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Stabilized urea for maize grown on an Amazonian Cerrado soil

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Abstract

Urea splitting and the use of stabilized ureas in corn (*Zea mays* L.) crops are management strategies that increase urea efficiency and reduce nitrogen (N) losses by volatilization and leaching. This study aimed to evaluate the effects of urea stabilized with urease inhibitor (UI) and nitrification inhibitor (NI) compared to conventional urea applied at three different schedules, on corn grain yield and the dynamics of inorganic nitrogen on an Amazonian Cerrado soil, Brazil. Two experiments were carried out, one in 2019 and the other one in 2021, in a randomized block design with four replications. Treatments were arranged in a factorial scheme (3 × 3), with three types of urea (urea, U; UI; and NI) and three application schedules (100% at planting, 30% at planting and 70% as topdressing, and 30% at planting and two topdressings with 35% N). In 2019, compared to U and UI, NI increased corn yield when 100% of urea was applied at planting. Regardless of the splitting management, NI ensured the same yields. In 2021, urea splitting was required to improve corn yields, and UI promoted higher yield in all urea application schedule. In 2019 and 2021, both NI and UI, respectively, ensured higher inorganic N levels in the soil, especially after the first topdressing. These N contents are reflected in yield gains. Urea with nitrification or urease inhibitor may be a relevant option for managing nitrogen fertilization in corn crops in the Amazonian Cerrado.

1 | INTRODUCTION

Nitrogen (N) is a nutrient required in higher amounts by corn (*Zea mays* L.) and its inadequate supply results in significant yield losses (Silva et al., 2017). Due to its high demand by crops and soil dynamics, N fertilizers are the most used in agriculture (Sigurdarson et al., 2018). Urea stands out among the main N sources for crops because it has a higher N concentration (45%–46%), relatively lower cost, and easier use (Artola et al., 2011). On the other hand, its efficiency is considered low not only because it provides more inorganic N to the soil than plants can assimilate within the first growth stages but also because of ammonia (NH_3) volatilization when urea is applied to the soil surface without incorporation (Chien et al., 2009).

Under urease action, urea applied to the soil surface is rapidly hydrolyzed into NH_3 (Cantarella et al., 2018) and can be lost by volatilization. NH_3 can also be oxidized via nitrification forming nitrate (NO_3^-), which is easily leached (Fu et al., 2020) from root absorption zones. In addition to these two processes, mineral N can be immobilized by

Abbreviations: 100GW, 100-grain weight; DMPP, 3,4-dimethylpyrazole phosphate; ED, ear diameter; EL, ear length; GY, grain yield; NBPT, N-(n-butyl) thiophosphoric triamide; NI, nitrification inhibitor; SOM, soil organic matter; UI, urease inhibitor.

microorganisms, forming a non-labile reserve, or even lost from the soil by denitrification (Gillette et al., 2017). Nitrogen losses in soil-plant systems negatively compromise crop yield.

Among N output forms, NH_3 volatilization is the most expressive, with losses of around 50% of N added to soil via mineral fertilizers (Coskun et al., 2017). On the other hand, edaphoclimatic conditions, such as sandy soils and rainfall, and high urea doses, favor N losses by leaching in the form of NO_3^- (Byrne et al., 2020). Sandy soils, high rainfall and temperature, and low organic matter content are observed in Amazonian Cerrado, especially in Roraima state, an important region of Brazil, with an increasing grain production. Thus, management strategies to reduce N losses have aimed to ensure nutrient availability in the soil according to crop demands. This result can be achieved by splitting the recommended dose of fertilizer (Quemada & Gabriel, 2016) and/or using more efficient fertilizers (Cantarella et al., 2018).

Splitting N during the early corn growth stages can increase both grain yield (GY) and nutrient-use efficiency (Davies et al., 2020). However, a larger number of applications throughout the crop cycle increases operations and work in the field, which commonly results in increases in production costs (Allende-Montalbán et al., 2021).

Ureas stabilized with urease and nitrification inhibitors (NIs) can reduce N losses from the soil-plant system. Urease inhibitors (UIs) act by inhibiting enzyme active sites, thus reducing urea hydrolysis, which releases N in the form of NH_3 (Afshar et al., 2018). *N*-(n-butyl) thiophosphoric triamide (NBPT) is the most relevant UI due to its market availability and practical importance for agriculture (Klimczyk et al., 2021). NIs, such as 3,4-dimethylpyrazole phosphate (DMPP), reduce the action of bacteria of the genus Nitrosomonas, which oxidize NH_4^+ into NO_3^-. Thereby, N is maintained in the soil in ammoniacal form for a longer time and nutrient losses through denitrification and NO_3^- leaching are reduced (Byrne et al., 2020; Coskun et al., 2017).

Corn responses to stabilized ureas are divergent (Cancellier et al., 2016; Lucas et al., 2019; Szulc et al., 2023). Results differ with cultivation conditions, such as soil type, organic matter content, and climatic conditions, especially water excess, right after the inhibitor application (Byrne et al., 2020; Cantarella et al., 2018). Soils with high organic matter content are greater to provide N for plants and also to adsorb NH_4^+ (Soinne et al., 2020; Klimczyk et al., 2021). Soil type, pH, moisture level, organic matter content, coverage, and microbiological activity are determinant for N loss processes from mineral fertilizers. Straw that remains in no-tillage system contributes for a higher urease activity and also difficults the contact of urea and soil. In this condition, NH_3 volatilization increases (Klimczyk et al., 2021).

Core Ideas

- Nitrification or urease inhibitors may be an option for managing nitrogen in corn crops in the Amazonian Cerrado.
- Edaphoclimatic conditions influence the stabilized ureas efficiency in corn cultivation in the Amazonian Cerrado.
- Urea with urease or nitrification inhibitor ensured higher level of available nitrogen in the soil for plants.

Stabilized urea studies in corn crops are required in different cereal-growing regions. Thus, this study aimed to evaluate the effects of urea stabilized with UI and NI compared to conventional urea applied at three different schedules on corn GY and the dynamic of inorganic nitrogen on an Amazonian Cerrado soil, Brazil.

2 | MATERIALS AND METHODS

Two experiments were performed under field conditions. The first one was implemented in July 2019 and the second one in May 2021, with the treatments in the same plots in both years. They were carried out in the experimental area of the Agricultural Sciences Center of the Federal University of Roraima–CCA/UFRR (2° 52′ 15.49″ N latitude, 60° 42′ 39.89″ W longitude, and 85-m altitude) in Roraima State, Brazil.

According to Köppen, the local climate is classified as Aw type, with two seasons, one rainy (April–September) and another dry (October–March). The total rainfall and average temperature during the experiment in 2019 were 1831 mm and 28.7°C and in 2021 were 1314 mm and 28°C, respectively. Figure 1a,b shows the average daily rainfall and temperature during the experiments.

