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OPTIMISING NITROGEN APPLICATION FOR MAIZE PRODUCTION: EFFECTS ON CROP BIOMASS, NITROGEN UPTAKE, AND SOIL NITROGEN DYNAMICS.

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Abstract

Predicting the optimum fertiliser N requirement for maize is often complicated due to the difficulty in accurately predicting mineralisation. This study investigated soil N dynamics in a maize-annual ryegrass crop system under a range of fertiliser N scenarios (0 to 320 kg N/ha).

This long-term study was initiated in the spring of 2021 at the Pioneer® Rukuhia Research Station (Waikato) on long-term cropped Allophanic soil. Four replicates of five fertiliser treatments were randomly allocated in a balanced incomplete block. The paper reports interim results for the first two years of the experiment.

Total dry matter (DM) yields ranged from 17,560 to 21,750 kg DM/ha (maize) and 3,139 to 5,152 kg DM/ha (annual ryegrass), with respective N removal rates of 177 to 208 and 51 to 94 kg N/ha. There were no significant maize silage DM yield differences for plots that received ≥80 kg N/ha (80N). During the maize cycle, estimated soil mineralisation was greatest under low N regimes (e.g., 177 kg N/ha at 0N) compared to 24 kg N/ha for the 320N treatment. Nitrogen was identified as the yield-limiting factor in control plots (0N). This was attributed to poor synchronisation between mineralisation and plant N demand. A negative soil N balance, which can be considered as potential N loss, was observed during the catch crop cycle whereby 89 kg N/ha was unaccounted for under the 320N treatment.

This study suggests that to optimise maize crop yields, without compromising on N demand and supply or soil fertility, fertiliser N application should be consistent with yield potential, compensating for actual, rather than potential mineralised N at side-dressing time.

Introduction

In today’s era, prudent use of fertiliser and other farm management practices are required to not only maximise farm productivity and profit but also reduce environmental impact. To maximise the efficiency of fertiliser application, crop nutrient demand, nutrients removed by harvested products, and the amount of soil nutrients supplied or lost should be considered before deciding on the total amount of additional fertiliser applications. Excessive and inefficient fertiliser use can damage the environment and reduce profitability whereas applying less fertiliser than crop demand would reduce crop production. An ideal fertiliser management strategy should result in optimising profits while reducing the environmental impact resulting from surplus applied nutrients.

Accurately predicting the right amount of nitrogen (N) required to meet crop needs and achieving synchrony between N supply and demand are prerequisites to optimising production and protecting the environment (Cassman and Dobermann, 2002). Predicting soil nutrient supply and the efficiency with which the applied fertiliser is utilised by the crop can be challenging. Weather unpredictability can also make the decision-making process even more problematic. Globally, N is the most widely used fertiliser, and yet, N fertiliser use efficiency (NFUE; the ratio of grain or silage yield to fertiliser N applied) is estimated at only 40 - 50% across crops and continents (Lassaletta et al., 2014; Cassman and Dobermann, 2022; Malinas et al., 2022), resulting in uncertainties around nutrient budgets (Zvang et al., 2020) and environmental impacts.

Globally, average N use per hectare of cropland increased from 51.7 kg N/ha to 69.4 kg N/ha between 1990 and 2020 (Statica, 2023). During the same period, N fertiliser use has increased by 629% in New Zealand (Statistics, New Zealand, 2023). There has been an increase in NFUE that has accompanied the genetic improvement of maize over time (Ciampitti & Vyn, 2012; Mu et al., 2015).

Maize is a high-yielding crop that requires a significant amount of nutrients, particularly N, to maximise yield. Given that N is an essential nutrient for regulating maize plant growth and yield, but can be a pollutant if it ends up in groundwater and water bodies, prudent N management is required in maize crop production. When crops are well managed and/or have greater yield potential, the proportion of fertiliser N taken up by the crops can approach 80%, though this proportion decreases as N application rates increase (Kovács et al., 1995; Udvardi et al., 2021). Prior to the maize crop's rapid vegetative growth stage (starting at the V6 stage), maize uses less than 10% of its total N requirement. In order to reduce N losses, growers should only apply a small amount of fertiliser N prior to this growth stage to reduce the risk of losses due to leaching. Research conducted on New Zealand ash soil indicated that leaching losses after late spring, which coincides with the commencement of the rapid vegetative growth phase of maize, were marginal, contributing less than 10% of the total annual N leaching losses from maize-based systems (Tsimba, 2021). Similar results have been reported by Thorup-Kristensen (2006) who observed no significant leaching over the summer when crop water use more closely matched rainfall on sandy soil in Denmark.

