Recovery of soil nitrogen by maize at various soil depths: a field study using ^{15}N-labelled fertiliser nitrogen

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Abstract

Nitrogen (N) recovery by maize (*Zea mays* L.) in harvested grain is typically only 30–45% of applied fertiliser N, with the remainder susceptible to leaching and denitrification. In New Zealand, nitrate-loss regulation has increased reliance on nutrient budgeting models such as OverseerFM®, which until recently assumed a maximum effective maize rooting depth of 60 cm, potentially under-representing N uptake by deep-rooted crops, e.g., maize.

Using ^{15}N labelled fertiliser, maize uptake, timing and partitioning of absorbed N from soil depths of 60, 90, and 120 cm were assessed under New Zealand field conditions. A two year field experiment was conducted on a Waikato allophanic soil, with ^{15}N applied at the V6 growth stage via subsurface injection beneath individual plants. Plant tissues were sampled through to maturity to trace depth specific uptake and redistribution.

Recovery of ^{15}N in aboveground biomass mostly occurred post-silking, and was 65-69%.

Results show that maize can access soil N from ≥120 cm depth, supporting improved representation of deep rooting and late-season N uptake in nutrient budgeting models.

Keywords: nitrate leaching, nutrient budgeting, post-silking uptake, remobilisation, root-zone dynamics

Introduction

Nitrogen (N) is critical for maize (*Zea mays* L.) growth, yet recovery from soil and fertiliser sources is often inefficient. Across a wide range of cropping systems, only a fraction of applied N is recovered in harvested grain, with reported recoveries of approximately 30–45% for cereals (Raun and Johnson 1999; Zhang et al. 2015).

The remaining N persists in soil or residues and is susceptible to leaching and denitrification, affecting water and air quality. While improved crop management and higher yield potential can increase fertiliser N recovery to as much as 80%, recovery generally declines as N application rates increase (Udvardi et al. 2021). Genetic improvement in maize has also contributed to greater N use efficiency over time (Ciampitti and Vyn 2012; Mu et al. 2015), but substantial uncertainty remains regarding the fate of N in soil–plant systems.

In New Zealand, concern over declining groundwater and surface water quality has intensified scrutiny of agricultural N losses. Regulatory frameworks increasingly require farmers to quantify or limit N leaching losses, particularly under intensive cropping systems. Direct measurement of N leaching is resource-intensive and impractical at scale.

Consequently, modelling approaches are widely used to estimate N losses by balancing N inputs against crop N removal. OverseerFM®, the primary nutrient budgeting model used in New Zealand, is widely applied in pastoral systems and increasingly used for arable cropping (Wheeler 2016; MPI 2021). However, until recently, OverseerFM® assumed a maximum effective crop rooting depth of 60 cm, raising concerns about its suitability for deep-rooted crops such as maize.

Numerous studies have demonstrated that maize roots can extend well beyond 120 cm in deep, friable soils, with maximum rooting depth typically achieved shortly after silking (Dwyer et al. 1988). Roots can exceed 300 cm, although density declines sharply with depth and very deep roots may contribute little to total uptake.

It is therefore important to distinguish maximum rooting depth from effective rooting depth, where substantial water and nutrient uptake occur. Field studies have reported effective rooting depths for maize of approximately 90–120 cm, with 20–35% of total water extraction occurring below 60 cm, depending on soil type and climate (Irmak and Rudnick 2014). These findings suggest that maize has the potential to access nutrients leached below shallow soil layers, particularly

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during later stages of crop development.

Maize capture of nitrate (NO_3^-) from deeper layers is especially relevant where rainfall exceeds evapotranspiration and moves mineral N downward. Experimental studies have shown that NO_3^- displaced to deeper soil layers remains accessible to roots and can be taken up later in the growing season (Dathe et al. 2016). Field evidence from New Zealand further indicates that deep-rooted crops such as maize can recover N leached below 60 cm before it moves beyond the root zone (Tsimba et al. 2021). However, quantifying the depth-specific uptake of N under field conditions remains challenging due to the spatial and temporal heterogeneity of soil N supply.