The experiments were carried out on a Latossolo Amarelo distrófico típico (Typic Hapludox, Soil Taxonomy) (Anjos & Schad, 2018), previously grown with cowpea in intercropping with cover crops, with subsequent succession with corn for three cycles. Before the experiment installation in 2019, the area was fallow for 1 year, with natural vegetation and predominance of herbaceous weeds. After corn harvest in 2019, *Urochloa brizantha* was planted, and the soil was kept under vegetation cover until the experiment installation in 2021.

Soil chemical attributes in the experimental area were analyzed (Table 1). Before the installation of each experiment, 10 soil simple samples (0.00- to 0.20-m depth layer) randomized in the experimental area were collected using a Dutch

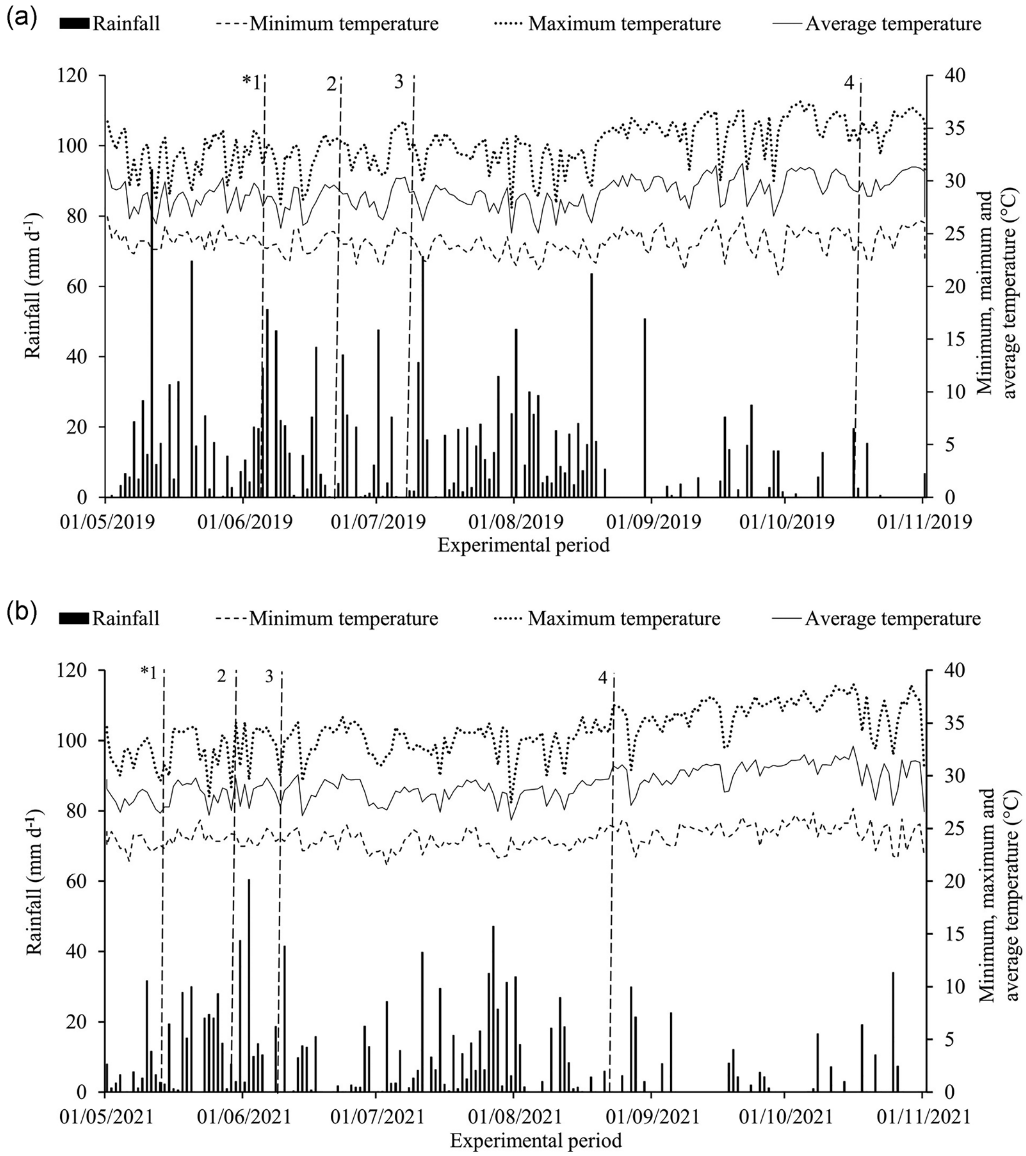

FIGURE 1 Data on daily rainfall (mm day^{-1}); minimum, maximum, and daily average temperature (˚C) during the experimental period (a) 2019 and (b) 2021; *1: Sowing and planting fertilization; 2: First topdressing (phenological stage V4–V6); 3: Second topdressing (phenological stage V6–V8); 4: Harvest. *Source*: National Institute of Meteorology—INMET, Boa Vista, RR, Brazil (2021).

TABLE 1 Soil chemical attributes, from the 0.00- to 0.20-m depth layer, before the installation of the two experiments.

Crop year	pH H_2O	P mg dm^{-3}	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	H + Al	CECe	SOM g kg^{-1}
			cmol$_c$ dm^{-3}						
2019	5.3	10.4	1.0	0.2	0.2	0.1	2.4	1.6	12.5
2021	5.3	8.5	0.9	0.3	0.1	0.2	2.4	1.4	9.7

Abbreviations: CECe, effective cation exchange capacity; SOM, soil organic matter.

auger to get a composite sample which was analyzed. The soil granulometric distribution in the experimental area is as follows: 670 g kg^{-1} sand, 48 g kg^{-1} silt, and 282 g kg^{-1} clay. Chemical and granulometric analyses were performed according to Teixeira et al. (2017).

2.1 | Experimental design and crop management

The two experiments were arranged in randomized blocks, in a 3 × 3 factorial scheme, with four replications. The first factor consisted of three types of urea (urea: U; with urease inhibitor “NBPT”: UI; and with nitrification inhibitor “DMPP”: NI), and the second factor was three application schedules (1: 100% N at planting; 2: 30% at planting and 70% in a single topdressing; and 3: 30% at planting and two topdressings with 35% N each).

Urea with NBPT was prepared with a mixture of 2.052 g AGROTAIN (1.08 kg L^{-1} density) per kilogram urea. Urea with UI was prepared for use at planting and later stored for topdressing fertilization.

Each experimental plot had 24 m^2 with eight 6-m-long rows spaced in 0.50 m. The useful area comprised the four central rows, with 4 m each one (8 m^2).