Applying a significant amount of N fertiliser earlier than the rapid growth stage could result in N loss either through leaching or denitrification, especially under cool wet spring weather conditions. It is also becoming increasingly important to understand how fertiliser N management at this stage of the crop cycle impacts soil microorganisms and their influence on soil N and carbon balance.

Most New Zealand soils generally have high organic matter (OM) levels which allow them to mineralise a significant amount of N over time. Based on OverseerFM® model estimates, some growers can underestimate the amount of N coming from soil reserves, which may result in over-application of N fertiliser. In highly fertile soils such as those coming out of the permanent pasture, soil mineralised N is typically the major source of crop N uptake (Stevens et al., 2005; Gardner and Drinkwater, 2009; Poffenbarger et al., 2018). Unlike artificial fertiliser, mineralised soil N is a more efficient source of crop N uptake because it is located in close proximity to crop roots (Drinkwater and Snapp, 2007).

This study helps growers understand how soil mineralisation can influence fertiliser N rates required to maximise maize yields while avoiding negative impacts on the environment from excess soil N and degradation of soil organic matter.

Methodology

A two-year N response study on maize was conducted on an Allophanic soil at the Pioneer® Rukuhia Research Station (37°51'33" S; 175°19'22"; 50 m asl.) near Hamilton between October 2021 and October 2023. The study area had been in a long-term maize silage - annual winter ryegrass rotation, but for two years prior to planting no N fertiliser was added to the maize silage crop or annual ryegrass. This was done to minimise extremes in residual N levels among plots. At the start of the study (October 2021) soil samples were collected for OM analysis, which was found to range between 12.4% and 14.4%.

Pioneer hybrid P9978 (CRM 99) was planted on 22 October 2021 and 27 October 2022 at 110,000 plants ha^{-1} using a precision planter. To maximise between-block variation as well as ensure that all treatment comparisons were made with equal precision, four sidedressing fertiliser treatments (80, 160, 240, and 320 kg N/ha) and a control (nil N fertiliser) were arranged in a balanced incomplete block design with four replications. Plots were four rows wide (0.76m spacing) x 8m long, and measurements were only conducted on the two centre rows.

Approximately two weeks before maize planting, two soil samples were collected by soil auger over a 150 mm soil depth of each plot to determine soil nutrient status and fertiliser requirements. The two samples were composited and sent to a commercial laboratory for standard soil nutrient and pH testing. Fertiliser rates, as determined by the soil test values, for all nutrients other than N were surface applied and disced in prior to planting. On average, 600 kg ha^{-1}, 100 kg ha^{-1}, 200 kg ha^{-1} and 2,000 kg ha^{-1} of Muriate of potash (50% K), Calmag (38% Mg; 1.7% S), Kieserite (18% S; 15% Mg) and Lime (0.3% Mg; 38% Ca), respectively, were broadcasted and incorporated into the soil just before planting.

At planting, 53 kg N ha^{-1} was band applied as starter fertiliser in the form of diammonium phosphate (17.6% N; 20% P; 1% S). Weeds were controlled with 3 l ha^{-1} of Roustabout (840 g l^{-1} Acetochlor) and 150 g ha^{-1} Sharpen (700 g kg^{-1} Saflufenacil) applied as a pre-emergence herbicide combination. For protection against above and below-ground insects, maize seed was coated with 600 g l^{-1} Clothianidin. In addition, the seed was further coated with 200 g l^{-1} Carboxin and 200 g l^{-1} Thiram for protection against seed-borne and soil-borne diseases.

At the V4 maize development stage, two soil samples were collected from each plot to a depth of 120 cm at 30 cm intervals using a modified 15 mm soil drill and composited at each depth by plot and analysed for mineral N (sum of NH_4^+ and NO_3^-). The soil mineral N pool size was determined by extracting NO_3^- and NH_4^+ with 2 M potassium chloride (KCl) (Adamsen et al., 1985) and subsequent measurement with colorimetry on a Lachat QC8500 Series 2 Flow Injection Analyser System (Lachat Instruments, USA).

