p \leq 0.05$ according LSD test.

The NFFS and NRS varied among sites and application forms. PCU does not alter the NFFS compared with conventional urea in site 1; however, in relation to the application forms, the NFFS with broadcast application was 2.5 times higher than for the in-furrow application (Table 4). In site 2, there was interaction F × A (Table 4).

The CUT, PCU30 and PCU30+60 resulted in 3.13 times greater amount of NFFS in the broadcast application than in the in-furrow application. For the CUP, NFFS was the same for the broadcast or in-furrow applications. For the in-furrow application, there was no difference with respect to fertilization treatments; on the other hand, with the broadcast application of CUT, the NFFS was 1.56 times higher than PCU30 and PCU30+60, which showed 2.25 times higher than CUP (Table 4).

In site 1, PCU did not change the NRS compared to conventional urea; but the NRS was 18.3% higher for the broadcast application than for the in-furrow application (Table 4); in other words, 60% more N-fertilizer was recovered from the soil in the case of the broadcast application than with the in-furrow application. In site 2, The CUT, PCU30 and PCU30+60 showed NRS 14% higher for the broadcast than for the in-furrow application. There were no significant differences between broadcast and in-furrow application for NRS of CUP. On this site, there was no difference in relation to fertilization treatments for the in-furrow application. On the other hand, with the broadcast application of CUT, the NRS was 9.75% higher than the PCU30 and PCU30+60, and NRS was 15.1% greater than CUP (Table 4); thus, with broadcast application, 68% more N-fertilizer was recovered from the soil than with in-furrow application.

The $NFFSP_1$ in site 1 for the in-furrow application recovered 81 kg $ha^{-1}$, 23% less than the broadcast application (105 kg $ha^{-1}$). Fertilization with CUT recovered 113.5 kg $ha^{-1}$, 24% more than other forms of fertilization (Table 6). In site 2, CUT recovered 32% more NFFSP with broadcast application than with in-furrow. For CUP, PCU30 and PCU30+60, there was no difference between the broadcast and in-furrow applications. For the broadcast application, CUT recovered 38% more NFFSP than the other fertilization treatments; with the in-furrow application, there was no difference in NFFSP between the fertilization treatments (Table 6).

Table 5. Combined analysis of variance between sites, fertilization and application forms of N fertilizer for: N from fertilizer in soil (NFFS), N recovery in soil (NRS), N from fertilizer in soil-plant system (NFFSP), N not recovered in soil-plant system ($NNRSP_1$), N use efficiency in soil-plant system (NUESP and N not recovered by soil-plant system ($NNRSP_2$)

| | NFFS | NRS | NFFSP |
|---|---|---|---|
| | Pr>F | | |
| Site (S) | <0.0001*** | <0.0001*** | <0.0001*** |
| Fertilization (F) | $0.7743^{ns}$ | $0.7759^{ns}$ | 0.0002** |
| Application (A) | <0.0001*** | <0.0001*** | 0.0009** |
| S × F | $0.7975^{ns}$ | $0.7991^{ns}$ | $0.2856^{ns}$ |
| S × A | $0.4366^{ns}$ | $0.4579^{ns}$ | 0.0006** |
| F ×A | 0.0242* | 0.0240* | $0.6110^{ns}$ |
| S × F × A | $0.2286^{ns}$ | $0.2255^{ns}$ | 0.0450* |
| CV% | 7.82 | 7.83 | 15.58 |
| | $NNRSP_1$ | NUESP | $NNRSP_2$ |
| | Pr>F | | |
| Site (S) | <0.0001*** | <0.0001*** | <0.0001*** |
| Fertilization (F) | 0.0002** | 0.0002** | 0.0002** |
| Application (A) | 0.0009** | 0.0011** | 0.0011** |
| S × F | $0.2856^{ns}$ | $0.3184^{ns}$ | $0.3184^{ns}$ |
| S × A | 0.0006** | 0.0007** | 0.0007** |
| F × A | $0.6110^{ns}$ | $0.5856^{ns}$ | $0.5856^{ns}$ |
| S × F × A | 0.0450* | 0.0432* | 0.0432* |
| CV% | 15.58 | 15.62 | 15.62 |

*Note.* $^{ns}$ not significant, * significant at 5%, ** significant at 1%, *** significant at less than 0.1% probability of error by the F test.