Corn was sown 30 days after natural vegetation desiccation and 48 days after *U. brizantha* desiccation in 2019 and 2021, respectively. Before desiccation, eight iron frames (0.25 m^2 each) were randomly placed within the planting area and straw was collected. Thereafter, plant material was dried in a forced-air circulation oven at 60°C until constant mass and weighed on a semi-analytical scale. In 2019 and 2021, vegetation cover in the experimental area corresponded to 10.6 and 13.3 Mg ha^{-1} dry mass, respectively.

The transgenic corn cultivar “30F35HR” was used and sown using a mechanized seeder with four seeding rows spaced at 0.50 m. Six seeds were distributed per meter and, 8 days after sowing, it was thinned out, maintaining three plants per meter (60.000 plants ha^{-1}).

For each experiment, fertilization was determined based on soil analysis (Table 1), as follows; 150 kg ha^{-1} N (source and splits according to treatments), 100 kg ha^{-1} K_2O (potassium chloride), 120 kg ha^{-1} P_2O_5 (triple superphosphate in 2019 and single superphosphate in 2021), and 50 kg ha^{-1} FTE BR 12 (1.8%, 0.8%, 2.0%, 9.0%, and 1.0% of B, Cu, Mn, Zn, and S, respectively). All N fertilizations were performed manually, parallel to 0.10 m from the planting row, and topdressings were carried out at the phenological stages of 4–6 (V4–V6, where V4 is four-leaf-stage and V6 is six-leaf-stage) and 6–8 (V6–V8 where V8 is eight-leaf-stage) leaves. The source of K was divided into three times, with 30% of dose at planting and the remainder divided into two topdressings, with nitrogen fertilization.

2.2 | Sampling and measurements

During the experiments, soil samples were taken to determine inorganic N (mg kg^{-1}) (NH_4^+-N + NO_3^--N) at four different times; 7 days after planting, 7 days after the first and second topdressing and at corn tasseling. In each plot, three simple soil samples were collected, 0.10 m from the planting rows, from three depth layers: 0–10, 10–20, and 20–40 cm. In the end, a composite sample was obtained for each depth, per plot, and at each sampling time.

Samples were collected with a Dutch auger and placed into plastic bags inside thermal boxes with ice. Right after sampling and in a refrigerated environment, samples were passed through 4-mm sieves and frozen for analysis of soil inorganic N (mg kg^{-1}) following the method of Tedesco et al. (1995).

At the end of the experiments, six ears from each plot were evaluated for ear length (EL, cm), using a graduated ruler, ear diameter (ED, mm) with a digital caliper, 100-grain weight (100GW, g), and GY (kg ha^{-1}) estimated by harvesting ears from all plants within the useful area of each plot. Grain moisture content was standardized to 13% for GY and 100GW determinations, using a G650 moisture and impurity analyzer (GEHAKA AGRI).

2.3 | Statistics and data analysis

Data were analyzed for normality using the Shapiro–Wilk test. Individual analysis of variance was performed for all variables, in each year, by the *F* test ($p \leq 0.05$). Joint analysis of the data was performed when the mean square of the residual ratio was less than 7:1, following Gomes (2000). Treatments means were compared by Tukey's test ($p \leq 0.05$). The analyses were performed using the statistical program SISVAR version 5.6 (Ferreira, 2014). Graphs were done using the ggplo2 package (Wickham, 2016) of R software (R Core Team, 2023).

3 | RESULTS

3.1 | Ear Length and Diameter

Figure 2a,b shows the interaction effects between urea types and application schedule and between crop years and urea application schedule on corn EL. Plants fertilized with NI or UI had similar EL for all urea application schedule. Two topdressings with U were necessary to observe an increase in EL.

The increase in topdressing fertilizations was required for U to provide the same EL as the other ureas studied. The superior efficiency of stabilized ureas may be related to higher N losses by U, explaining the lower performance. When analyzing EL as a function of the application schedule in both crop years, all application schedules promoted the same EL values in 2019 with an average of 15.8 cm. The increase in topdressing fertilizations increased EL in 2021. Regardless of urea type, EL was higher in 2019 when 100% of urea was added at planting.

In 2019, corn ED averaged in 47.8 mm for all treatments. In 2021, the application of 100% U at planting promoted the lowest ED (Figure 2c). For application schedule 2, only UI provided differences in ED between crop years, higher in 2021, which showed its higher efficiency in making urea

