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# Nitrapyrin application at different topographic positions affects corn productivity and economic returns

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## Abstract

Nitrogen (N) use efficiency on claypan soils is often low; therefore, adopting effective management practices is crucial for increasing corn (*Zea mays* L.) productivity and maximizing economic returns. The objective of this 4-year field study (2019–2022) was to evaluate the impact of anhydrous ammonia (AA) with or without a nitrification inhibitor (nitrapyrin) on corn productivity, grain quality, partial factor productivity (PFP), and economic returns across different topographic positions (shoulder, backslope, and footslope) within a landscape. Averaged over the years, AA + nitrapyrin treatment had over 6.4% yield advantage compared to AA alone. Grain N removal was 11 kg ha$^{-1}$ higher and PFP was 3.6 units higher with AA + nitrapyrin compared to AA treatment. Although the expected net returns with nitrapyrin were lower at the footslope and higher at the shoulder position, the incremental yields, economic yield difference, and net economic gains at the footslope were consistently greater than those at the backslope and shoulder. Averaged over site-years, the footslope position generated higher net economic gains (\$200.07 ha$^{-1}$), which were \$46.04 and \$125.37 ha$^{-1}$ higher than the backslope and shoulder positions, respectively. These findings emphasize the importance of site-specific N management with nitrapyrin for optimizing yields, enhancing nutrient use efficiency, and maximizing economic returns under varying landscapes.

## Plain Language Summary

Sloping fields often have variations in soil properties across the landscape, which affect soil-water movement, nutrient availability, and crop yields. Farmers often use nitrogen stabilizers to improve nitrogen availability and increase yields, but their effectiveness can vary depending on topographic position. We tested whether adding a stabilizer (nitrapyrin) at different slope positions would improve corn yields and economic returns. We found that nitrapyrin improved corn yields, nutrient use efficiency, and profitability across three topographic positions (shoulder, backslope, and

**Abbreviations:** AA, anhydrous ammonia; NI, nitrification inhibitor; PFP, partial factor productivity; TP, topographic position.

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footslope). These results show that the effectiveness of nitrogen stabilizers varies across topographic positions and growing season conditions. These findings can help farmers develop better nitrogen management strategies for corn production.

## 1 | INTRODUCTION

Inefficient nitrogen (N) use remains a major constraint to achieving optimal crop yields, with nitrogen use efficiencies (NUEs) averaging only 35% globally and 41% in US corn (*Zea mays* L.) production systems (Omara et al., 2019; USDA ERS, 2021). Low NUE not only reflects limited uptake by the crop but also highlights the susceptibility of applied N to various loss pathways. Nitrogen losses through leaching (Hussain et al., 2020), denitrification (Burzaco et al., 2013; Butterbach-Bahl et al., 2013; Drury et al., 2009), and volatilization (Timilsena et al., 2015; Woodley et al., 2020) can reduce the amount of N available during critical growth stages, especially under conditions that limit soil retention and plant uptake. These challenges are particularly pronounced in claypan soils, where smectitic clay layers with low saturated hydraulic conductivity (<10 mm $h^{-1}$) restrict water movement, limit drainage, and create conditions favorable for losses (Lerch et al., 2013; Nash et al., 2012). Such problematic soils are widespread in major corn-producing states of the US Midwest, especially within the Central Claypan Areas (Major Land Resource Area [MLRA] 113) and the Southern Illinois and Indiana Thin Loess and Till Plain (MLRA 114). Central Claypan Areas spans 32,778 $km^2$, with 69% located in Illinois and 31% in Missouri, while Southern Illinois and Indiana Thin Loess and Till Plain covers 26,904 $km^2$, including 47% in Indiana, 38% in Illinois, and 15% in Ohio. Despite geographic variation, both regions face similar N management challenges due to restrictive subsoil properties and a high potential for N loss and low NUE.

Several studies have quantified these losses under claypan or poorly drained soil conditions, highlighting the importance of site-specific N management. For example, Johnson et al. (2022) reported that denitrification losses from anhydrous ammonia (AA) application could range up to 7.6% of applied N in Missouri claypan soils, particularly under poorly drained conditions. In a 3-year study, Nash et al. (2015) observed that volatilization losses reached 7.8% of applied N when non-coated urea was surface applied in 2010, with the greatest losses occurring under warm and dry conditions in central Missouri. In Iowa, a multi-year field study found that nitrate ($NO_3^-$) losses through tile drainage ranged from 23 to 63 kg $ha^{-1}$, depending on precipitation and management practices (Kanwar et al., 1988). Similarly, in Illinois, David et al. (1997) reported that tile drainage removed approximately 25%–85% of residual nitrate-N. Kranz and Kanwar (1995) further noted that up to 70% of leached nitrate could originate from less than 30% of the field area, typically the most poorly drained zones. These findings highlight the need for improved N management to reduce losses and enhance fertilizer use efficiency in claypan soils.

Incorporating a nitrification inhibitor (NI) to N fertilization strategies is recommended as a best management practice for claypan soils to improve fertilizer use efficiency, particularly under warm and wet conditions that promote denitrification and leaching (Kaur et al., 2020; Steusloff et al., 2019a, 2019b). Among available NIs, nitrapyrin has been widely studied in claypan landscapes, especially when applied with AA. Several studies have demonstrated that this practice improves corn yield by enhancing N retention and synchronizing N availability with crop demand (Johnson et al., 2016; Motavalli et al., 2013; Nash et al., 2012; Nelson & Motavalli, 2013). In addition to yield improvements, nitrapyrin has also been shown to reduce N losses via gaseous emissions and leaching pathways. Owens (1987) observed that nitrapyrin lowered the conversion rate of ammonium to nitrate and reduced N losses by 27%. Similarly, Randall et al. (2003) reported a 13%–18% reduction in nitrate losses through tile drainage when nitrapyrin was applied with late-fall AA in a corn–soybean rotation on claypan soils. In Illinois, David et al. (1997) found significantly lower nitrate-N concentrations in tile drainage water following nitrapyrin application. Nash et al. (2015) further demonstrated that nitrapyrin reduced denitrification and ammonia ($NH_4^+$) volatilization losses under waterlogged conditions typical of claypan soils. However, the effectiveness of nitrapyrin in improving yield and reducing losses is not consistent across all conditions. H. Kaur and Nelson (2024) observed that nitrapyrin reduced cumulative $NH_3$ losses compared to the control during a wet year but had no measurable effect under dry conditions. Moreover, Kaur et al. (2020) reported that nitrapyrin's ability to delay the transformation of $NH_4^+$ to $NO_3^-$ was limited under saturated soil conditions. Similarly, others have noted that the agronomic and environmental benefits of nitrapyrin are strongly influenced by soil hydrology, application timing, and seasonal weather variability (Nash et al., 2012; Quemada et al., 2013; Wolt, 2004).

Topographic positions (TPs) are closely associated with soil physical properties such as clay content, sand content, pH, organic matter content, and soil hydrological properties and water distribution (Ovalles & Collins, 1986). These factors affect nutrient uptake and the efficacy of an NI in corn

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production on claypan soils (Scharf et al., 2005; Schmidt et al., 2007). The effect of topography on corn performance has been extensively studied and varies substantially across claypan soils, with productivity largely dictated by precipitation patterns in dryland systems (Adler et al., 2020; Jiang & Thelen, 2004; Kaur et al., 2023; Kumhálová et al., 2008; Singh et al., 2016, 2022). Jaynes et al. (2011) reported significant yield variability across slopes, with corn yielding higher on upper slopes and lower on TPs such as footslopes and depressions. Kravchenko and Bullock (2000) found that lower TPs yielded less than well-drained upper TPs. Similarly, Singh et al. (2016) observed a comparable trend where upper slopes had low productivity due to drought stress, while lower slope positions, often prone to water accumulation, also produced lower yields. During dry seasons, lower TPs (footslopes, toeslopes, and depressions) tend to yield more than upper slopes due to higher moisture retention since water tends to move downslope and is accumulated on the lower slope positions (da Silva & Silva, 2008; Kaspar et al., 2024). In contrast, in wet years, better drainage at upper TPs such as shoulders and backslopes typically results in higher yields (Ebeid et al., 1995; Lindstrom et al., 1986). Overall, grain yield on TPs is variable and is generally based on the prevailing weather conditions during the growing season. Increased plant N uptake and recovery efficiency have also been observed in low-lying TPs when polymer-coated urea and AA were used, compared to urea alone (Noellsch et al., 2009). The individual effects of topography and nitrapyrin on corn yields and N uptake have been studied extensively; however, no research to date has quantified the interactive effects of TPs and nitrapyrin on corn productivity.