$NNRSP_1$ in site 1 was lower in the broadcast application than the in-furrow application. The $NNRSP_1$ in the broadcast application was 15 kg $ha^{-1}$, 61% less than with the in-furrow application (40 kg $ha^{-1}$). CUP, PCU30 and PCU30+60 did not recovered 34 kg $ha^{-1}$, 79% more than the CUT (Table 6).

The NUESP was higher in site 1 than in site 2 (Table 5). The results of the broadcast application in site 1 were bigger than those in site 2. The CUT had better performance in both sites, except for the in-furrow application in site 2, which had the same results as all fertilization treatments (Figure 3).

Table 6. Analysis of variance between fertilization and applications forms for site 1 and site 2 for: N derived from fertilizer in soil-plant system (NFFSP) and N not recovered in soil-plant system ($NNRSP_1$)

| Fertilization † | Site 1 | | | Site 2 | | |
|---|---|---|---|---|---|---|
| | Broadcast | In furrow | Mean(F) | Broadcast | In furrow | Mean(F) |
| *NFFSP (kg ha$^{-1}$)* | | | | | | |
| CUT | 121.1 | 105.8 | 113.5 a | 75.3 Aa | 51.6 Ba | 63.4 |
| CUP | 102.2 | 71.4 | 86.8 b | 42.6 Ab | 60.5 Aa | 51.6 |
| PCU30 | 98.9 | 71.4 | 85.1 b | 45.9 Ab | 50.4 Aa | 48.2 |
| PCU30+60 | 98.3 | 73.3 | 85.8 b | 51.2 Ab | 55.1 Aa | 53.2 |
| Mean (A) | 105.2 A | 80.5 B | | 53.8 | 54.4 | |
| Fertilization(F) | 0.0176* | | | 0.0292* | | |
| Application(A) | 0.0005** | | | $0.6676^{ns}$ | | |
| F × A | $0.8220^{ns}$ | | | 0.0107* | | |
| CV % | 13.26 | | | 18.87 | | |
| *$NNRSP_1$ (kg ha$^{-1}$)* | | | | | | |
| CUT | 0.0 | 14.2 | 7.1 b | 41.1 Bb | 64.8 Aa | 53.0 |
| CUP | 17.8 | 48.6 | 33.2 a | 73.8 Aa | 55.9 Aa | 64.9 |
| PCU30 | 21.1 | 48.6 | 34.9 a | 70.5 Aa | 66.0 Aa | 68.3 |
| PCU30+60 | 21.7 | 46.7 | 34.2 a | 65.2 Aa | 61.3 Aa | 63.3 |
| Mean (A) | 15.2 B | 39.5 A | | 62.7 | 62.0 | |
| Fertilization(F) | 0.0176* | | | 0.0292* | | |
| Application(A) | 0.0005** | | | $0.6676^{ns}$ | | |
| F × A | $0.8220^{ns}$ | | | 0.0107* | | |
| CV % | 13.26 | | | 18.87 | | |

*Note.* † CUT = Conventional urea topdressing; CUP = Conventional urea at corn planting; PCU30 = PCU to release in 30 days applied at corn planting; PCU30+60 = Mixing of PCU to release in 30 and 60 days applied at corn planting. $^{ns}$ not significant, * significant at 5%, ** significant at 1% probability of error by the F test; values followed by the same lowercase letters in columns and uppercase letters in rows are not significantly different at $p \leq 0.05$ according LSD test.