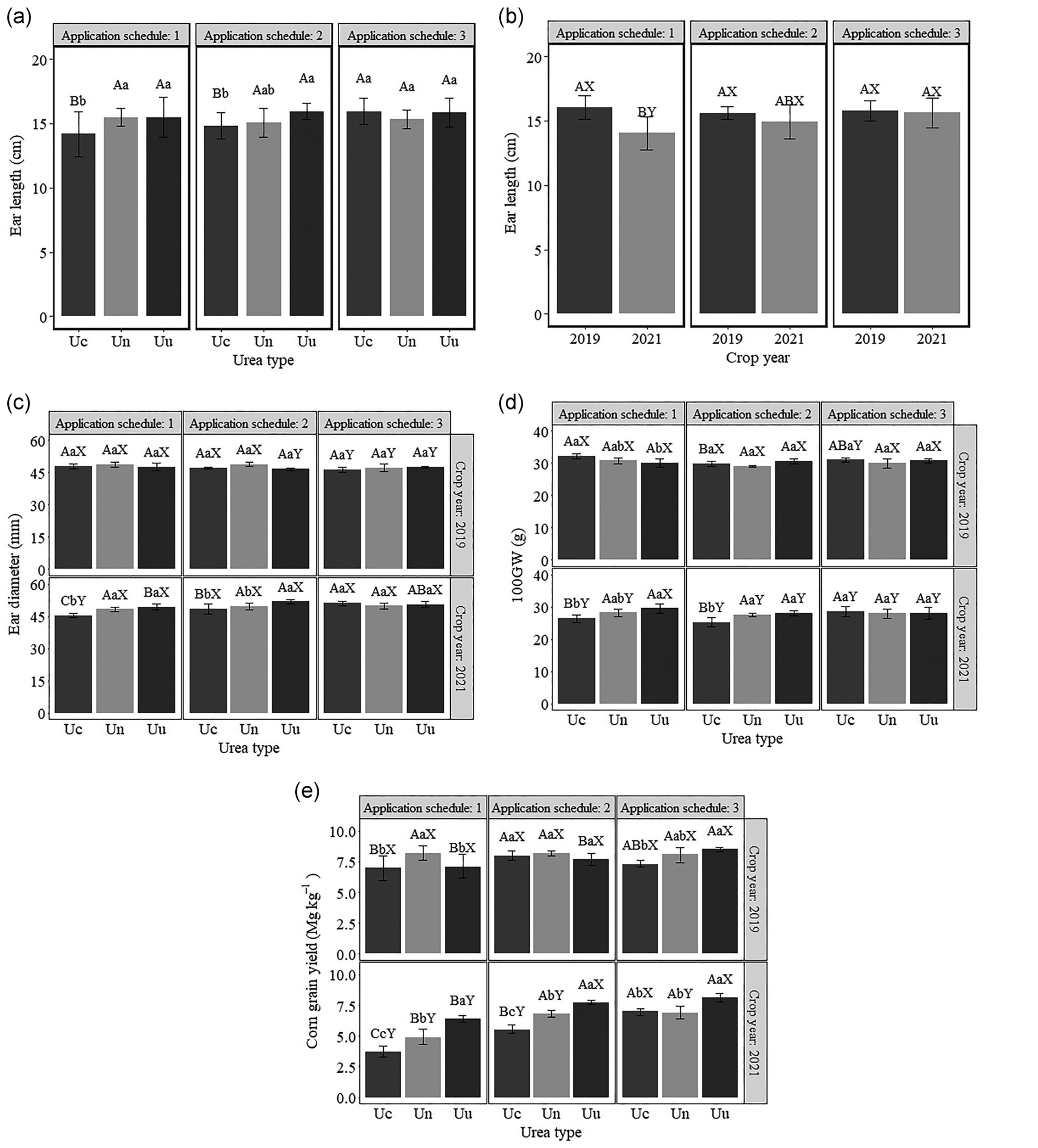

FIGURE 2 Ear length due to the interactions between the factors urea types and application schedules (a), and application schedules and crop year (b). Ear diameter (c), 100-grain weight (100GW) (d), and corn yield (e) due to the interactions between the factors urea types, application schedules, and crop years. Bars followed by different lowercase letters (a, b, and c) indicate statistical differences between urea types, for each year and application schedule. Bars followed by different uppercase letters (A, B, and C) indicate statistical differences between application schedule for each urea type and each year. Bars followed by different letters (X and Y) indicate statistical differences between crop years for each urea type and application schedule. Means were compared by Tukey's test at 5% probability. Error bars are the standard error of the mean. Boa Vista, Roraima State, Brazil.

available for plants in that year. Only NI maintained ED values in any of the application schedule. The efficiency of U in increasing ED varied mostly with the number of topdressings since one or two topdressings increased it.

3.2 | Weight of 100 grains and corn yield

A difference was observed between the ureas in terms of 100GW in 2019, only when 100% of the recommended N dose was applied at planting (Figure 2d) with U. The use of U allowed the grains to present higher M100G than those cultivated with UI. The NI presented the same M100G as the other ureas. In the same year, stabilized ureas did not differ in terms of the application schedule.

In 2021, the use of UI applied 100% at planting promoted a higher M100G than that with the use of U. For twice application, stabilized ureas had higher values than U. There was no difference among ureas when N fertilizing was divided three times (Figure 2d). Both in 2019 and 2021, U showed differences in 100GW among application schedule. For all treatments, except for UI applied 100% at planting, 100GW was higher in 2019.

As for yield, application of 100% U and UI recommended dose at planting reduced GYs in 2019 (Figure 2e). Likewise, application of 100% NI at planting provided a yield of 8.2 Mg ha^{-1}, which was superior to the other sources by at least 13%. Regardless of the number of topdressings, NI maintained the same yield average.

The effects of treatments on GY were different between 2019 and 2021. In 2021, regardless of the application schedule, UI ensured the highest yields. However, like other ureas, UI required at least two applications to increase yield (Figure 2e).

3.3 | Soil inorganic N (NH_4^+-N + NO_3^--N)

The soil inorganic N (NH_4^+-N + NO_3^--N mg kg^{-1}) analyses in the first evaluation in 2019 showed higher inorganic N levels in the 0- to 10-cm depth layer when NI and U were used and fewer applications were made (Figure 3a). The same result could still be observed in the second and third evaluations, only for NI (Figures 4a and 5a). Therefore, this higher N availability led to a reduction in the number of applications in 2019.

Despite the highest inorganic N concentration in the first depth layer using NI in 2019, lower N levels were found in the deeper layers when compared to those obtained using U. This result could be observed in the 10- to 20-cm depth layer when 100% of the recommended dose was applied at planting (Figure 3b) and in the 20- to 40-cm depth layer regardless of the application schedule (Figure 3c).

In the first evaluation in 2021, urea types showed differences in soil N contents in the 0- to 10-cm depth layer when 100% of the recommendation was applied at planting with UI providing higher levels (Figure 3a). However, this application schedule showed no differences for N levels among urea types in the second and third evaluations (Figures 4a and 5a).

In 2021, with reduced applications, NI provided lower N content in the 0- to 10-cm depth (Figure 3a) and 10- to 20-cm depth (Figure 3b) layers than did U, but similar levels in the 20- to 40-cm depth layer (Figure 3c). Thus, the higher soil N levels in 2019 demonstrated the influence of management history in the experimental area (Figure 3a).

In both years, in the first two soil depth layers, the application schedule 3 provided similar N levels in the soil for the three urea types (Figure 3a,b). Overall, the highest inorganic N levels were obtained by the application schedule in which urea addition was higher, due to the proposed treatment, which was observed until the third evaluation (Figures 3–5).

In 2019, the second evaluation revealed that UI provided higher inorganic N levels between 20- and 40-cm depth (Figure 4c), that is, N moved down to deeper layers. Therefore, the use of this type of urea can contribute to N output from the root zone of corn plants, which at the time of evaluation were between the phenological stages V5 and V6.

In 2021, even with no difference in N contents in the 0- to 10-cm depth layer between urea types applied 100% at planting, UI provided higher N contents than NI in the deeper layers of the soil. When urea application was split into two and three times, UI provided higher N availability for corn plants than U in the three depth layers, except for application schedules 3 and 2, in 10- to 20-cm and 20- to 40-cm depth layers, respectively (Figure 4).

In the third evaluation in 2019 (Figure 5a), NI was more efficient in providing higher inorganic N levels than U in 0–10 cm (application schedules 1 and 2) and in 10–20 cm soil depth layers (Figure 5b). However, it showed no difference from U in the 0–10 cm (application schedule 3) and in 20–40 cm soil depth layers (Figure 5c). In the deepest layer, UI applied twice and three times provided higher N contents than did NI and U, respectively.

Figure 5 still shows that in 2021 soil N content variations between urea types were not verified in the 0–10 cm soil depth layer, regardless of the application schedule. However, in the 20- to 40-cm depth layer, UI and U had the highest N contents in the application schedules 1 and 3.