The overall objective of this study was to evaluate the effects of TP (shoulder, backslope, and footslope) and nitrapyrin application on corn productivity and grain quality within a terraced claypan field. The study also aimed to assess the economic impact of nitrapyrin application across TPs. We hypothesized that TP would influence corn grain yield and quality, and that applying nitrapyrin with AA would increase yield and net returns compared to AA alone, particularly at the footslope position.

**Core Ideas**

- Topographic positions significantly affect corn grain yields and grain quality parameters.
- Nitrapyrin with anhydrous ammonia increased corn yields across all topographic positions.
- Footslope had higher incremental yield and net economic gains with nitrapyrin.
- Partial factor productivity increased with the application of nitrapyrin.

## 2 | MATERIALS AND METHODS

### 2.1 | Site description and experimental design

The field study was conducted from 2019 to 2022 at the University of Missouri Lee Greenley Jr. Memorial Research Farm near Novelty, MO (40°1′41.4″ N, 92°11′18.6″ W). The soil series at this site was dominated by Kilwinning (fine, smectitic, mesic Vertic Epiaqualfs) and Leonard (fine, smectitic, mesic Vertic Epiaqualfs) silt loams, which have slow permeability and are poorly drained due to the presence of a subsurface montmorillonite claypan at a depth of 45–60 cm (Nelson et al., 2011). Parallel terraces at the experimental site were constructed in 1981. Terraced fields were classified into three TPs, including a shoulder, backslope, and footslope (Adler et al., 2020), with slopes ranging from 0.019% to 3.476%, 3.477% to 6.847%, and 6.848% to 22.063%, respectively (Figure 1 and Figure S1). In this study, the terms "TP" and "landscape position" are used interchangeably to refer to distinct elevation-based slope positions (shoulder, backslope, and footslope). The digital elevation models (DEMs) developed using Light Detection and Ranging (LIDAR) data were obtained from the Missouri Spatial Data Information Service (Missouri Spatial Data Information Service [MSDIS], 2025). The DEM raster resolution was 1.2 m × 1.2 m. Three TPs, shoulder, backslope, and footslope, were delineated in ArcGIS Pro v3.4 (ESRI) software using a slope position classification model developed by Evans et al. (2016), which was a modification of the topographic position index (TPI) tool created by Jenness (2006). A radius of 36.576 m was used to determine the TPI since these terraces were made on 36.576 m transects (120 ft). The study was arranged as a randomized complete block design with two N application treatments: anhydrous ammonia with nitrapyrin (N-Serve, Dow Agrosciences), N-stabilizer (AA + nitrayrin AA + nitrapyrin), and anhydrous ammonia without nitrapyrin (AA) present within each TP. The terraces used in this study were adjacent to each other, and they have been under a rainfed corn–soybean rotation. During odd years (2019 and 2021), treatments were replicated six times, and ten times in even years (2020 and 2022) (Figure 1). During the study period, minimum and maximum air temperatures and precipitation data were recorded using an on-farm automated weather station (Campbell Scientific, Inc.). The historical yearly average cumulative precipitation (2000–2018) received at the study site was 975 mm, and the average yearly temperature (2000–2018) was 11.4°C.

### 2.2 | Cultural management practices

Corn was no-till planted with Case IH 1245 PT in all 4 years. Corn hybrid DKC 63-55 (Bayer) was planted at 79,000 seeds

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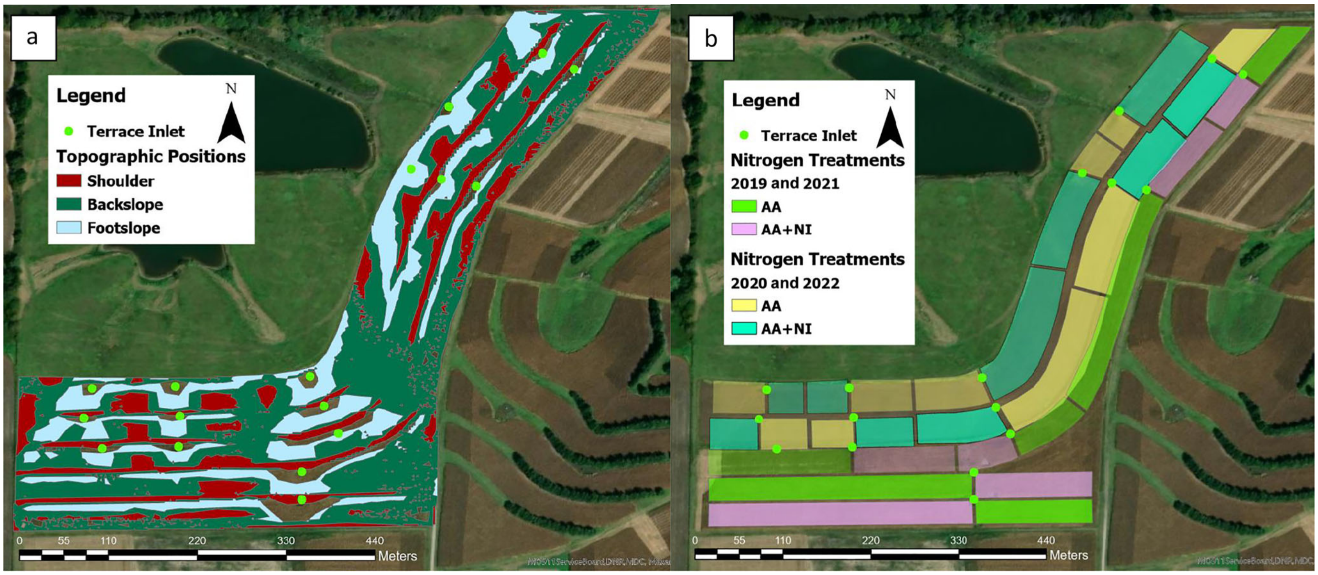


**FIGURE 1** The terraced fields with topographic positions at the study site (a) and treatment layout during the 4-year study period (b). AA, anhydrous ammonia, NI, nitrification inhibitor.

ha$^{-1}$ in 2019 and 84,000 seeds ha$^{-1}$ in 2020 and 2021. In 2022, G12S75-5112 (Golden Harvest Seeds) was planted at 79,000 seeds ha$^{-1}$ (Table 1). AA was knife-injected into the soil using a Dalton toolbar, except in 2022, when a John Deere 2510 applicator was used. Nitrapyrin was co-injected downstream with AA using a Sidekick injection system, as detailed in Singh and Nelson, 2019. The total N rate within each season was the same for both treatments; however, the only difference was the presence of nitrapyrin. The total N applied was 228 kg ha$^{-1}$ in 2019, 194 kg ha$^{-1}$ in both 2020 and 2021, and 180 kg ha$^{-1}$ in 2022 (Table 1). The rate of nitrapyrin was always 0.56 kg a.i. ha$^{-1}$ applied with AA in all years. All crop management operations, including weed management, were conducted in accordance with the prevailing regional agricultural practices in Northern Missouri (Table 1).

## 2.3 | Data collection and analysis

Block-wise pre-plant soil samples were collected in the spring of 2021 and 2022 at a 0- to 15-cm depth using stainless-steel push probes. These samples were analyzed for soil fertility parameters (Table 2) at the University of Missouri's Soil and Plant Testing Laboratory. Soil samples were also collected post-harvest in 2021 and 2022 from 0- to 15-cm depth from all treatments. Soil samples were air-dried and analyzed by the University of Missouri's Soil and Plant Testing Laboratory for soil fertility analysis following the procedures detailed in Nathan and Sunet (2006).