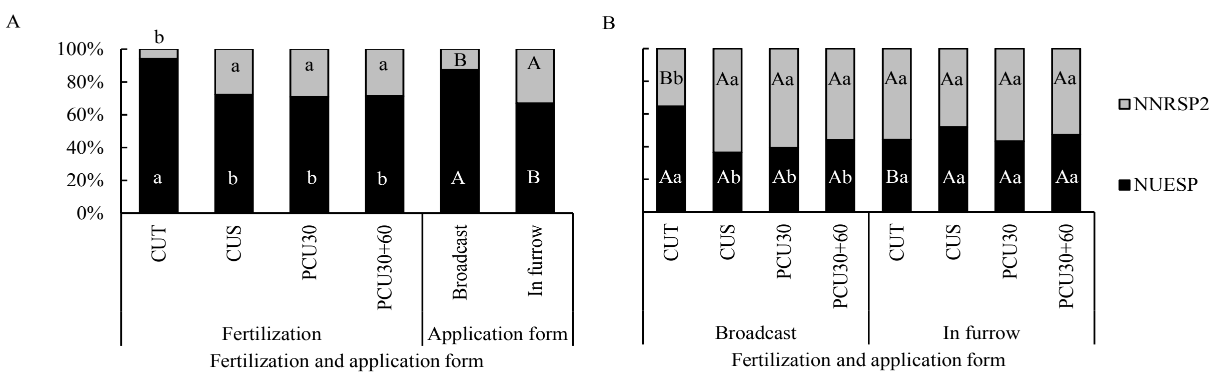


Figure 3. N use efficiency in soil-plant system (NUESP) and N not recovered by soil-plant system ($NNRSP_2$) obtained with Conventional urea topdressing (CUT), Conventional urea at corn planting (CUP), PCU to release in 30 days applied at corn planting (PCU30) and mixing of PCU to release in 30 and 60 days applied at corn planting (PCU30+60) applied broadcasted and in furrow in site 1 (A) e site 2 (B). lowercase letters compare fertilization treatments and uppercase letters compare application forms

## 4. Discussion

The corn yield was not affected, despite differences in performance of the fertilization treatments and application mode, the N rate used, and the soil as a source of N at both sites provided the nutrient required for the yields obtained. The appropriate concentration of N in leaves (Malavolta et al., 1997), and the similar total N in each situation, prove this assertion (Tables 2 and 3; Figure 2).

The supply of N during the corn cycle by topdressing (CUT) or gradual release of N (PCU30 and PCU30+60) was not beneficial to the plants. The N-leaves was adequate in all situations (Table 2); corn yield and total N accumulation were unchanged (Table 2 and Figure 2). The effectiveness of the PCU depends on the conditions of climate and soil (Noellsch et al., 2009; Malhi et al., 2011; Gagnon et al., 2012; Suter et al., 2013). These fertilizers are no better than conventional urea in many conditions (Hadi et al., 2008; Hyatt et al., 2010; Massey et al., 2011; Grant et al., 2012; Halvorson & Del Grosso, 2013; Khakbazan et al., 2013).

The PCU did not reduce palisadegrass N uptake by releasing in later times when the palisadegrass is completely shaded by the corn. This advantage is not necessary, because NFFP in both cases was small and ranged from 2% in the broadcast application and 1% in the in-furrow application in site 1 and 1.3% in site 2 (Table 3).

Intercropping corn and palisadegrass in crop and livestock integration systems is viable because the fertilization treatments and application forms did not affect the mass production of either the palisadegrass or the corn. NFFP is 1% or less of all NPF found in the corn and the palisadegrass together. Success of intercropping corn and palisadegrass without yield reduction and with good establishment of palisadegrass are common in the literature (Borghi et al., 2013; Ceccon et al., 2013; Almeida et al., 2017a, 2017b).

The conditions for $NH_3$ volatilization were different between sites. In site 1, fertilizer application at planting occurred seven days after a rain, when the soil was dry (Figure 1). This situation persisted for ten days and then it rained 62 mm in three days, which reduced the potential for volatilization in the broadcast application. Sahrawat (1984) reported that urease activity is zero in the case of dry soil conditions, and volatilization losses are negligible in conditions of low humidity. On this site rained 15 mm a few minutes after the application of CUT (Figure 1), which was enough for urea incorporation of the broadcast application. This statement is supported by the greater amount of NFFSP found with CUT in site 1 (Table 6). Proctor et al. (2010) reported that to reduce losses due to ammonia volatilization after the application of urea, application should be conducted in dry soil conditions or immediately before a significant rain event.