Stable isotope ^{15}N provides a powerful tool to trace the uptake and redistribution of N from specific soil depths and application timings. Previous ^{15}N studies have demonstrated strong remobilisation of vegetatively absorbed N to the grain during grain filling, with 60–85% of plant N present at flowering ultimately translocated to kernels (Ta and Weiland 1992; Gallais et al. 2007; Ning et al. 2017). While many studies have examined the timing and partitioning of N uptake, fewer field-based investigations have directly quantified the effectiveness of maize roots in acquiring N from deep soil layers.

This study used ^{15}N-labelled fertiliser to determine maize root capacity to extract N from 60, 90, and 120 cm under New Zealand field conditions. A secondary objective was to assess the timing and partitioning of absorbed N among maize plant components throughout crop development. Improved understanding of deep N uptake will support better crop model representation, N management, and nitrate-leaching risk assessment.

Materials and Methods

Site description and experimental design

A two year ^{15}N enriched maize study was conducted during the 2019–20 and 2020–21 growing seasons on an allophanic soil near Te Awamutu. The experimental paddock had been under a long term (>15 years) maize silage–annual winter ryegrass (*Lolium multiflorum* Lam.) rotation. To avoid potential carryover effects from the previous season's ^{15}N application, the experiment was established in a different paddock in the 2020–21 season.

Before planting, soil was sampled to determine baseline soil fertility and fertiliser requirements. At the start of each season, two soil cores per plot were collected at depths of 0–60, 60–90, and 90–120 cm using a modified soil auger and composited by depth within each plot. Soil samples were extracted with 2 M KCl for NH_4^+N and NO_3^-N (Adamsen et al. 1985) and analysed using a 2-channel flow injection analyser (Lachat Instruments, USA).

Crop establishment, treatments, soil sampling and crop management

Pioneer® maize hybrid P0640 (CRM 106) was planted with a precision planter on 10 October 2019 and 17 September 2020 at 100,000 plants ha^{-1}, representative of local management for this soil type. Treatments comprised three ^{15}N placement depths (60, 90, or 120 cm depth) and an unlabelled control, arranged in a randomised complete block design with four replicates. Plots comprised 2-m long x three rows (0.76 m spacing) established at 10 plants m^{-2}. Soil mineral N was assessed at planting and post-harvest as described above. No insect pests or diseases were observed to affect crop performance.

^{15}N application and injection procedure

At V6, approximately one week after urea application at V5, ^{15}N enriched potassium nitrate (KNO_3; 5 atoms % ^{15}N) was applied at a rate equivalent to 30 kg N ha^{-1} to the three labelled treatments. In control plots, 30 kg N ha^{-1} was applied as unlabelled urea. In labelled plots, the ^{15}N solution was injected beneath 12 plants in the centre row of each plot, with two plants at each end of the row left as borders.

Injection holes (18-mm diameter) were drilled using a standard drill at a 10° angle from vertical, using distances from the plant base appropriate to each depth measured perpendicular to the row direction. A bulk solution of ^{15}N enriched KNO_3 was prepared in distilled water at a concentration of 9.53 g N L^{-1}. Using a modified 8-mm diameter stainless steel injection tube (Hodgen et al. 2009), 30 mL of solution was injected at the base of each hole beneath each target plant, followed by a 30 mL distilled water flush to the same depth. Holes were immediately backfilled with soil. The injection apparatus was thoroughly rinsed with distilled water between plots to minimise cross contamination, and rinse water was disposed of offsite.

Plant sampling and processing

Ten consecutive bordered plants in the centre row of each plot were permanently marked. Sampling was designed to trace ^{15}N uptake and redistribution among plant components formed at different growth stages (Hodgen et al. 2009).

At V14, the uppermost collared leaf and the two leaves above it were identified on each marked plant. Four 6-mm discs were collected from the upper third of each leaf blade between the midrib and margin, giving 12 discs per plant. The procedure was repeated at silking, defined as 50% of plants in a plot showing silk emergence. To minimise contamination, control plots were sampled first, followed by the 120, 90, and 60 cm treatments, with ethanol cleaning between plots.

Leaf discs were composited by plot and oven-dried at 30°C to constant weight. Senescing leaves from marked plants were collected periodically, air-dried,

Table 1 Comparison of the long-term (2009-2019) Te Awamutu average monthly rainfall and temperature with that of the 2019-20 and 2020-21 seasons.