At the V5 maize development stage, urea (46% N) was broadcast across all fertiliser treatment plots, using the median mineral N value obtained in control plots as the baseline for determining the actual N rate application per plot. No urea fertiliser was applied in the control plots. At the same time, a 200 ml/ha product of Arietta (active ingredient: 336 g l^{-1} Topramezone) was applied as a post-emergence herbicide.

When aboveground maize biomass had reached about 35% whole plant dry matter (DM) content (14 March 2022 and 22 March 2023), two centre rows from each maize plot were harvested as silage using a 2-row small plot "Wintersteiger" silage chopper. Dry matter and N contents were measured using a calibrated Near Infrared Spectroscopy (NIRS) system mounted on the chopper (Williams, 2001).

Soon after maize silage harvesting, soil samples were collected from each plot to a depth of 120 cm and used to estimate residual soil N using the procedure described above. Within a week of maize silage harvesting, plots were drilled with winter annual ryegrass, "Hogan®" (25 kg/ha) as a catch crop, with the sole purpose of "mopping up" excess soil N remaining after the maize crop. Consequently, no fertiliser was applied to the winter annual. When the winter annual had reached a 30 - 40 cm height, two 0.5 m x 5 m strips were cut using a push lawn mower to estimate aboveground biomass, leaving residuals of 5 cm. A subsample (approximately 1 kg) was oven-dried at 65°C to determine percent DM. A separate subsample was also sent to a commercial laboratory for total N content analysis. The resultant tissue biomass and N concentration were used to determine crop N uptake on each sampling occasion.

Data were analysed using Genstat version 22 (VSN International, 2022) as a combined analysis of the two seasons with a mixed model using treatments and seasons as fixed factors and plots as random factors. Multiple means comparisons were performed with a Fisher's least significant difference (LSD) procedure. For all statistical tests conducted, the type I error rate was set at 0.05 and where a season x treatment interaction did not exist, data were combined and reported accordingly.

Results

Weather data

The 2021-22 maize growing season (October to March) received about 100 mm less rain than the long-term (2000 – 2023) average, whereas the 2022-23 growing season was 400 mm wetter than average (Table 1). The mean temperature for the two maize growing seasons averaged 18°C, compared to the long-term average of 17°C. Whereas the 2022-23 rainfall total for the winter annual ryegrass growing period (April – August) was similar to the long-term, 2021-22 was 30% wetter than the long-term average for the same period.

Table 1: Comparison of the long-term (2000-2023) average monthly rainfall and temperature with that of the 2021-22 and 2022-23 seasons, Rukuhia, New Zealand.

Month	Monthly total rainfall, mm			Average Tmin, °C			Average Tmax, °C		
	2021-22	2022-23	2000-23	2021-22	2022-23	2000-23	2021-22	2022-23	2000-23
Sep	174	134	114	6	7	7	16	16	16
Oct	116	202	106	10	9	8	19	19	18
Nov	64	193	87	12	12	10	22	22	20
Dec	87	112	108	14	14	12	24	24	22
Jan	6	232	83	12	16	13	27	24	25
Feb	91	130	84	15	15	13	27	24	25
Mar	67	62	75	12	10	11	25	23	24
Apr	23	34	91	9	11	9	22	21	21
May	144	190	117	7	10	7	19	19	17
Jun	241	152	127	7	5	5	16	16	15
Jul	228	62	128	7	6	4	15	15	14
Aug	112	70	114	6	3	5	16	15	15
Average*	1,353	1,575	1,234	10	10	9	21	20	19

* Rainfall values are annual totals

Maize yields and soil N balance

Initial measurements conducted at the V4 maize stage indicated a total mineral soil N averaging about 90 kg N/ha across all treatments (Table 2). Considering variable N application rates and initial mineral soil N at sidedressing, N levels for the 0 - 120 cm soil depth ranged between 87 and 411 kg N/ha.

Table 2: Soil N dynamics and maize silage DM yields on a Waikato ash soil for the 2021-22 and 2022-23 maize growing seasons. Means followed by the same letter within the same column are not statistically different (P<0.05).