At corn tasseling in 2019, the main differences in N soil contents were observed in the 0–10 cm soil depth layer. U promoted higher soil N content in this depth layer when applied 100% at planting than the other application schedules and higher than the stabilized ureas. In application schedules 2 and 3, NI presented higher N content than U and lower than U

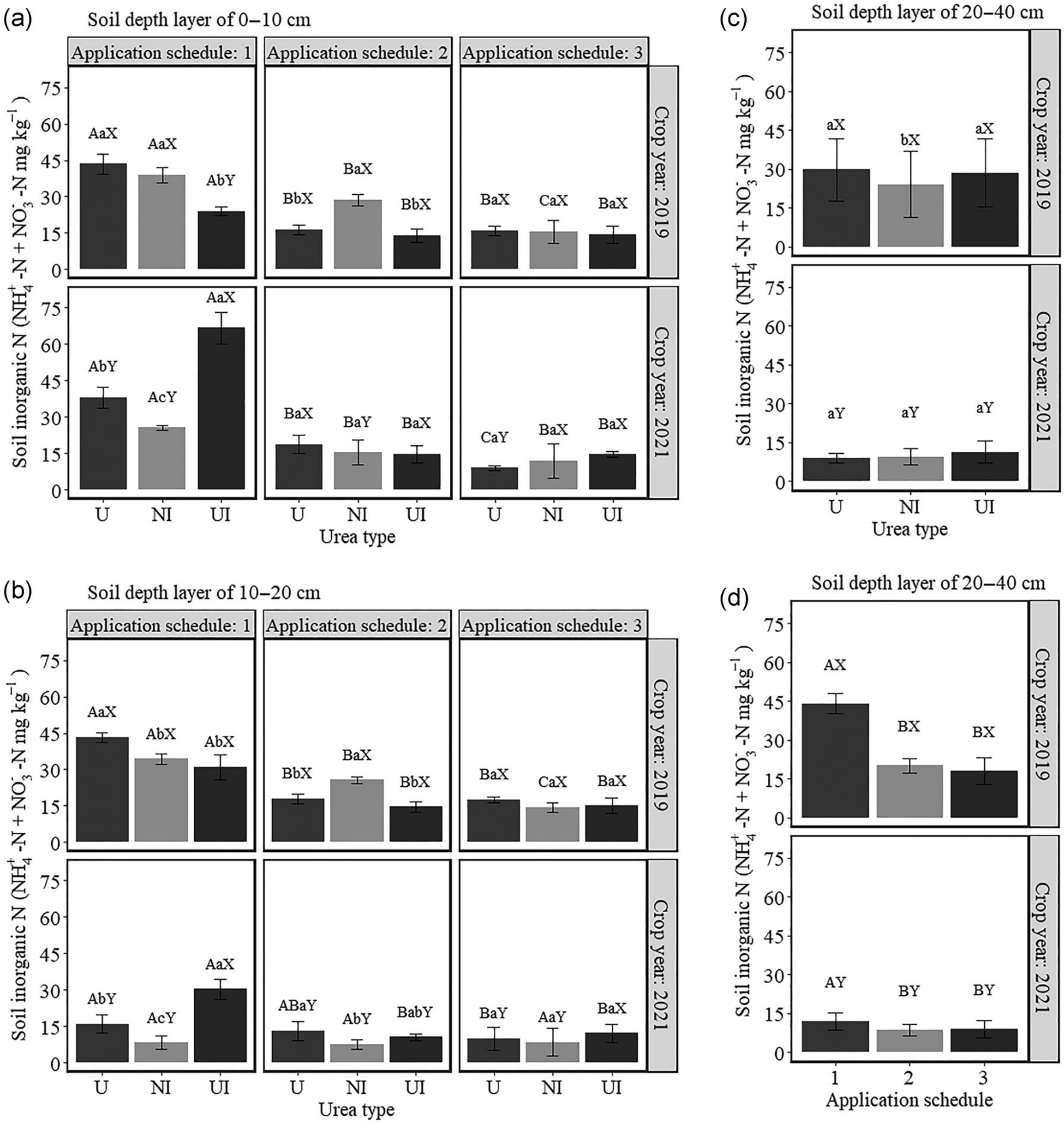

FIGURE 3 Soil inorganic N (NH$_4{}^+$-N + NO$_3{}^-$-N mg kg^{-1}) in three soil depth layers, 7 days after planting fertilization, due to the interactions between the factors; urea types, application schedules, and crop years (a: 0–10 cm; b: 10–20 cm); urea type and crop year (c: 20–40 cm), and application schedule and crop year (d: 20–40 cm). Bars followed by different lowercase letters (a, b, and c) indicate statistical differences between urea types for each year and application schedule. Bars followed by different uppercase letters (A, B, and C) indicate statistical differences between application schedule for each year and urea type. Bars followed by different letters (X and Y) indicate statistical differences between crop years for each urea type and application schedule. Means were compared by Tukey's test at 5% probability. Error bars are the standard error of the mean. Boa Vista, Roraima State, Brazil.

and UI, respectively. Only UI presented the same soil N average in the three application schedules (Figure 6a).

In 2021, U presented N content, in the 0- to 10-cm depth layer, similar to stabilized ureas. However, UI provided higher N content than NI (Figure 6a). UI had the highest N content in the deepest layer (Figure 6c) and lowest in the 10- to 20-cm depth layer (Figure 6b). Splitting urea into three applications provided similar N contents at all studied depths.

4 | DISCUSSION

4.1 | Ear Length and Diameter

Both EL and ED are parameters related to the number of grains per row and number of grain rows per ear, and hence potential yield (Mendes-Moreira et al., 2014). Therefore, the lowest EL and ED values observed may be related to the