Plant populations were calculated by measuring plants from a 244 cm row length of plots in 2021 and 2022 at each landscape position. Corn was harvested each year with a 6140 combine (Case IH). The combine had a harvesting width of 6.096 m, which corresponded to eight harvested rows. The combine collected geo-referenced point yield data using a yield monitor (AFS 162, Trimble Inc.), which was calibrated for weight and moisture. Grain yields were adjusted to 150 g kg$^{-1}$ moisture content prior to analysis.

Approximately ten ears of corn were manually collected from every treatment and landscape position in 2020, 2021, and 2022 to conduct grain quality analysis. The collected ears were manually threshed, and the obtained grain samples from each treatment were analyzed for protein, oil, and starch concentration using a Foss Infratec 1241 Grain Analyzer. After grain quality analysis, the grain samples were analyzed by Brookside Labs for grain N content analysis using an Elementar EL Cube C/N combustion analyzer following the method by Gavlak et al. (2005). To evaluate the relationship between input application and crop output, partial factor productivity (PFP) was calculated as $Y/F$, where $Y$ represents the grain yield of the harvested portion of corn and $F$ represents the amount of nutrient applied (Fixen et al., 2015).

## 2.4 | Statistical and economic analysis

Inconsistent data yield points, likely due to significant uncertainties such as positional errors, speed variations, partial swath entry into the combine, operational interruptions, and sensor malfunctions, were excluded from the dataset prior to statistical analysis (Sudduth et al., 2012). Point grain yield data with latitude and longitude coordinates for 2019–2022 were extracted based on TPs delineated in ArcGIS Pro v3.4 (ESRI) and were evaluated for normality, homogeneity

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**TABLE 1** Details of selected crop management practices for corn from 2019 to 2022.

| Field information | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|
| Tillage | No-till | No-till | No-till | No-till |
| Date of planting | June 5 | April 23 | May 2 | May 17 |
| Variety | DKC 63-55 | DKC 63-55 | DKC 63-55 | G12S75-5122 |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 | 76.2 |
| Population (Seeds ha$^{-1}$) | 79,074 | 84,016 | 84,016 | 79,074 |
| **Fertilizers** | | | | |
| AA rate (kg N ha$^{-1}$) | 202 | 168 | 168 | 168 |
| AA application date | April 22 | April 6 | November 19 | November 30 |
| Supplemental NPKS (kg ha$^{-1}$) | 26-29-74-0 | 26-29-112-0 | 26-29-74-0 | 12-24-74-11 |
| Sources (NPKS) | DAP, MOP | DAP, MOP | DAP, MOP | DAP, MOP, elemental sulfur |
| NPK application date | Spring | April 7 | Spring | February 24 |
| Total-N applied (kg N ha$^{-1}$) | 228 | 194 | 194 | 180 |
| **Herbicides** | | | | |
| Pre-plant | Acetochlor (2.21 kg a.i. ha$^{-1}$) atrazine (1.60 kg a.i. ha$^{-1}$) mesotrione (0.09 kg a.i. ha$^{-1}$) | NA | Saflufenacil (0.02 kg a.i. ha$^{-1}$) glyphosate (1.14 kg a.i. ha$^{-1}$) UAN (0.59 kg a.i. ha$^{-1}$) MSO (0.30 kg a.i. ha$^{-1}$) | Saflufenacil (0.02 kg a.i. ha$^{-1}$) dimethenamid-P (0.2 kg a.i. ha$^{-1}$) glyphosate (1.88 kg a.i. ha$^{-1}$) UAN (0.59 kg a.i. ha$^{-1}$) MSO (0.88 kg a.i. ha$^{-1}$) |
| Pre-emergence | NA | Glyphosate (2.28 kg a.i. ha$^{-1}$) saflufenacil (0.04 kg a.i. ha$^{-1}$) dimethenamid-P (0.20 kg a.i. ha$^{-1}$) UAN (1.18 kg a.i. ha$^{-1}$) MSO (0.60 kg a.i. ha$^{-1}$) | NA | Atrazine (2.01 kg a.i. ha$^{-1}$) Glyphosate (0.94 kg a.i. ha$^{-1}$) Mesotrione (0.94 kg a.i. ha$^{-1}$) MSO (0.25 kg a.i. ha$^{-1}$) |
| Post-emergence | NA | Acetochlor (1.54 kg a.i. ha$^{-1}$) atrazine (2.01 kg a.i. ha$^{-1}$) glyphosate (1.14 kg a.i. ha$^{-1}$) mesotrione (0.12 kg a.i. ha$^{-1}$) | Atrazine (1.85 kg a.i. ha$^{-1}$) Metolachlor (1.78 kg a.i. ha$^{-1}$) Mesotrione (0.12 kg a.i. ha$^{-1}$) Glyphosate (1.26 kg a.i. ha$^{-1}$) MSO (0.25 kg a.i. ha$^{-1}$) | NA |
| Harvest date | November 7 | October 13 | September 27 | October 5 |

*Note*: Acetochlor (2-chloro-2′-methyl-6′ethyl-N-ethoxymethylacetanilide); atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine); dimethenamid-P, (RS)-2-Chloro-N-(2,4-dimethyl-3-thienyl)-N-(2-methoxy-1-methylethyl)acetamide; glyphosate, (N-(phosphonomethyl)glycine); mesotrione, (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione); saflufenacil, N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; metolachlor, 2-chloro-2′-ethyl-6′-methyl-N-(2-methoxy-l-methylethyl)acetanilide; methylated seed oil (Methanesulfonate).

Abbreviations: DAP, diammonium phosphate; MOP, muriate of potash; MSO, methylated seed oil; NA, none applied; UAN, urea ammonium nitrate.

of variance, and outliers. The GLIMMIX procedure with a restricted maximum likelihood analysis was used for statistical analysis (SAS Institute, 2008). Data were analyzed for individual years as well as combined over the years. For data split based on the years TPs, and N treatments were considered fixed factors, whereas replications were considered random factors with a spatial covariance structure based on latitude and longitude coordinates. For data combined over the years, TPs and N treatments were considered fixed factors, whereas years and replications were considered random factors with a spatial covariance structure based on latitude and longitude coordinates. The T-grouping of least-square

**TABLE 2** Soil fertility analysis of preplant soil samples for various soil properties in 2021 and 2022.

| Soil property | Topographic positions | 2021 | 2022 |
|---|---|---|---|
| $pH_s$ (0.01 M $CaCl_2$) | Shoulder | 4.85 ± 0.28[a] | 4.69 ± 0.24 |
| | Backslope | 4.95 ± 0.31 | 5.25 ± 0.52 |
| | Footslope | 4.94 ± 0.25 | 5.20 ± 0.49 |
| Ca (kg $ha^{-1}$) | Shoulder | 4091 ± 285 | 3522 ± 289 |
| | Backslope | 3927 ± 239 | 3903 ± 553 |
| | Footslope | 4100 ± 292 | 4169 ± 641 |
| CEC ($Cmol_c$ $kg^{-1}$) | Shoulder | 17.94 ± 0.72 | 17.51 ± 2.06 |
| | Backslope | 17.60 ± 0.60 | 15.42 ± 1.74 |
| | Footslope | 17.45 ± 0.66 | 17.41 ± 2.51 |
| Mg (kg $ha^{-1}$) | Shoulder | 525 ± 6.90 | 428 ± 2.06 |
| | Backslope | 500 ± 11.10 | 383 ± 1.74 |
| | Footslope | 564 ± 12.02 | 547 ± 2.51 |
| N.A. ($Cmol_c$ $kg^{-1}$) | Shoulder | 7.25 ± 1.50 | 7.30 ± 1.57 |
| | Backslope | 6.25 ± 1.10 | 4.75 ± 1.95 |
| | Footslope | 7.25 ± 1.19 | 5.15 ± 2.10 |
| OM (g $kg^{-1}$) | Shoulder | 27.8 ± 2.8 | 25.4 ± 2.22 |
| | Backslope | 29.5 ± 2.8 | 27.4 ± 2.32 |
| | Footslope | 31.0 ± 2.0 | 25.3 ± 2.50 |
| P (kg $ha^{-1}$) | Shoulder | 61.50 ± 6.21 | 86.8 ± 34.11 |
| | Backslope | 60.96 ± 6.80 | 81.54 ± 27.76 |
| | Footslope | 69.60 ± 5.55 | 89.49 ± 31.61 |
| K (kg $ha^{-1}$) | Shoulder | 328 ± 35 | 321 ± 45 |
| | Backslope | 356 ± 48 | 378 ± 63 |
| | Footslope | 400 ± 59 | 446 ± 58 |

Abbreviation: CEC, cation exchange capacity; N.A., neutralizable acidity.
[a]Standard deviation.

means at an alpha level of 0.05 was used to test the significant differences in the treatment means.