Nitrogen treatment	Initial soil N at V4 stage (kg N/ha)	Applied N fertiliser (kg N/ha)	Maize DM yield (kg DM/ha)	Maize N removal (kg N/ha)	Soil mineral N after maize (kg N/ha)		Estimated soil N supply after V4 stage (kg N/ha)
					NH_4^+	*NO_3^-*	
0N	87a	0a	17,560a	177a	63a	19a	177c
80N	98a	73b	20,490b	208bc	48a	27a	114bc
160N	96a	155c	20,530b	192ab	58a	60ab	66ab
240N	92a	239d	21,750b	211b	44a	103bc	42a
320N	87a	324e	21,250b	206b	54a	162c	24a
SE	*10.5*	*9.5*	*663.3*	*11.6*	7.4	22.8	*31.1*

Long-term maize silage crop N removal for the trial site has normally averaged about 200 kg N/ha (Genetic Technologies data, unpublished). Including initial soil N and N sidedressing applications, all but two treatments (0N and 80N) had sufficient N available to sustain these long-term crop N removal rates (Table 2).

Maize silage DM yields and N removal rates were similar in all plots that received sidedressing fertiliser. Similarly, the maize silage crop N removal rates from these plots were consistent with the long-term trends of about 200 kg N/ha, while the unfertilised control plots removed 25 kg less N/ha. Compared to 240N and 320N, the nil and low N input treatments (0N, 80N and 160N) showed a significant amount of soil mineral N after maize harvest, indicating greater net mineralisation (Table 2). Also, the soil mineral N values from these low N treatments had a much greater proportion of NH_4^+ (≥49%), relative to NO_3^-. On average, OM levels in the 0N, 80N and 160N treatments decreased from 13.8% to 12.2% compared to a 5% decrease for the higher N treatments (13.6% to 12.9%). These measurements are ongoing and will be covered in more detail in the future.

At catch crop establishment, initial mineral soil N ranged from 79 - 229 kg N/ha (Table 3). Winter catch crops established after maize at 0N, 80N and 160N, averaged 3,240 kg DM/ha compared to 4,911 kg DM/ha for the higher N treatments. Catch crop N uptake ranged between 51 and 94 kg N/ha. At the end of the catch crop season (spring), mineral N levels were similar across all treatments, averaging 47 kg N/ha.

Table 3: Soil N dynamics and catch crop biomass yields on Waikato ash soil for the 2021-22 and 2022-23 catch crop growing seasons. Means followed by the same letter within the same column are not statistically different (P<0.05).

Nitrogen treatment	Soil mineral N after Maize (kg N/ha)	Catch DM yield (kg DM/ha)	Catch crop N removal (kg N/ha)	Soil mineral N after catch crop (kg N/ha)		Estimated soil N supply (kg N/ha)*
				NH_4^+	*NO_3^-*	
0N	87a	3,290a	52a	43a	3a	15a
80N	79a	3,139a	51a	40a	2a	22a
160N	128ab	3,293a	51a	36a	2a	-34ab
240N	162b	4,670b	82b	45a	6a	-31ab
320N	229c	5,152b	94b	35a	6a	-89b
SE	*26*	*516.1*	*9.5*	*7.1*	*1.7*	*34.6*

*A negative value indicates unexplained N loss from the system

During the catch-crop cycle, 89 kg N/ha was unaccounted for when 320 kg N/ha was applied, compared to a net N gain of 15 kg N/ha when nil N was added into the system. Unlike in the maize cycle there was a clear distinction in the component constitution of mineral N, with the catch crop, the proportion of NH_4^+ in the mineral N component was much higher than that for NO_3^- in high for both low and high N treatments (≥85%).

Discussion

For the two seasons reported here, maize yields did not necessarily increase in proportion to N fertiliser applied, indicating the inherent ability of high OM soils to supply N when needed. The amount of mineralised soil N was hence, greater in plots that received nil or low fertiliser N rates. For instance, the estimated soil N supply from soils that received nil N fertiliser was 177 kg N/ha, compared to 24 kg N/ha when 320 kg N/ha was applied. The future focus of this study will be to establish the sustainability of maintaining high maize silage yields with low fertiliser N rates.

Ammonium-N and NO_3^--N are the main forms of soil inorganic N essential for plant growth. Even though mineralisation assays (Hart et al., 1994) are required to more accurately measure soil N availability, the greater ratio of NH_4^+-N vs. NO_3^-N observed in nil or low N plots likely implies, among other factors, reduced nitrification due to the low soil N. In cropped soils, NH_4^+ is usually quickly converted to NO_3^- during mineralisation, resulting in lower NH_4^+ concentrations compared to NO_3^- (Robertson, 1997). The greater proportion of NH_4^+-N in all plots at the end of the catch crop cycle could reflect nitrification inhibition either due to lower temperatures or oxygen availability (Dannenmann et al., 2006) or possible NO_3^- depletion through plant uptake or loss from the system.