	Monthly total rainfall (mm)			Monthly mean temperature (°C)		
	2019-20	2020-21	2009-2019	2019-20	2020-21	2009-2019
October	68	54	104	13.2	13.9	13.0
November	44	156	87	14.3	15.8	14.5
December	59	52	108	17.9	16.5	17.2
January	9	77	87	18.3	18.2	18.5
February	18	42	87	19.9	19.1	19.1
March	74	152	74	17.0	17.4	17.4
April	76	85	98	14.5	14.9	14.8
Season total/mean	348	618	645	16.4	16.5	16.4

Source: Weather data obtained from the National Institute of Water and Atmospheric Research (NIWA) CliFlo database.

and composited by plot. Approximately 2–4 weeks after physiological maturity, ears were harvested, oven-dried at 65°C to constant weight and shelled. Husks were combined with previously collected leaves and hereafter referred to as "leaf." Stalks, including leaf sheaths, were cut approximately 10 cm above ground, sectioned into 10-cm lengths, air-dried, and then oven-dried.

Sample preparation and isotopic analysis

Dried plant components (leaf, stalk, and grain) were ground using a Wiley mill to pass a 2 mm screen, followed by further grinding to pass a 100 mesh screen using a roller mill (Arnold and Schepers 2004). Grinding followed the same order as sampling (control, 120, 90, then 60 cm treatments), with ethanol cleaning between plots.

Samples were analysed for total N and atom % ^{15}N by elemental analysis–isotope ratio mass spectrometry (Sercon Ltd., UK). Cobs were analysed for N but not ^{15}N. Alfalfa flour was used as the working plant standard (Bronson et al. 2019). Natural abundance ^{15}N in unlabelled control plants was assumed to be approximately 0.366 atom %, with minor enrichment (≈0.37 atom %) considered typical of soil derived N (Shearer and Kohl 1986; Fry 2006).

$$\%\ ^{15}\text{N recovered} = 100 \times T \times \frac{(c-b)}{f \times (a-b)}$$

Calculation of ^{15}N recovery and statistical analysis

The percentage recovery of applied ^{15}N in plant components was calculated according to Hauck and Bremner (1976):

where T is the total N content of the plant component (kg N ha^{-1}), a is the atom % ^{15}N in the fertiliser, b is the atom % ^{15}N in the corresponding plant component from the control treatment, c is the atom % ^{15}N in the labelled plant component, and f is the rate of labelled N applied (kg N ha^{-1}).

Data were analysed using linear mixed models in Genstat V22 (VSN International 2022), with season and treatment as fixed effects and with replicate and plot as random effects. Means were compared using Fisher's LSD ($P \leq 0.05$). Where season × treatment interactions were not significant, data were pooled across seasons.

Results

Weather and mineral soil N

Total rainfall during the 2019–20 growing season (October–March) was 54% of the long term Waikato mean, whereas rainfall in 2020–21 was similar to the long-term average (Table 1). During the critical December–February period, rainfall amounted to 30% and 60% of the long-term mean in 2019–20 and 2020–21, respectively.

Initial and final soil mineral N contents (NH_4^+N + NO_3^-N) averaged across all plots and selected ^{15}N injection depths are presented in Table 2. Initial soil mineral N in the top 60 cm was substantially greater in 2019–20 than in 2020–21. In addition to background soil N, 158 kg N ha^{-1} was applied as fertiliser. Despite contrasting initial soil mineral N, mineral N in the top 60 cm declined markedly by harvest in both seasons to approximately 20 kg N ha^{-1}, while soil mineral N below 60 cm remained largely unchanged.

Maize leaf nitrogen concentration and ^{15}N uptake by growth stage

Across both seasons, mean leaf N concentration was approximately 2.7% at V14 (Table 3). By silking, leaf N concentration declined by 13% in 2019–20 and 6% in 2020–21 (averaged across depths). Leaf N concentration at maturity was approximately 80% lower than at silking. The atom % ^{15}N in plant tissue from non-enriched plots averaged 0.37%, consistent with natural soil ^{15}N abundance. Enrichment above this value reflected uptake of applied ^{15}N.