In site 2, applications of CUP, and PCU30 PCU30+60 occurred in conditions of moist soil; there was 7.5 mm of rain before the applications and two days later it rained 4 mm, which was insufficient for incorporation of urea in the broadcast application, which enhanced the loss by volatilization (Sahrawat, 1984; Proctor et al., 2010). Even in this situation, eighteen days after the application, it rained 50 mm in one day and 20 mm the next day (Figure 1). The volatilization loss also occurred in the application of the CUT in site 2, but to a lesser extent because it rained 7 mm two days after application, 17 mm on the fifth day and 16 mm the sixth day after the application (Figure 1).

The weather conditions occurring in the sites resulted in the differences in response to application modes in site 1 and in site 2, as explained S × A interactions in Table 1 and 6. In general, the broadcast application was better than the in-furrow application in site 1, and otherwise in site 2, except for the CUT, which was applied at another time, when weather conditions were more favorable to the broadcast application than to other fertilization treatments applied at planting (Figure 1).

The PCU did not enable the broadcast application. In site 2, where volatilization was facilitated, the PCU30 and PCU30+60 did not reduce N losses because NUEC and NUEP were equal to the CUP. With the broadcast application, these fertilization treatments resulted in recovery of 27.5 kg ha$^{-1}$ in corn and 1 kg ha$^{-1}$ in palisadegrass. In site 1, where water distribution favored broadcast application, PCU30 and PCU30+60 also had similar performance to CUP—corn recovered 61 kg ha$^{-1}$ of $^{15}$N-fertilizer for PCU and 66 kg ha$^{-1}$ with CUP. For palisadegrass, the N recovery using PCU30 and PCU30+60 was 3 kg ha$^{-1}$ and 2.7 kg ha$^{-1}$ for CUP (Table 3).

For good performance in the broadcast application, the PCUs are dependent on the rainfall distribution, as is conventional urea. The delayed release was not enough to prevent volatilization in site 2 because there were 18 consecutive days without rain after the broadcast application on soil moist (Figure 1). Volatilization mainly occurs in the first 2 or 3 weeks after application (Gong et al., 2013). The EEF do not always guarantee higher efficiency by reducing N losses in broadcast application (Noellsch et al., 2009; Malhi et al., 2011; Gagnon et al., 2012; Nash et al., 2013; Suter et al., 2013).

The greater amount of NFFS by broadcast application over in-furrow application in site 1 (Table 4 and Figure 4) occurred due to the dry soil condition, which reduced the loss by volatilization, and, thus, more N infiltrated into the first inches of soil. The distribution of the fertilizer on the soil surface increases the exposure of N to microbial action and, therefore, immobilization. There are other studies that demonstrated greater immobilization of nitrogen in broadcast applications than in in- furrow applications (Malhi & Nyborg, 1991; Malhi et al., 2001).

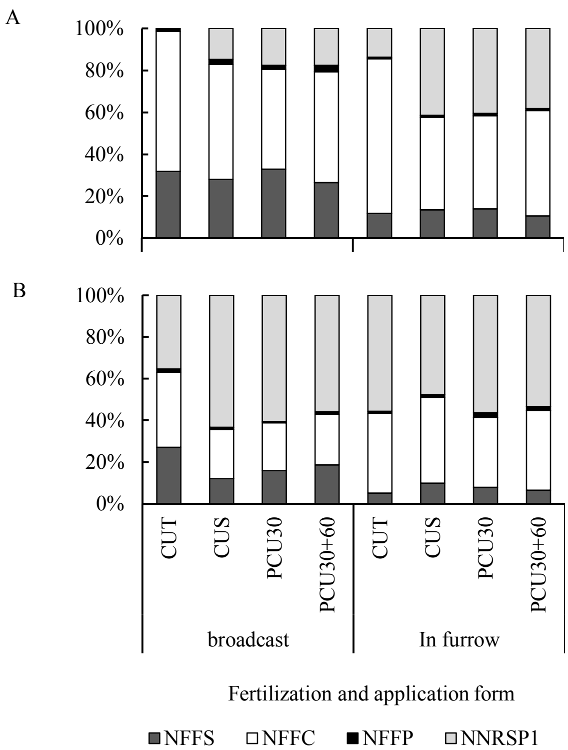


Figure 4. Balance of N-Fertilizer with proportion of N from fertilizer soil (NFFS); N from fertilizer corn (NFFC), N from fertilizer palisadegrass (NFFP); N not recovery in soil plant system ($NNRSP_1$) obtained with Conventional urea topdressing (CUT), Conventional urea at corn planting (CUP), PCU to release in 30 days applied at corn planting (PCU30) and mixing of PCU to release in 30 and 60 days applied at corn planting (PCU30+60) applied broadcasted and in furrow in site 1 (a) e site 2 (b)