An economic analysis evaluated the impact of AA + nitrapyrin application compared to the application of AA alone over a 4-year period. Partial budgets were calculated for each TP and nitrapyrin treatment as detailed in the Missouri Crop and Livestock Enterprise Budgets-2022, developed by the University of Missouri Extension (University of Missouri Extension, 2022). The average corn prices per kilogram in Missouri for 2019, 2020, 2021, and 2022 were \$0.1445, \$0.1807, \$0.2421, and \$0.2673, respectively (USDA, 2024). Year-to-year variability in input costs (seed, fertilizer, and crop protection chemicals), operating, and ownership costs were considered in budget calculations to capture fluctuations in profitability across years. In addition, all costs and prices were adjusted to January 2025 dollars using the Gross Domestic Product Implicit Price Deflator from the Bureau of Economic Analysis (U.S. Bureau of Economic Analysis [USBEA], 2025).

Incremental yield differences between AA + nitrapyrin and AA treatments, associated degrees of freedom, and their standard errors were obtained using the contrast function from the emmeans package in RStudio (v4.5; R Core Team, 2025). Standard errors for all yield-derived economic metrics were estimated using the delta method (Dowd et al., 2014), which was used to quantify the uncertainty associated with these metrics based on the standard error of the incremental yields (Piikki & Stenberg, 2017). Statistical significance for the yield-derived economic metrics was evaluated using a two-tailed *t*-test at different significance levels in Excel with the formula = T.DIST.2T (ABS[estimate/SE], *df*), where estimate refers to the yield-derived metric, SE is the associated standard error, and *df* is the degrees of freedom from the mixed-effects model.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Weather data

Rainfall magnitude and distribution affect nutrient losses and crop nitrogen (N) utilization from applied fertilizers. During the study period, the experimental site exhibited notable variability in precipitation patterns. The annual precipitation totals were 1297 mm in 2019, 797 mm in 2020, 1116 mm in 2021, and 776 mm in 2022 (Figure 2). Relative to the 19-year average precipitation, excess rainfall totaling 322 and 126 mm was observed in 2019 and 2021, respectively. However, 205 and 227 mm deficit precipitation occurred in 2020 and 2022, respectively. During the cropping season, rainfall accounted for 45%, 57%, 59%, and 47% of the total annual precipitation in 2019, 2020, 2021, and 2022, respectively. These fluctuations emphasize the critical role of rainfall variability in influencing N dynamics and crop performance, underscoring the need for adaptive management strategies over diversified landscapes.

### 3.2 | Corn grain yields

The impact of TPs on corn grain yield was significant across all individual years and the 4-year average (2019–2022) (Table 3). Nitrogen treatments also increased grain yields (553–890 kg $ha^{-1}$) in all years except 2019. A significant interaction between TPs and N treatments was observed in 2020 and for the overall 4-year average. This highlights the importance of site-specific N management over a landscape. In 2019, the shoulder position had the highest yield of 13,139 kg $ha^{-1}$, which was 13% higher than the backslope (11,607 kg $ha^{-1}$) and 16% higher than the footslope (11,326 kg $ha^{-1}$). In 2020, AA + nitrapyrin application at the backslope showed a yield advantage of 652 kg $ha^{-1}$.

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**TABLE 3** Corn grain yields and moisture content for the main effects of topographic positions, nitrogen treatments and their interaction for individual years 2019, 2020, 2021, and 2022 and averaged over the years (2019–2022).

| Topographic positions (TP) | Nitrogen treatment (NT) | Grain yield (kg ha$^{-1}$) | | | | | Grain moisture (g kg$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **2019** | **2020** | **2021** | **2022** | **2019–2022** | **2019** | **2020** | **2021** | **2022** | **2019–2022** |
| Shoulder | | 13139a | 11698b | 9430a | 8686c | 10772a | 165c | 150c | 136b | 169c | 155c |
| Backslope | | 11607b | 12650a | 8605b | 9738b | 10847a | 167b | 152b | 138a | 178b | 160b |
| Footslope | | 11326b | 11779b | 5411c | 10558a | 10129b | 173a | 154a | 130c | 185a | 161a |
| | AA + nitrapyrin | 12141 | 12319a | 8260a | 10009a | 10908a | 169a | 152b | 134b | 178a | 159 |
| | AA | 11906 | 11766b | 7370b | 9313b | 10258b | 168b | 153a | 136a | 176b | 159 |
| Shoulder | AA + nitrapyrin | 13384 | 11556c | 9790 | 9032 | 10911b | 166 | 149 | 136b | 170 | 156 |
| Shoulder | AA | 12895 | 11840c | 9071 | 8339 | 10632c | 165 | 150 | 136b | 167 | 155 |
| Backslope | AA + nitrapyrin | 11687 | 12976a | 9084 | 10108 | 11143a | 168 | 152 | 138a | 179 | 160 |
| Backslope | AA | 11527 | 12324b | 8126 | 9368 | 10551c | 166 | 152 | 138a | 177 | 159 |
| Footslope | AA + nitrapyrin | 11514 | 12423b | 5907 | 10885 | 10668c | 174 | 154 | 127d | 186 | 162 |
| Footslope | AA | 11138 | 11134d | 4915 | 10231 | 9590d | 172 | 155 | 133c | 184 | 161 |
| **Source of variation** | ***df*** | ***p*-value** | | | | | | | | | |
| TP | 2 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 |
| NT | 1 | 0.8460 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | 0.0004 | 0.0057 | ≤0.0001 | ≤0.0001 | 0.1109 |
| TP × NT | 2 | 0.6516 | ≤0.0001 | 0.0632 | 0.7083 | ≤0.0001 | 0.9219 | 0.3272 | ≤0.0001 | 0.6222 | 0.3465 |

*Note*: Similar letters within a column are not significantly different from each other at $p < 0.05$ within a factor. Underlined *p*-values indicate significant type-3 fixed effects model values.

Abbreviations: AA, anhydrous ammonia applied without nitrapyrin; AA + nitrapyrin, nitrogen applied as anhydrous ammonia with nitrapyrin; *df*, numerator degrees of freedom.