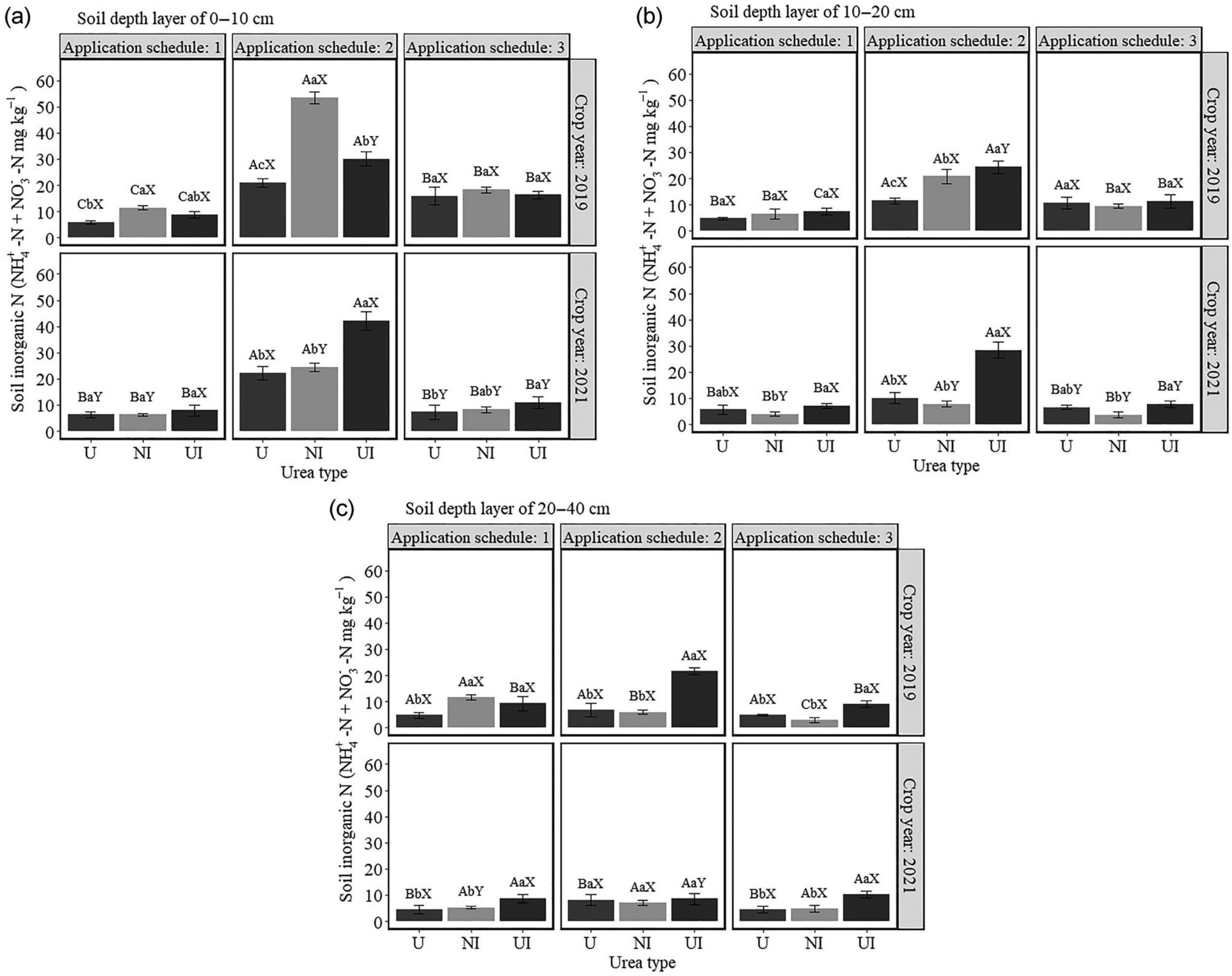

FIGURE 4 Soil inorganic N (NH_4^+-N + NO_3^--N mg kg^{-1}) in three soil depth layers, 7 days after the first topdressing, due to the interactions between the factors; urea types, application schedules, and crop years (a: 0–10 cm; b: 10–20 cm; c: 20–40 cm). Bars followed by different lowercase letters (a, b, and c) indicate statistical differences between urea types for each year and application schedule. Bars followed by different uppercase letters (A, B, and C) indicate statistical differences between application schedule for each year and urea type. Bars followed by different letters (X and Y) indicate statistical differences between crop years for each urea type and application schedule. Means were compared by Tukey's test at 5% probability. Error bars are the standard error of the mean. Boa Vista, Roraima State, Brazil.

lowest N recovery, applied at higher levels (100% at planting), as observed with the use of U. This fertilizer has low use efficiency due to a high inorganic N availability in the soil at development stage when corn has a lower N demand than in the first vegetative stages (Chien et al., 2009). However, early N loss can cause insufficiency at critical crop stages, reducing EL and ED and possibly reflecting in lower yields. According to Okumura et al. (2013), high N levels applied to the soil have lower recovery and hence increasing chances of loss. However, splitting urea (Davies et al., 2020) and using NI and UI (Cantarella et al., 2018), even at higher levels, show higher recovery (Okumura et al., 2013), thus explaining the higher ear lengths and diameters observed in our study.

4.2 | Weight of 100 grains and corn yield

M100G is not a variable commonly affected by urea types (Lucas et al., 2019). In these studies, corn grain weights promoted by stabilized ureas did not differ from that by U. Our findings highlighted a potential asynchrony between N supply and demand during plant growth. This lack could be a result of N losses with the use of U as the number of applications decreased.

In 2019, NI provided the better averages for corn yield (Figure 2e). Our results suggest that high rainfall, low sol organic matter (SOM) content, and soil texture influenced N outputs from the root zone and reduced N use from U and UI,