In site 2, the N remaining after volatilization losses in the broadcast application was primarily immobilized by micro-organisms because the greater NFFS in broadcast application in relation to in-furrow in all fertilization treatments except the CUP (Table 4). Thus, little N was available to corn and palisadegrass, which together recovered only 24%, on average, of CUP, PCU30 and PCU30+60 fertilizations. On the other hand, CUT had 38% of NUEC and greater NRS (Table 4 and Figure 4) because the loss of N by volatilization was lower in relation to other forms, and thus, more N remained in the soil–plant system.

The broadcast application in site 1 recovered an average of 88% in the soil–plant system, a quantity greater than for the in-furrow application, wherein the recovery was 67%. There are two reasons for this difference: (i) the efficiency of the broadcast application in this site, and (ii) the greater immobilization of N in the soil with the broadcast application (Malhi & Nyborg, 1991; Malhi et al., 2001).

In site 1, the rain after the broadcast application favored reduction of volatilization but damaged the incorporation of N into the soil. In this experiment, the denitrification potential was higher because the Hapludalf in site 1 have high water holding capacity due to the block structure and 590 g $kg^{-1}$ clay in subsurface. This situation creates many areas of temporary anaerobiosis where denitrification occurs. Maharjan and Venterea (2013) determined higher denitrification with in-furrow application in relation to broadcast application, and when PCU was used, $N_2O$ losses were even greater. For Halvorson and Del Grosso (2013), the emission of a greater quantity of $N_2O$ occurred with the in-furrow application with various sources of urea in relation to the broadcast fertilizer.

In site 2, the NFFSP was higher with the broadcast application of CUT. At this location, the rains that occurred at the time of topdressing reduced the loss by volatilization, compared to rains at the time of planting (Figure 1). The N-fertilizer remaining promoted the greatest amount of N from the CUT present in the system and provided greater utilization by plants, as indicated by the greater NUEC than PCU attained by broadcasting at planting (Table 4). The broadcast CUT also favored NFFSP and NUESP compared with broadcast CUP, PCU30 and PCU30+60, all of which had more NNRSP (Table 6 and Figure 3).

The $NNRSP_2$ in this study varied between zero and 63% (Figure 3). Part of the losses was volatilization, mainly in the broadcast applications (Cai et al., 2002; Rochette et al., 2013). Leaching of N is another source of loss, which was more significant for in-furrow applications because of lower soil retention due to immobilizing the N (Ottman et al., 2000; Syswerda et al., 2012). Denitrification also resulted in loss, this process may have been more significant in furrow applications (Hadi et al., 2008; Grageda-Cabrera et al., 2011; Halvorson & Del Grosso, 2013; Maharjan & Venterea, 2013). Finally, losses of N by the plant shoots after anthesis also happen (Farquhar et al., 1979; Francis et al., 1993); these losses occur in greater proportion in situations where NUEC was higher, and thus, more $^{15}N$ was remobilized from the leaves to the grains, with a greater chance of loss.

## 5. **Conclusions**

Corn performance neither the biomass production of palisadegrass were affected by fertilization (CUT, CUP, PCU30 and PCU30+60) or with application form. PCU does not promote greater recovery of N-fertilizer for corn and palisadegrass compared to conventional urea.

The N from the fertilizer uptake in intercropped palisadegrass is less than 1% of all accumulated N in soil-plant system and is a maximum of 2% of N-fertilizer applied.

The controlled release urea does not enable broadcast application and depends on the same climatic conditions as the conventional urea to obtain good performance.

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