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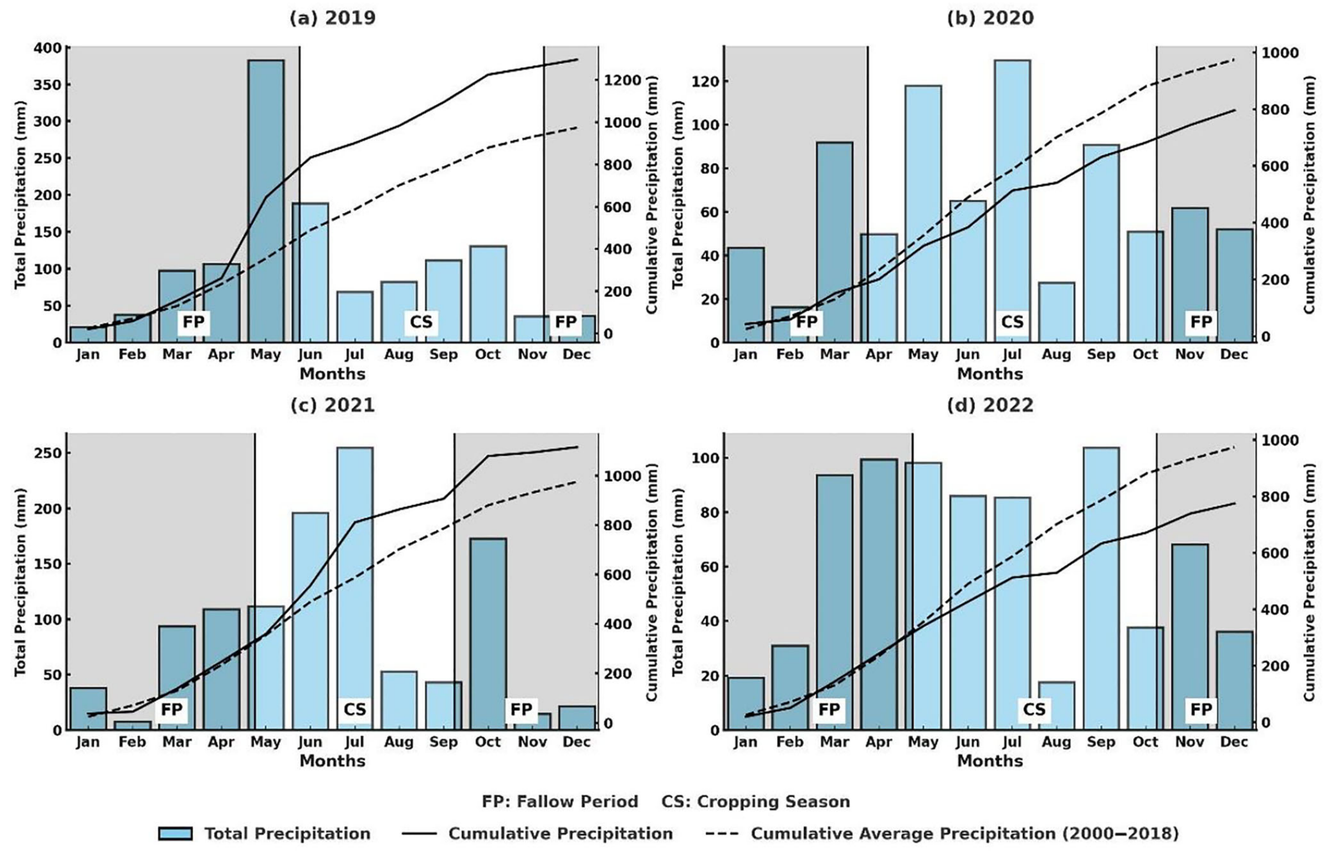


**FIGURE 2** Monthly total precipitation and cumulative precipitation during the 2019 (a), 2020 (b), 2021 (c), and 2022 (d) growing seasons at Lee Greenley Jr. Memorial Research Farm near Novelty, MO. Cumulative precipitation each year (solid line) is compared with the 19-year average (dotted line) cumulative precipitation (2000–2018). Shaded regions indicate fallow periods (FP) before planting and after harvest, while cropping seasons (CS) are shown between these periods.

Nitrapyrin application with AA increased yields by 5.3% and 12% at backslope and footslope positions, respectively, compared to AA. Nitrapyrin showed no significant difference in yield at the shoulder TP. In 2021, the shoulder position maintained a 10% yield advantage over the backslope and a 74% advantage over the footslope. However, footslope recorded the highest yields in 2022, with increases ranging from 1147 to 2199 kg ha$^{-1}$ compared to backslope and shoulder. The AA + nitrapyrin treatment in 2022 also exhibited an 8% yield advantage over AA alone. Over the 4-year average, the footslope demonstrated the greatest yield increase (11%) with nitrapyrin application, followed by backslope (6%) and shoulder (3%). These findings demonstrate the significant influence of TPs and N treatment interactions on corn grain yields and emphasize the value of tailored N management practices to optimize productivity.

TPs and their interaction with both the amount and distribution of precipitation have been shown to significantly influence NUE and corn grain yields (Kravchenko & Bullock, 2000; Leuthold, Quinn, et al., 2021; Leuthold, Salmerón, et al., 2021; Martinez-Feria & Basso, 2020). Higher rainfall during critical growth stages, such as V6–V12 in 2019 and R1 in 2021, combined with elevated temperatures, likely exacerbated N losses through surface water runoff and denitrification. These effects have been particularly pronounced in the footslope areas, which are more susceptible to waterlogging (H. Kaur et al., 2023, 2024). Studies by Singh et al. (2016) indicate that improved drainage characteristics at the shoulder and backslope positions maintained more stable yields during wetter years like 2019 and 2021. Nitrapyrin further helped stabilize N availability across all years, leading to more consistent yields, especially at the footslope position. In 2022, lower and uneven rainfall patterns during the V12–V14 growth stages likely stressed the crop (Willison et al., 2021). This stress was most evident at the shoulder position (personal observations), where reduced moisture availability may have limited plant N uptake. However, backslope and footslope positions appeared to benefit from late-season rainfall in September, which likely supported grain filling and contributed to partial yield recovery. Overall, well-drained soils at the shoulder TP tended to perform better in years with moderate to high rainfall. In contrast, footslope areas, which retain more moisture, were advantageous in drier years but were highly

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susceptible to waterlogging in wet years. H. Kaur et al. (2023) reported increased soil wetness measured using soil moisture sensors at channel and footslope positions on a terraced field and observed a 45%–70% reduction in corn grain yield due to waterlogging. Nitrogen losses are excessive in wet years, particularly on claypan soils on the footslopes, and nitrapyrin treatment had the greatest yield increase as reported in this study.

## 3.3 | Grain moisture content

The main effects of TPs and N treatment significantly affected grain moisture content across all years, while the interaction effect was only significant in 2021 (Table 3). In 2019, the footslope had 5% and 4% higher grain moisture content than the shoulder and backslope, respectively. Similar trends were observed in 2020, where the footslope was 2.7% and 1.3% higher than the shoulder and backslope, respectively. In 2021, the AA + nitrapyrin treatment at the footslope position resulted in 4.5% lower grain moisture content compared to AA treatment, while the other treatment interactions did not show significant differences. In 2022, the footslope exhibited grain moisture content that was 39 and 95 g kg$^{-1}$ higher than the backslope and shoulder, respectively. The AA + nitrapyrin had 0.6% and 1.2% higher moisture content than AA in 2019 and 2022, whereas it had lower grain moisture in 2020. When averaged over years, the footslope position consistently had 6%–39% higher moisture content compared to other slope positions. The overall trend of TPs was ranked: footslope > backslope > shoulder and may be attributed to rainfall coinciding with critical growth stages, as well as the higher moisture retention capacity of footslope positions. This aligns with findings by da Silva and Silva (2006) and H. Kaur et al. (2023), who observed that footslope positions tend to retain moisture for longer periods due to their relative position within a landscape that subsequently contributes to higher grain moisture content.