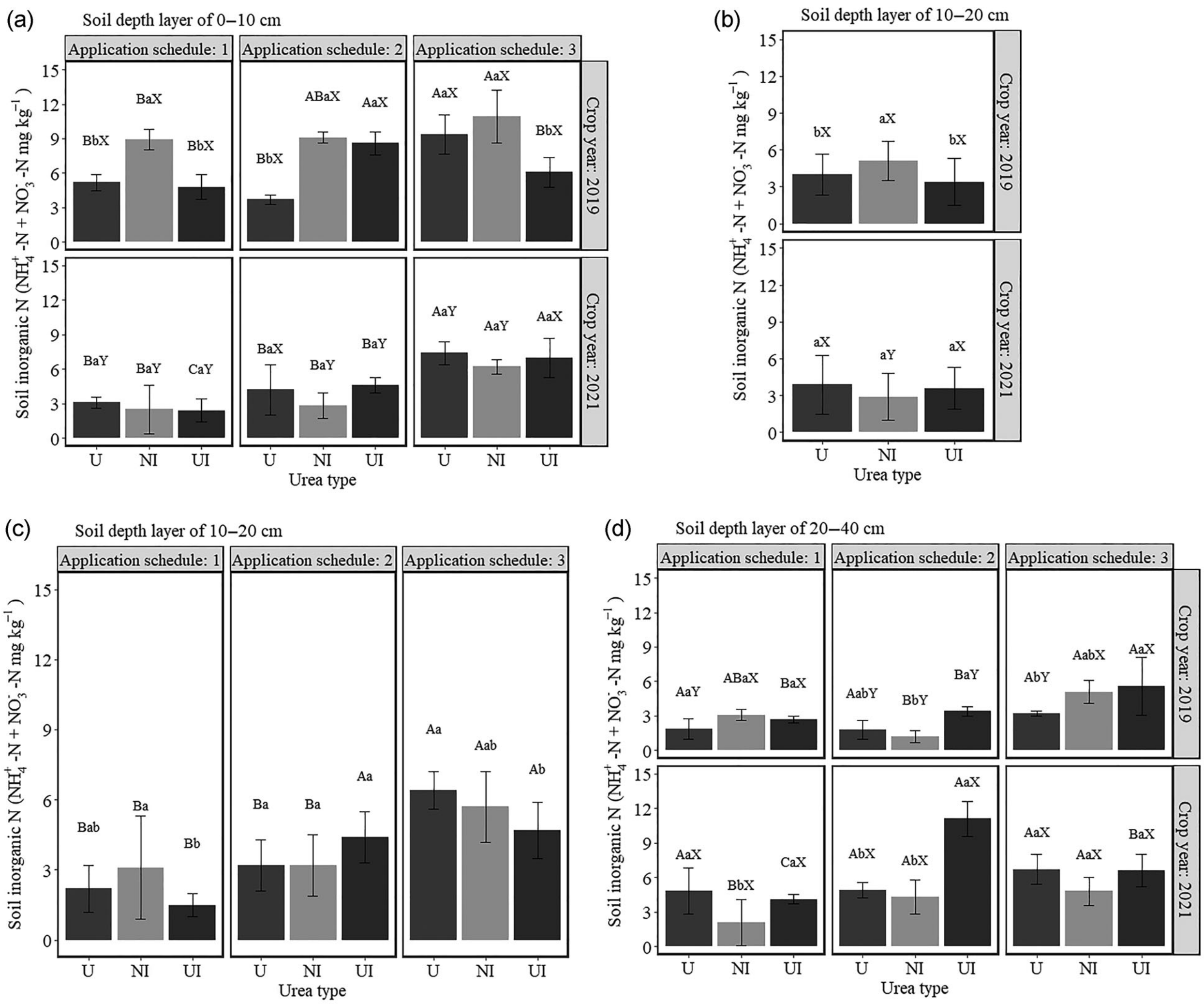

FIGURE 5 Soil inorganic N (NH_4^+-N + NO_3^- -N mg kg^{-1}) in three soil depth layers, 7 days after the second topdressing, due to the interactions between the factors; urea types, application schedules, and crop years (a: 0–10 cm; d: 20–40 cm); urea types and crop years (b: 10–20 cm); and application schedules and urea types (c: 10–20 cm). Bars followed by different lowercase letters (a, b, and c) indicate statistical differences between urea types for each year and application schedule. Bars followed by different uppercase letters (A, B, and C) indicate statistical differences between application schedule for each urea type and year. Bars followed by different letters (X and Y) indicate statistical differences between crop years for each urea type and application schedule. Means were compared by Tukey's test at 5% probability. Error bars are the standard error of the mean. Boa Vista, Roraima State, Brazil.

in 2019. In June of the same year, when planting was carried out, monthly accumulated rainfall was 432 mm, with rainfall of 1048 mm until the R1 stage of corn growth (Figure 1a). Ghiberto et al. (2011) found that accumulated rainfalls of 326 and 297 mm within 17 and 18 days, respectively, were enough to cause N losses by leaching in sugarcane grown on an Oxisol.

In 2021, U showed the highest differences in yield among all management types. When the entire dose was applied at planting, corn yield was reduced by 46.6% when compared to the same urea splitting three times (Figure 2e). During the first corn development stages and under high rainfall and temperatures, as in the state of Roraima, urea splitting can increase corn yield and nutrient use efficiency, ensuring N for the crop according to its demand (Davies et al., 2020; Quemada & Gabriel, 2016).

In 2021, there was a higher accumulation of straw in the soil, with predominance of *U. brizantha* (13.3 Mg ha^{-1}), than in 2019, with predominance of natural vegetation (10.6 Mg ha^{-1}). In the same year, less intense rains were observed right after planting and 6 days after (Figure 1b). Therefore, application of urea on denser straw of *U. brizantha*, added to lower rainfall, made it difficult to incorporate urea into the soil. Under these conditions, nitrogen fertilizers that did not contain a UI were more exposed to the action of the enzyme present in straw and soil, which may have increased N losses by volatilization. Low rainfall (from 5 to 40 mm) before and after application of urea is known to not be enough to

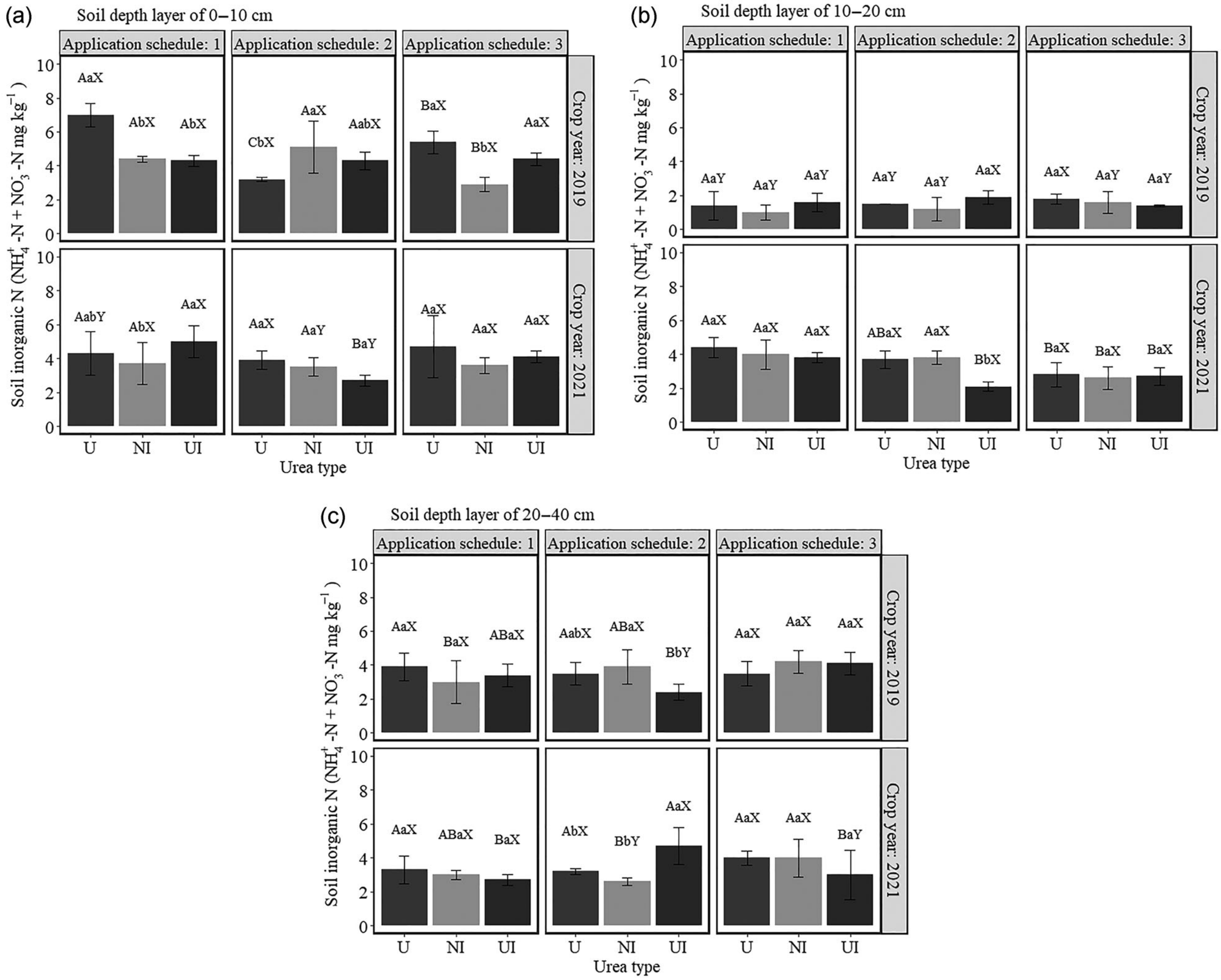

FIGURE 6 Soil inorganic N ($NH_4{}^+$-N + $NO_3{}^-$-N mg kg^{-1}) in three soil depth layers in the maize tasseling stage, due to the interactions between the factors: urea types, application schedules, and crop years (a: 0–10 cm; b: 10–20 cm; and c: 20–40 cm). Bars followed by different lowercase letters (a, b, and c) indicate statistical differences between urea types for each year and application schedule. Bars followed by different uppercase letters (A, B, and C) indicate statistical differences between application schedule for each year and urea type. Bars followed by different letters (X and Y) indicate statistical differences between crop years for each urea type and application schedule. Means were compared by Tukey's test at 5% probability. Error bars are the standard error of the mean. Boa Vista, Roraima State, Brazil.