In 2019–20, significantly greater leaf ^{15}N enrichment

Table 2 Initial (pre-planting) and final (post-harvest) soil extractable mineral N (NH_4^+-N and NO_3^-N) levels (mean ± SE) by soil depth on a Waikato ash soil site in Te Awamutu.

Soil depth (cm)	2019-20				2020-21			
	Initial soil N		Final soil N		Initial soil N		Final soil N	
	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N
	kg N ha^{-1}							
0 - 60	7.2	103.8	11.1	10.5	16.4	80.7	10.0	9.5
60 - 90	2.2	11.3	3.7	4.8	2.8	6.1	3.3	4.3
90 - 120	2.4	7.5	4.2	3.8	3.3	2.6	3.8	3.4
SE	1.03	5.57	2.79	2.58	2.01	11.51	1.31	1.04

Table 3 Total N % and atom % ^{15}N of maize leaf samples collected at V14, 50% silking and maturity stages, as affected by depth of ^{15}N insertion on a Waikato ash soil in Te Awamutu.

^{15}N injection depth	2019-20			2020-21		
	V14	Silking	Maturity	V14	Silking	Maturity
	N					
0	2.74	2.26	0.41	2.64	2.44	0.47
60	2.74	2.45	0.47	2.67	2.52	0.56
90	2.53	2.23	0.43	2.66	2.52	0.56
120	2.63	2.27	0.43	2.59	2.41	0.46
SE	*0.061*	*0.060*	*0.015*	*0.032*	*0.037*	*0.016*
	atom % ^{15}N					
0	0.37	0.37	0.37	0.37	0.37	0.37
60	0.70	0.92	0.72	0.58	0.70	0.86
90	0.58	0.76	0.71	0.39	0.40	0.66
120	0.38	0.43	0.54	0.39	0.40	0.54
SE	*0.049*	*0.070*	*0.044*	*0.031*	*0.045*	*0.055*

Table 4 Aboveground biomass yield and N removal as affected by depth of ^{15}N insertion on a Waikato ash soil in Te Awamutu.

^{15}N injection depth	2019-20				2020-21			
	Leaf	Stalk	Grain	Cob*	Leaf	Stalk	Grain	Cob*
	Biomass yield kg DM ha^{-1}							
	Leaf	Stalk	Grain	Cob*	Leaf	Stalk	Grain	Cob*
0	6,135	5,302	9,545	1,529	6,830	3,699	11,782	2,292
60	6,565	5,422	11,756	1,934	5,171	3,045	9,531	1,528
90	5,870	5,049	9,310	1,524	6,652	4,009	12,394	1,937
120	6,062	5,150	10,123	1,602	5,494	3,051	9,443	1,791
SE	*129.4*	*144.2*	*399.2*	*68.2*	*334.2*	*202.6*	*684.9*	*116.6*
	Total N removal kg N ha^{-1}							
0	25.0	17.3	88.4	5.9	31.9	13.3	104.7	8.5
60	30.9	14.3	126.7	8.6	28.8	10.7	84.7	5.7
90	25.3	12.1	96.9	6.6	36.1	15.1	122.8	8.0
120	26.3	15.0	101.2	6.6	25.3	10.3	80.4	6.4
SE	*1.30*	*0.90*	*6.61*	*0.42*	*1.70*	*0.86*	*7.48*	*0.51*