## 3.4 | Grain N content and N removal

Grain N content and grain N removal were not measured in 2019. Grain N content was significantly influenced by the main effects of N treatments in 2022 and when averaged over all site years (Table 4). However, TPs and their interaction with N treatments did not significantly affect grain N content. The AA + nitrapyrin treatments resulted in higher grain N content than the AA alone, with a difference of 0.8 g kg$^{-1}$ in 2022 and 0.3 g kg$^{-1}$ when averaged over 3 years. These findings are consistent with previous research, which has reported similar increases in grain N content with the use of nitrapyrin (H. Kaur et al., 2023; Singh et al.,

**TABLE 4** Corn grain nitrogen content, grain nitrogen (N) removal, and partial factor productivity (PFP) for the main effects of topographic positions and nitrogen treatments.

| Topographic positions (TPs) | Nitrogen treatments (NT) | Grain N content (g kg$^{-1}$) | | | | Grain N removal (kg ha$^{-1}$) | | | | PFP (kg kg$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2021 | 2022 | 2020–2022 | 2020 | 2021 | 2022 | 2020–2022 | 2020 | 2021 | 2022 | 2020–2022 |
| Shoulder | | 10.7 | 9.1 | 11.1 | 10.5 | 127 | 85a | 94b | 104 | 62 | 48a | 46c | 53 |
| Backslope | | 9.9 | 9.4 | 11.2 | 10.3 | 124 | 82a | 107a | 108 | 64 | 44a | 53b | 55 |
| Footslope | | 9.8 | 9.2 | 11.1 | 10.2 | 116 | 51b | 118a | 102 | 60 | 28b | 59a | 52 |
| | AA + nitrapyrin | 1.028 | 0.912 | 1.158a | 1.051a | 128a | 75 | 113a | 110a | 64a | 43a | 54.25 | 55a |
| | AA | 1.003 | 0.936 | 1.069b | 1.012b | 117b | 70 | 100b | 99b | 60b | 38b | 51.68 | 52b |
| **Source of variation** | ***df*** | ***p*-values** | | | | | | | | | | | |
| TP | 2 | 0.0966 | 0.4937 | 0.9535 | 0.4465 | 0.1448 | <u>≤0.0001</u> | <u>0.0012</u> | 0.3065 | 0.1416 | <u>≤0.0001</u> | <u>≤0.0001</u> | 0.1872 |
| NT | 1 | 0.4627 | 0.3099 | <u>0.0038</u> | <u>0.0334</u> | <u>0.0322</u> | 0.1918 | <u>0.0147</u> | <u>0.0017</u> | <u>0.0096</u> | <u>0.0231</u> | 0.2369 | <u>0.0115</u> |
| TP × NI | 2 | 0.7161 | 0.4214 | 0.2215 | 0.1377 | 0.9698 | 0.9475 | 0.6605 | 0.8735 | 0.4301 | 0.8417 | 0.8326 | 0.7551 |

*Note*: Similar letters within a column are not significantly different from each other at $p < 0.05$. Underlined $p$-values indicate significant type-3 fixed effects model values.

Abbreviations: AA, Anhydrous ammonia without nitrapyrin; AA + nitrapyrin, nitrogen applied as anhydrous ammonia with nitrapyrin; *df*, numerator degrees of freedom; PFP, partial factor productivity.

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2022; Singh & Nelson, 2019). The observed enhancement in grain N content under AA + nitrapyrin treatment suggests that the inhibitor may reduce N losses via leaching, runoff, or denitrification, thereby improving N availability for plant uptake.

In contrast, grain N removal was influenced by TPs in 2021 and 2022 as well as by N treatments in 2020, 2022, and when averaged over all years. The interaction between TPs and N treatments was not significant in any individual year or in the overall analysis. In 2021, the highest grain N removal was observed at the shoulder position (85 kg ha$^{-1}$), which was significantly higher compared to the footslope position (51 kg ha$^{-1}$). These findings highlight the role of topography in influencing N uptake dynamics, which were likely due to differences in topsoil depth, water retention, and drainage across TPs. The shoulder position may have better water and nutrient retention due to higher topsoil depth than the steeper backslope and the more eroded footslope TP. In 2022, the footslope position exhibited the highest grain N removal (118 kg ha$^{-1}$), which was 24 kg ha$^{-1}$ greater than the shoulder. This shift in N removal across TPs between the 2 years may reflect variations in seasonal rainfall patterns and their effects on soil moisture and N availability. The footslope, typically a zone of higher moisture retention, could have promoted higher N uptake in 2022 compared to 2021, when the shoulder position had more favorable growing conditions. The nitrapyrin treatments consistently enhanced grain N removal compared to AA across all years, with increases of 11 kg ha$^{-1}$ in 2020, 13 kg ha$^{-1}$ in 2022, and 11 kg ha$^{-1}$ when averaged over years. In the year 2021, grain N uptake was higher by 5 kg ha$^{-1}$ for AA + nitrapyrin treatment compared to AA but was non-significant. The year 2021 was a wet year, whereas the years 2020 and 2022 were relatively dry years, which might have dictated the results observed for nitrogen treatments (Figure 2). These consistent gains in grain yield support the role of nitrapyrin in improving crop N uptake, contributing to greater NUE in corn production. These results align with findings from Nelson (2018) and Singh and Nelson (2019), who reported that NIs reduced N losses and enhanced plant N availability, thereby promoting higher grain N removal.

## 3.5 | Partial factor productivity

PFP was significantly influenced by TPs in 2021 and 2022, and by N treatments in 2020, 2021, and the 3-year average (Table 4). In 2021, the shoulder position recorded a PFP of 44 kg kg$^{-1}$ during a wet year, which was 20 kg kg$^{-1}$ higher than the footslope. However, during the drier growing season in 2022, the footslope position had PFP that was 6 kg kg$^{-1}$ higher than the backslope and 13 kg kg$^{-1}$ higher than the shoulder. The reduced PFP observed at the shoulder position in 2022 may be attributed to limited plant-available moisture and reduced nutrient uptake in higher TPs. These results align with Kravchenko and Bullock (2000), who observed reduced productivity at elevated landscape areas due to reduced water and nutrient availability.

The backslope position exhibited intermediate PFP values, ranging from 53 to 55 kg kg$^{-1}$, which is consistent with studies by Timlin et al. (1998) and Senthilkumar et al. (2009). These studies reported that backslope areas often benefit from balanced moisture and nutrient conditions but may experience occasional limitations due to soil erosion. Similarly, Singh et al. (2022) noted that fertilizer applied on backslope areas may result in reduced productivity due to erosion-induced nutrient loss. The footslope consistently recorded the highest PFP values (52–59 kg kg$^{-1}$), likely due to improved water retention, reduced erosion, and greater nutrient availability at lower TPs. These results are in agreement with Noellsch et al. (2009), who found that N uptake and nutrient recovery efficiency were highest at footslopes when enhanced-efficiency fertilizers like polymer-coated urea were used.

Across multiple years and TPs, the AA + nitrapyrin treatment demonstrated a 6.6% higher PFP than AA alone, indicating improved N utilization efficiency. This effect was most pronounced during wet years, likely due to enhanced N uptake and reduced losses under high moisture conditions (H. Kaur et al., 2023). In contrast, PFP differences between treatments in 2020 were not significant, possibly due to uneven rainfall distribution that may have limited N availability and uptake. Overall, these findings emphasize the importance of integrating topographic variations with enhanced N management practices to optimize productivity and efficiency across diverse field conditions.

## 3.6 | Corn grain quality and plant population

Corn grain quality is often influenced by a range of agronomic factors, including N management and topographic variations. In this study, neither TPs nor the interaction with N treatments were significant for oil ($p = 0.2024$), protein ($p = 0.3962$), test weight ($p = 0.4165$), starch content ($p = 0.4773$), and plant population ($p = 0.7037$). However, N treatments alone had a significant impact on grain quality parameters. Specifically, AA + nitrapyrin significantly decreased grain oil content while increasing both protein content and test weight compared to AA alone (Table 5). On average, AA-treated plots had a 0.6 g kg$^{-1}$ higher grain oil content, whereas AA + nitrapyrin plots exhibited a 3 g kg$^{-1}$ increase in protein and a 1.5 kg hL$^{-1}$ increase in test weight. This inverse relationship between grain protein and oil content has been well-documented at higher N rates and is attributed to N allocation within the plant, where increased N availability promotes protein synthesis over lipid accumulation (Hammad et al., 2023; McNeill

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**TABLE 5** Corn grain oil, protein, test weight, starch content and plant population for nitrogen treatments.

| Nitrogen treatments (NT) | | Oil (g kg$^{-1}$) | Protein (g kg$^{-1}$) | Test weight (kg hL$^{-1}$) | Starch content (g kg$^{-1}$) | Plant population (plant ha$^{-1}$) |
|---|---|---|---|---|---|---|
| AA + nitrapyrin | 36.7b | 74.4a | 72.2a | 724.82 | 86222 | |
| AA | | 37.3a | 71.4b | 70.7b | 724.33 | 86165 |
| **Source of variation** | ***df*** | ***p*-value** | | | | |
| TP | 2 | 0.3406 | 0.0693 | 0.0935 | 0.4168 | 0.4362 |
| NT | 1 | 0.0057 | 0.0255 | 0.0008 | 0.6612 | 0.9813 |
| TP × NT | 2 | 0.2024 | 0.3967 | 0.4165 | 0.4773 | 0.7037 |

*Note*: Similar letters within a column are not significantly different from each other at $p < 0.05$. Underlined *p*-values indicate significant type-3 fixed effects model values. Abbreviations: AA, Anhydrous ammonia without nitrapyrin; AA + nitrapyrin, nitrogen applied as anhydrous ammonia with nitrapyrin; *df*, numerator degrees of freedom; TP, topographic position.