A greater proportion of NO_3^--N in the higher N fertiliser plots could have environmental consequences due to its greater soil mobility. However, previous research conducted on a similar soil type showed that irrespective of the mineral soil N, N leaching losses during the maize growing cycle are marginal (Tsimba et al., 2021). While leaching losses could be greater in winter due to greater drainage, the use of catch crops such as annual ryegrass, oats or forage kale can reduce N loss by up to 90% (Carey et al., 2016; 2017; Malcolm, et al., 2016; Tsimba et al., 2021).

A general trend of soil OM reduction with fertiliser N decrease was also observed. These results are consistent with previous studies that concluded that under low soil N levels, microbes met their N demand by decomposing OM, leading others to conclude that N fertilisation decreased OM decomposition (Moorhead and Sinsabaugh, 2006; Spohn et al., 2016; Zang et al., 2016; Liu et al., 2017; Mahal et al., 2019). Brown et al. (2014) also observed that fertiliser N (vs. control) reduced the C: N ratio, which results in decreased microbial N mining through lower N demand. Nitrogen mining (OM decomposition) can lead to a decline in the long-term fertility and productive capacity of the soil, as well as potential off-site environmental impacts (Huang et al., 2024). He et al., 2023 also noted that not only do excessive mineralisation rates, as observed in the low N plots, result in a net loss of soil OM, but also increase CO_2 emissions. For instance, other studies have reported an 8 - 15% reduction in CO_2 emissions when N fertiliser was used (Janssens et al., 2010; Liu and Greaver, 2010).

Reliance on N fertiliser to conserve soil OM is however unsustainable and could result in an increased environmental impact through leaching or denitrification. This was evidenced in our study where increased potential N losses were observed when excessive fertiliser N was applied. Fertiliser N rates should be consistent with plant demand and soil OM status and efficient fertiliser use is crucial to maintain and maximise profits while minimising the environmental impact. Unlike other research showing luxury N uptake in maize under excess

N levels (e.g., Muchow, 1998), there was no difference in the N concentration of the harvested maize silage across all N fertiliser regimes. This finding further emphasises the importance of prudent N use to minimise the environmental impact as the maize plant appears to remove only the N that it requires.

Despite evidence of residual soil N after maize harvest in the zero N (control) plots that were actually N depleted, maize yields were significantly lower than in fertilised plots, suggesting poor synchronisation between plant N demand and soil N supply. During the active growth phase, maize N uptake can reach 4 kg N/ha/day (Olson and Kurtz, 1982) and if the soil supply cannot meet demand, yields will be impacted. Maize N uptake is expected to exceed 60% of the total plant requirement by the silking stage (Bender et al., 2013). Short-term deficiency during early or late vegetative development could therefore lower yield potential, even if overall soil N balance appears adequate. Even though 1 - 2% of soil organic N can be mineralised every year (Schepers and Mosier, 1991), the process is driven by soil microbes, which rely on soil temperature and moisture to be active. Under typical New Zealand dry summers, particularly in dryland cropping, achieving synchrony between plant N demand and soil N supply can be challenging. Reliance on soil OM as a source of N in long-term cropping situations can hence be considered unreliable.

Conclusion

Provided weather conditions do not deviate much from normal, maize crop N requirements can be easily estimated based on paddock and crop yield potential and regular soil testing. Even though most soils can mineralise N from OM, synchronising soil N release and plant N demand is not guaranteed, particularly in long-term rainfed cropping situations. Uptake has to occur if soil N is required to substitute fertiliser N. To minimise the risk of maize crops running out of N, synthetic N is therefore required and should be applied at rates that match measured soil available N, crop removals and potential N losses that are not avoidable. To minimise any potential environmental impact, excess soil N left after maize silage harvest should be “mopped up” by establishing winter catch crops.

Relying on soil OM to supply crop N requirements can significantly reduce fertiliser costs, improve FNUE and reduce N leaching and denitrification losses. On the flip side, continued degradation of soil OM could significantly reduce soil fertility and productivity over time, as well as increase greenhouse gas emissions. While some researchers would argue that soil OM should be increased through organic inputs rather than reducing mineralisation, we would argue that the best option is to do both, but in a measured way.

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