* Cob without grain

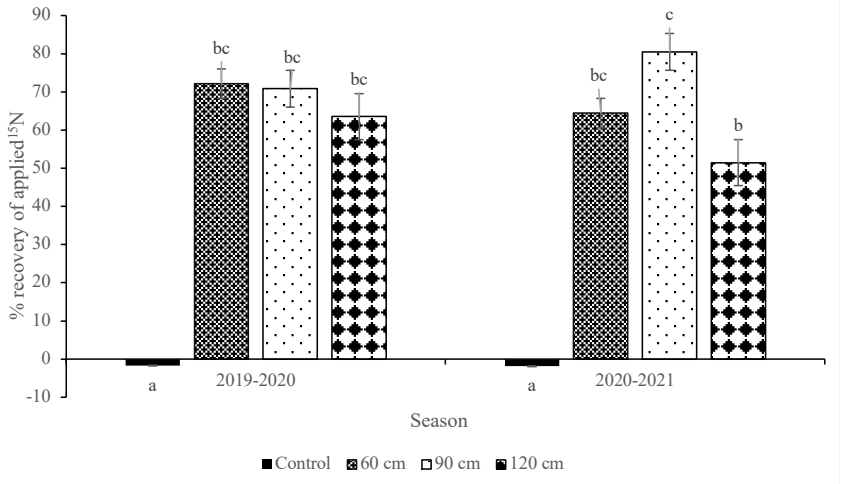


Figure 1 Nitrogen-15 recovery percentage of aboveground maize plants at maturity as affected by depth of ^{15}N insertion at V6 on a Waikato ash soil in Te Awamutu. Bars show standard errors; means not sharing a letter differ significantly ($P \leq 0.05$). Control plots received no labelled N.

at V14 and silking occurred with 60 and 90 cm injection depths compared with the control. In contrast, in 2020–21, ^{15}N uptake at these growth stages was only detected following 60 cm injection. In both seasons, appreciable uptake of ^{15}N from the 120 cm depth was only evident at maturity, indicating that roots reached this depth primarily after silking.

Biomass production, nitrogen uptake and ^{15}N recovery

Depth of ^{15}N injection did not significantly affect total aboveground maize biomass yield in either season (Table 4). Although maize stalk biomass differed significantly between seasons, total aboveground N removal did not, indicating that injection depth of 30 kg N ha^{-1} as ^{15}N had no effect on biomass production or plant N uptake. Except for cob biomass and cob N removal, no significant season × depth interactions were observed; seasonal results for individual plant components are therefore presented separately.

Cumulative N removal by aboveground plant components averaged approximately 150 kg N ha^{-1}. Grain contributed about 50% of total aboveground biomass but contained approximately 70% of total plant N uptake. Stalk biomass accounted for ~20% of aboveground dry matter but only ~10% of total plant N, with the remainder contained in leaves. At maturity, total leaf N concentration was 16% lower and stalk N concentration 14% higher in 2019–20 than in 2020–21, while grain N concentration was similar between seasons.

At maturity, mean recovery of applied ^{15}N in aboveground biomass was 69% in 2019–20 and 65% in 2020–21 (Figure 1). Recovery did not differ significantly among injection depths in 2019–20. In 2020–21, recovery from 90 cm was significantly greater than from 120 cm ($P \leq 0.05$), with 60 cm intermediate and not differing from either.

Discussion

Influence of weather on soil N availability, yield and N distribution

Lower initial soil mineral N in 2020–21 followed a very dry autumn, which likely constrained mineralisation over autumn and winter (Myers et al. 1982). Mineralisation generally increases with soil moisture until saturation reduces aeration and microbial activity (Cassman and Munns 1980; Myers et al. 1982; Quemada and Cabrera 1997), consistent with the observed seasonal differences.

Despite large seasonal differences in rainfall, total aboveground biomass and grain yield were similar between years. Total growing season rainfall (54% vs. 96% of average) did not translate directly into yield differences, likely because nutrient supply was not limiting and much of the crop N uptake occurred before severe late season moisture deficits. Instead, differences in rainfall were reflected more strongly in post-silking N distribution among plant components.

Depth dependent and temporal patterns of ^{15}N uptake

Application of ^{15}N-labelled KNO_3 at V6 allowed root access to soil N pools to be traced over time. Detection of ^{15}N from 60 cm by V14 in both seasons indicates root access to this depth within about 30 days of application. Uptake from 90 cm at V14 in 2019–20 suggests deeper root penetration under drier conditions, while the absence of detectable uptake from 120 cm before

Table 5 Concentration of atom ^{15}N percent and percentage of ^{15}N recovery of maize leaf, stalk and grain at maturity stage on a Waikato ash soil in Te Awamutu.