**TABLE 6** Average soil parameters for topographic positions, nitrogen treatments and their interaction effect averaged over 2 years (2021 and 2022).

| Topographic positions (TPs) | Nitrogen treatments (NT) | pHs | N.A. (meq 100 g$^{-1}$) | OM (g kg$^{-1}$) | Bray I P (kg ha$^{-1}$) | Mg (kg ha$^{-1}$) | K (kg ha$^{-1}$) | CEC (Cmol$_c$ kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Shoulder | | 4.7b | 7.4a | 28.0 | 87b | 508a | 329b | 18.3a |
| Backslope | | 5.1a | 5.8b | 29.5 | 80b | 451b | 313c | 18.1a |
| Footslope | | 5.0a | 6.3b | 30.1 | 124a | 555a | 416a | 16.6b |
| | AA + nitrapyrin | 4.9 | 6.8a | 30.1a | 98 | 534a | 346 | 18.0 |
| | AA | 5.0 | 6.2b | 28.3b | 95 | 476b | 360 | 17.3 |
| **Source of variation** | ***df*** | ***p*-values** | | | | | | |
| TP | 2 | 0.0029 | 0.0026 | 0.1077 | 0.0003 | 0.0023 | ≤0.0001 | 0.0068 |
| NT | 1 | 0.3091 | 0.0758 | 0.0378 | 0.7878 | 0.0249 | 0.4367 | 0.1699 |
| TP × NT | 2 | 0.3585 | 0.2988 | 0.8390 | 0.7170 | 0.7591 | 0.5746 | 0.9085 |

*Note*: Similar letters within a column are not significantly different from each other at $p < 0.05$. Underlined *p*-values indicate significant type-3 fixed effects model values. Abbreviations: AA, anhydrous ammonia without nitrapyrin; AA + nitrapyrin, nitrogen applied as anhydrous ammonia with nitrapyrin; Bray 1 P, phosphorous; CEC, cation exchange capacity; *df*, numerator degrees of freedom; Mg, exchangeable magnesium; N.A., neutralizable acidity; OM, organic matter; pHs, measured as 0.01 M calcium chloride $CaCl_2$.

et al., 2005). Additionally, previous research has shown that NIs like nitrapyrin can enhance grain protein and test weight by reducing N losses and improving plant N uptake (Kaur et al., 2017; Singh & Nelson, 2019).

## 3.7 | Soil properties

The TPs showed significant differences for most of the soil parameters except organic matter (OM), while N treatments had no significant effect on soil pH, Bray I phosphorus (P), potassium (K), and cation exchange capacity (CEC) (Table 6). The interaction between TPs and N treatments was non-significant for all analyzed parameters. The shoulder position (4.7) had a lower pH compared to the backslope (5.0) and footslope (5.1), which was probably due to increased weathering and leaching (Kravchenko & Bullock, 2000; Singh et al., 2016). In contrast, neutralizable acidity (N.A.) was higher at the shoulder position (7.4 meq 100 g$^{-1}$), followed by the footslope (6.3 meq 100 g$^{-1}$), and the backslope (5.8 meq 100 g$^{-1}$), which could be due to higher acidity in elevated positions where OM had decomposition (Jiang & Thelen, 2004). Phosphorus (P) availability was significantly greater at the footslope (124 kg ha$^{-1}$), compared to the shoulder at 87 kg ha$^{-1}$ and the backslope at 80 kg ha$^{-1}$. Studies by Singh et al. (2016) and Kravchenko and Bullock (2000) observed greater P accumulation in lower TPs. Similarly, soil potassium (K) content at the footslope was 16% higher than the backslope and 26% higher than the shoulder position. Timlin et al. (1998) and Singh et al. (2016) reported that nutrient concentrations in lower slope positions tended to increase due to greater OM content and moisture availability. CEC was highest at the shoulder (18.3 Cmol$_c$ kg$^{-1}$), which was 1.7 Cmol$_c$ kg$^{-1}$ higher than the footslope and 0.2 Cmol$_c$ kg$^{-1}$ higher than the backslope. The AA + nitrapyrin had higher N.A., which could be due to delayed and prolonged nitrification during the cropping season.

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### 3.8 | Risk and profit analysis

Over the 4 years, production costs increased annually; however, corn grain yields varied significantly by both years and TPs. Spring application of nitrapyrin with AA consistently resulted in positive and statistically significant gross returns (Table 7). Averaged over years, expected net returns were highest on the backslope, with values \$5.5 ha$^{-1}$ higher than the shoulder and \$187 ha$^{-1}$ higher than the footslope. No significant net returns were observed at footslope positions during 2019 and 2021.

The agronomic and economic response to nitrapyrin varied with TP, indicating differences in the potential to translate yield gains over AA into economic returns across the landscape. Incremental yield gain was not significant for any of the TPs in 2019, nor for the shoulder in 2020. However, in other years, all TPs showed significant gains compared to AA alone. The footslope exhibited the highest average incremental yield gain (\$948.2 ha$^{-1}$), which was 192 and 523 kg ha$^{-1}$ higher than the backslope and shoulder, respectively. Correspondingly, incremental revenue gains were highest at the footslope position (\$227.39 ha$^{-1}$), which was \$46.04 and \$125.37 ha$^{-1}$ higher than backslope and shoulder, respectively. Despite footslopes' susceptibility to waterlogging, these findings demonstrate that nitrapyrin improved both yield and profitability at this position.

The TPs with negative incremental yields correspondingly showed negative economic yield differential (EYD) and net economic gains. The EYD was significant in all years except 2019. These nonsignificant outcomes and negative gains highlight the impact of variable precipitation and agronomic conditions on the profitability of nitrapyrin. The footslope recorded the highest average EYD (834.31 kg ha$^{-1}$), which exceeded the backslope by 191.99 kg ha$^{-1}$ and the shoulder by 522.79 kg ha$^{-1}$. While input costs varied across the study period, profitability was largely driven by a combination of yield improvements and market conditions, such as input and corn prices. The average net economic gains associated with the incremental yields over the years followed the trend: footslope (\$200.07 ha$^{-1}$) > backslope (\$154.03 ha$^{-1}$) > shoulder (\$74.7 ha$^{-1}$). This indicates the benefits of nitrapyrin in enhancing economic returns at the footslope position compared to other TPs. In contrast, the shoulder position exhibited minimal average net economic gains, particularly in years with suboptimal precipitation (e.g., 2022), likely due to moisture stress and limited N mineralization within the crop growth season.

The results demonstrate that the spring application of nitrapyrin with AA was a cost-effective strategy for increasing yields and economic returns over diversified landscapes. This was particularly evident in areas with favorable soil moisture and nutrient retention, such as the footslope position. The higher net economic gains at the footslope indicate that lower TPs provide a more conducive environment for N uptake, likely due to reduced N losses through leaching and nitrapyrin protection to denitrification. This aligns with findings from prior studies (H. Kaur et al., 2023; Singh et al., 2022) that reported footslope areas were more efficient in nutrient utilization due to their ability to retain moisture and nutrients for longer periods if the drainage is managed properly and N is protected by an NI. In contrast, the backslope and shoulder positions showed relatively lower economic gains, highlighting the challenges of managing N efficiency in these areas. The backslope, with its moderate productivity, may benefit from additional soil conservation practices to mitigate erosion and enhance N retention. Meanwhile, the shoulder position's minimal economic gains in years with suboptimal precipitation suggest that these areas are particularly vulnerable to climatic variability, but during wet years, enhanced drainage is beneficial. This aligns with Kravchenko and Bullock (2000), who observed that higher TPs are more prone to nutrient runoff and reduced productivity due to lower water availability.