incorporate urea and hence mitigate N losses by volatilization (Barth et al., 2020; Cantarella et al., 2018; Degaspari et al., 2020; Mira et al., 2017; Zaman et al., 2008).

Nitrogen supply from SOM can result in yield gains (Soinne et al., 2020). According to Table 1, SOM accumulation was higher in 2019 than in 2021. Such difference may have contributed to higher corn yields in that year. Furthermore, in years prior to 2019, cowpea cultivation in the experimental area may have contributed to N supply for corn cultivation in 2019.

Another potential explanation for yield differences between both years is straw quality. *U. brizantha* straw has a higher carbon/nitrogen ratio than herbaceous plants from fallow areas (Teixeira et al., 2014). Therefore, during *U. brizantha* straw decomposition, microorganisms immobilize N. Most likely, in 2021 there was considerable immobilization of N from ureas added to the soil, contributing to the reduction in nutrient availability in the first stages of maize development.

The higher yields promoted by UI compared to U do not corroborate the findings of Barth et al. (2020) or Cantarella et al. (2018). The first authors stated that although NBPT urea application reduced NH_3 losses by up to 60%, it promoted no sugarcane yield gains; the latter reported that NBPT added to urea reduced NH3 volatilization losses by 52%, but sugarcane yields only increased by 6%. Our study shows that a proper UI application in corn crops may be an efficient management tool to ensure yield increases in the Cerrado of Roraima, Brazil.

4.3 | Soil inorganic N (NH_4^+-N + NO_3^--N)

According to Figures 3a, 4a, and 5a, NI maintained higher levels of N in the soil, when compared to the other ureas, mainly in the 0- to 10-cm depth layer. NI reduces NO_3^- leaching once urea is hydrolyzed, making N available in its ammoniacal form. As a cation, NH_4^+ is less leachable than NO_3^-, as it electrostatically binds to negatively charged surfaces of clay minerals and functional groups of organic matter in soil (Cancellier et al., 2016; Do Vale et al., 2013). This result highlights the importance of NI in soils with low effective cation exchange capacity and intense rainfall, such as the soil in the present study (Table 1 and Figure 1a). Thus, this inhibitor causes N to be close to fertilizer application sites (Espindula et al., 2021).

In 2021, even though UI reduced corn yield when applied 100% at planting compared to the others UI application schedules, this urea provided higher yields compared to the other types (Figure 2e). Thus, the initial inorganic N availability provided by UI was essential for a superior yield concerning the other ureas.

NBPT UI acts in the soil for up to 14 days. It delays and reduces NH_3 losses by volatilization, but does not fully inhibit them, losing efficiency over time (Espindula et al., 2021; Soares et al., 2012). Its use with reductions in the number of applications does not necessarily provide enough N for corn crops until critical growth stages.

The largest losses of inorganic N in the soil profile were not observed with the use of U, as there were certainly considerable losses of N by volatilization as well. The highest N contents in soil depth layer of 20–40 cm, after the first topdressing, in 2019 and 2021, were observed with the use of UI. This was because as volatilization losses reduced, more N became available not only to plants but also for conversion to NO_3^- and hence, with high rainfall, leached to great soil depths (Allende-Montalbán et al., 2021).

The higher soil N availability until the third evaluation, mainly in the first layer, may have coincided with the synchronism between N supply and N crop demand, which was in the V8 stage. Silva et al. (2017) found that more N should be made available at this stage due to high corn demand. Thus, the highest N concentration up to this stage contributed to crop performance, especially with NI in 2019.

At corn tasseling, the differences in N content did not reflect in corn yield (Figure 6). This behavior was only observed in this evaluation; in the other evaluations, stabilized ureas provided equal levels to or higher than those of U. Thus, soil inorganic N content at corn tasseling did not define the yield obtained.

The response mentioned above is influenced by several factors such as N availability and assimilation rate, which must coincide with crop stages of higher N demand. Studies have shown that between V4 and V14 stages, corn has the largest N accumulation (Bender et al., 2013; Mueller et al., 2019; Silva et al., 2017). Moreover, at phenological stage R1, corn plants reached 65%–70% of their total N requirement and, from this period onward, N assimilation by the crop gradually decreased (Abendroth et al., 2011; Bender et al., 2013; Mueller & Vyn, 2016). These factors, therefore, can explain why the N content at this stage did not reflect the obtained yield.

In the current study, even with the variations between years, the N content saved by using stabilized ureas can lengthen the time between topdressing fertilizations. Thus, in case of any difficulty to carry out urea fertilization, stabilized ureas ensure a longer N permanence in the soil.

5 | CONCLUSIONS

Corn grains yield on an Amazonian Cerrado soil is higher with the use of stabilized ureas when compared to conventional one, depending on the urea application schedules and the edaphoclimatic conditions. In 2019, under high rainfall, natural vegetation, and low SOM, the NI provided higher GY when all urea was applied at planting. In 2021, when soil was under dense *U. brizantha* straw and less intense rainfall to incorporate the urea applied to the soil, the UI was more efficient, regardless of the application schedule.

The nitrification or UIs ensured higher nitrogen availability for maize, mainly in the first soil layers, resulting in higher GY. This indicates that stabilized ureas can be a viable option to improve corn GY in the Amazonian Cerrado. However, it is important to consider the specific soil and climate conditions to decide the best nitrogen fertilization strategy in order to obtain better GYs.

AUTHOR CONTRIBUTIONS

Thaís Santiago Castro: Formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Paulo Roberto Ribeiro Rocha**: Conceptualization; formal analysis; investigation; methodology; writing—review and editing. **Glauber Ferreira Barreto**: Formal analysis; investigation. **Sonicley da Silva Maia**: Investigation. **Sandra Cátia Pereira Uchôa**: Writing—review and editing. **Valdinar Ferreira Melo**: Writing—review and editing. **Karine Dias Batista**: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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