	2019-20			2020-21		
^{15}N injection depth	Leaf	Stalk	Grain	Leaf	Stalk	Grain
	Concentration of atom % ^{15}N					
0	0.37	0.37	0.37	0.37	0.37	0.37
60	0.72	0.82	1.07	0.86	0.88	1.21
90	0.71	0.92	1.31	0.66	0.88	1.15
120	0.54	0.96	1.18	0.54	0.87	1.12
SE	*0.044*	*0.068*	*0.109*	*0.055*	*0.067*	*0.118*
	% ^{15}N Recovery					
0	-0.34	-0.20	-1.16	-0.40	-0.18	-1.32
60	7.03	3.99	61.14	9.54	3.75	51.16
90	5.69	4.73	60.41	7.20	5.38	67.90
120	2.84	6.24	54.44	2.72	3.71	45.04
SE	*0.799*	*0.674*	*7.059*	*1.143*	*0.597*	*8.598*

maturity indicates that effective rooting to this depth occurred mainly after silking. These findings align with rhizotron observations and published studies showing that effective rooting depth lags maximum root depth and increases with crop age and hybrid maturity (Dwyer et al. 1988). Effective rooting depth in this study likely ranged from 60–90 cm at V14 and 90–120 cm by silking, reaching ≥120 cm post silking. The appearance of ^{15}N in aboveground plant components at maturity following 120 cm injection supports this interpretation.

Water uptake profiles for maize show a substantial extraction below 60 cm later in the season (Irmak and Rudnick 2014; Reyes et al. 2015). Because NO_3^- mass flow to roots closely follows water uptake (Chapman et al. 2012), depth dependent N uptake patterns in this study were consistent with known water extraction dynamics.

Nitrogen partitioning and remobilisation during grain filling

At maturity, total leaf N concentration was lower in 2019–20 than in 2020–21, consistent with enhanced remobilisation under drier conditions (Masclaux Daubresse et al. 2008). Grain N concentration, however, was similar between years, reflecting prioritisation of N allocation to reproductive sinks. The higher proportion of recovered ^{15}N in grain (~85%) compared with total N partitioning highlights the strong sink strength of developing kernels.

Differences in leaf ^{15}N recovery among injection depths indicate that leaves act primarily as transient N sinks, particularly for N acquired earlier in the season. Even under good growing conditions, grain N demand cannot be fully met by post-silking uptake, requiring remobilisation of N assimilated before silking (Rajcan and Tollenaar 1999; Hirel et al. 2007). Limited post silking allocation of newly absorbed N to leaves is consistent with previous findings (Mueller and Vyn 2016; Nasielski et al. 2019). Similar ^{15}N concentrations in stalks and grain across injection depths show maize accessed N between 60 and 120 cm and preferentially allocated it to structural and reproductive tissues.

Implications for deep rooting, N use efficiency and water stress adaptation

Although late season N applications at depth may be vulnerable to losses if roots do not reach the fertiliser zone in time (Nafziger et al. 2021), deep soil N represents a significant resource once maximum rooting depth is achieved. Approximately 30–40% of maize N uptake typically occurs post-silking, a proportion increased in modern hybrids (Mueller and Vyn 2016; de Oliveira Silva et al. 2017). The mean ^{15}N recovery of 65–69% observed here indicates efficient recovery of applied tracer N, although it should not be interpreted as equivalent to whole-field fertiliser NUE.

A key implication is that ^{15}N was detected in aboveground tissues following injection at 90 and 120 cm, even where mineral N remained available in the upper soil profile. This provides direct evidence that maize can access N below 60 cm without prior depletion of mineral N in the upper 0–60 cm soil layer.

Yield maintenance during the drier 2019–20 season reflects maize's capacity to adapt through deeper rooting, altered biomass partitioning, and N remobilisation. Elevated stalk ^{15}N concentrations at maturity suggest temporary nitrate storage, indicating that N availability did not limit yield despite water stress. These responses are consistent with known maize adaptations to drought (Yan et al. 2022).

Conclusions

This study demonstrates that maize grown under New Zealand field conditions can access and utilise soil N from depths of at least 120 cm. Uptake below 90 cm occurred mainly after silking, reflecting progressive root development and late-season crop N demand. Recovery of applied ^{15}N in aboveground biomass averaged 65–69%, with absorbed N predominantly allocated to grain, confirming the importance of late-season N uptake. Detection of ^{15}N in aboveground tissues following injection at 90 and 120 cm provides direct evidence that maize can access N below 60 cm, even when mineral N remains available in the upper profile. However, because the point-source ^{15}N method traces root access and uptake timing rather than whole-field N balance, further field-scale work is needed to quantify implications for crop N budgets and nitrate leaching risk. These findings support continued refinement of nutrient budgeting models to better represent deep rooting and late-season N uptake in maize systems.