These findings also emphasize the influence of market conditions, such as corn prices, on the economic viability of a nitrapyrin application. While yield improvements are critical, the economic gains were influenced by the profitability threshold set by market conditions. In years with low corn prices or minimal yield increases, the breakeven yield requirement may not be met, reducing the economic incentive to apply nitrapyrin. This emphasizes the importance of integrating agronomic practices with economic considerations to maximize profitability under varying environmental and market conditions. Overall, the study highlights the potential of nitrapyrin to improve NUE and economic returns, particularly in favorable TPs like the footslope. However, its efficacy is influenced by site-specific factors, such as precipitation patterns and topographic variability, as well as external factors like market prices.

## 4 | CONCLUSIONS

This study demonstrated that classifying agroecosystems into variable productivity zones using the TPI is an effective approach for capturing spatial yield variability in terraced claypan landscapes. Variation in the magnitude and distribution of total annual precipitation across site years coincided with shifts in corn grain yields among TPs, with shoulder areas yielding higher in years with above-normal precipitation and footslope and backslope positions performing better in relatively drier years. The disparities in yield and PFP across different TPs suggest that integrating NI (like nitrapyrin) with TPI-informed management practices could further stabilize

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**TABLE 7** Estimated gross returns, production costs, expected net returns, profit difference, incremental yield gain, breakeven yield gain, economic yield gains, and net economic gains based on yields of the three topographic positions with nitrapyrin from 2019 to 2022.

| Year | Topographic positions (TPs) | Yields (kg ha$^{-1}$) | Gross returns ($ ha$^{-1}$) | Production costs ($ ha$^{-1}$) | Expected net return ($ ha$^{-1}$)s | Incremental yield gain[a] (kg ha$^{-1}$) | Incremental revenue gain[b] ($ ha$^{-1}$) | Breakeven yield gain[c] (kg ha$^{-1}$) | Economic yield difference[d] (kg ha$^{-1}$) | Net economic gain[e] ($ ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2019 | Shoulder | 13357 | 1955.11*** | 1252.13 | 702.98*** | 488.70 | 70.61 | 162.64 | 326.06 | 47.11 |
| 2019 | Backslope | 11663 | 1679.01*** | 1252.13 | 426.88* | −159.52 | −23.05 | 162.64 | −322.16 | −46.55 |
| 2019 | Footslope | 11490 | 1629.50*** | 1252.13 | 377.37 | 376.19 | 54.35 | 162.64 | 213.55 | 30.85 |
| 2020 | Shoulder | 11532 | 2211.04*** | 1326.25 | 884.79*** | −283.64 | −51.26 | 130.04 | −413.69** | −74.76** |
| 2020 | Backslope | 12949 | 2395.94*** | 1326.25 | 1069.69*** | 651.83*** | 117.79*** | 130.04 | 521.78*** | 94.29*** |
| 2020 | Footslope | 12398 | 2270.23*** | 1326.25 | 943.98*** | 1289.66*** | 233.05*** | 130.04 | 1159.62*** | 209.55*** |
| 2021 | Shoulder | 9770 | 2417.73*** | 1510.16 | 907.57*** | 719.25*** | 174.15*** | 97.06 | 622.19*** | 150.65*** |
| 2021 | Backslope | 9066 | 2271.98*** | 1510.16 | 761.82*** | 957.80*** | 231.91*** | 97.06 | 860.74*** | 208.41*** |
| 2021 | Footslope | 5895 | 1494.45*** | 1510.16 | −15.71 | 992.07*** | 240.20*** | 97.06 | 895.01*** | 216.70*** |
| 2022 | Shoulder | 9013 | 2428.33*** | 1663.64 | 764.69*** | 693.65*** | 185.43*** | 87.91 | 605.75*** | 161.93*** |
| 2022 | Backslope | 10087 | 2761.59*** | 1663.64 | 1097.95*** | 739.77*** | 197.76*** | 87.91 | 651.86*** | 174.26*** |
| 2022 | Footslope | 10862 | 2862.76*** | 1663.64 | 1199.12*** | 653.99*** | 174.83*** | 87.91 | 566.08*** | 151.33*** |
| Average (2019–2022), expressed in January 2025 dollars) | Shoulder | 10918 | 2618.20*** | 1438 | 956.08*** | 425.43*** | 102.02*** | 119 | 311.52** | 74.70** |
| | Backslope | 10941 | 2623.72*** | 1438 | 961.59*** | 756.23*** | 181.35*** | 119 | 642.32*** | 154.03*** |
| | Footslope | 10161 | 2436.67*** | 1438 | 774.54*** | 948.22*** | 227.39*** | 119 | 834.31*** | 200.07*** |

*Note*: Production costs, nitrapyrin cost (NI), and corn prices are assumed to be given (i.e., non-stochastic) in this analysis. As a result, no statistical significance is reported for breakeven yield gain and production costs, which are deterministic functions. Statistical significance is only reported for metrics derived from the estimated yield response and its standard error. The 2019–2022 average values were adjusted to January 2025 dollars, using the Bureau of Economics (2025) gross domestic product implicit price deflator.

[a]Incremental yield gain = Yield of the nitrapyrin treatment-yield of control treatment (AA).

[b]Incremental revenue gain = Incremental yield gain × corn price.

[c]Breakeven yield gain = Cost of NI/corn price.

[d]Economic yield difference = Incremental yield gain—Breakeven yield gain.

[e]Net economic gain = Incremental revenue gain—Cost of NI.

*, **, *** represent the significance at the alpha level of 0.10, 0.05, and 0.01, respectively; no symbol indicates $p > 0.10$ (not statistically significant).

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yields across the diversified landscapes, including terraces. During years with lower precipitation under rainfed farming conditions, there is a risk of N being tied up in the ammonium form longer, and as a result, corn yield can be affected, but overall, when grain yield is analyzed over the long term, there is a net positive economic return from the use of nitrapyrin. Therefore, the general recommendation would be to use NI across all TPs. However, to maximize the net economic returns, adopting site-specific N management with variable source application of NIs is recommended. This approach promotes efficient N use and supports economic sustainability by aligning input applications with the unique needs of each TP, ultimately minimizing environmental impacts.

In addition to agronomic benefits, our analysis compared the cost of applying AA with and without nitrapyrin and assessed the yield improvements required to offset additional costs. The effectiveness of nitrapyrin varied across different TPs during four site-years from 2019 to 2022. The footslope position showed significant average incremental yields and, thus, average net economic gains compared to other TP. This suggests that these areas may be more responsive to the benefits of NIs like nitrapyrin under varying environmental conditions. However, the variability in corn prices over the years also played a critical role in influencing the net economic gains from nitrapyrin application. Higher corn prices tended to increase the profitability of nitrapyrin, particularly when combined with substantial yield gains at the footslope. In summary, applying NIs within TPI-defined management zones offers a promising strategy to optimize yields, enhance economic returns, and reduce environmental risk. Aligning N management practices with landscape variability supports both agronomic efficiency and long-term economic sustainability in corn production systems.

## AUTHOR CONTRIBUTIONS

**Pranay Kumar Kadari**: Formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Gurbir Singh**: Conceptualization; data curation; formal analysis; validation; writing—review and editing. **Kelly A. Nelson**: Data curation; project administration; resources; writing—review and editing. **Gurpreet Kaur**: Conceptualization; data curation; investigation; methodology; writing—review and editing. **Adauto Rocha Junior**: Data curation; investigation; methodology; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available on request from the corresponding author.

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