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REFERENCES

Adamsen FJ, Bigelow DS, Scott GR. 1985. Automated methods for ammonium, nitrate, and nitrite in 2 M KClphenylmercuric acetate extracts of soil. *Communications in Soil Science and Plant Analysis 16*: 883-898. https://doi.org/10.1080/00103628509367651

Arnold SL, Schepers JS. 2004. A simple rollermill grinding procedure for plant and soil samples. *Communications in Soil Science and Plant Analysis 35*: 537-545. https://doi.org/10.1081/CSS-120029730

Bronson KF, Hunsaker DJ, Meisinger JJ, Rockholt SM, Thorp KR, Conley MM, Williams CF, Norton ER, Barnes EM. 2019. Improving nitrogen fertiliser use efficiency in subsurface dripirrigated cotton in the desert southwest. *Soil Science Society of America Journal 83*: 1712-1721. https://doi.org/10.2136/sssaj2019.07.0210

Cassman KG, Munns DN. 1980. Nitrogen mineralisation as affected by soil moisture, temperature and depth. *Soil Science Society of America Journal 44*: 1233-1237. https://doi.org/10.2136/sssaj1980.03615995004400060020x

Chapman N, Miller AJ, Lindsey K, Whalley WR. 2012. Roots, water and nutrient acquisition: let's get physical. *Trends in Plant Science 17*: 701-710. https://doi.org/10.1016/j.tplants.2012.08.001

Ciampitti IA, Vyn TJ. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. *Field Crops Research 133*: 48-67. https://doi.org/10.1016/j.fcr.2012.03.008

Dathe A, Postma JA, Postma-Blaauw MB, Lynch JP. 2016. Impact of axial root growth angles on nitrogen acquisition in maize depends on environmental conditions. *Annals of Botany 118*: 401-414. https://doi.org/10.1093/aob/mcw112

de Oliveira Silva A, Camberato JJ, Coram T, Filley T, Vyn TJ. 2017. Applicability of a "multi-stage pulse labeling" ^{15}N approach to phenotype N dynamics in maize plant components during the growing season. *Frontiers in Plant Science 8*: 1360. https://doi.org/10.3389/fpls.2017.01360

Dwyer LM, Stewart DW, Balchin D. 1988. Rooting characteristics of corn, soybeans and barley as a function of available water and soil physical characteristics. *Canadian Journal of Soil Science* 68: 121–132. https://doi.org/10.4141/cjss88-011

Fry B. 2006. Stable isotope ecology. Springer, New York, pp. 40-42. https://doi.org/10.1007/0-387-33745-8

Gallais A, Coque M, Quilléré I, Le Gouis J, Prioul JL, Hirel B. 2007. Estimating the proportion of nitrogen remobilization and of postsilking nitrogen uptake allocated to maize kernels by nitrogen-15 labeling. *Crop Science 47*: 685-691. https://doi.org/10.2135/cropsci2006.08.0523

Hauck RD, Bremner JM. 1976. Use of tracers for soil and fertiliser nitrogen research. *Advances in Agronomy 28*: 219-266. https://doi.org/10.1016/S0065-2113(08)60556-8

Hirel B, Le Gouis J, Ney B, Gallais A. 2007. The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. *Journal of Experimental Botany 58*: 2369-2387. https://doi.org/10.1093/jxb/erm097

Hodgen PJ, Ferguson RB, Shanahan JF, Schepers JS. 2009. Uptake of point source depleted ^{15}N fertiliser by neighbouring corn plants. *Agronomy Journal 101*: 99-105. https://doi.org/10.2134/agronj2008.0186

Irmak S, Rudnick DR. 2014. Corn soil-water extraction and effective rooting depth in a silt-loam soil. University of Nebraska–Lincoln Extension NebGuide G2245. Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln. https://extensionpubs.unl.edu/publication/g2245/2014/html/view

Masclaux-Daubresse C, Reisdorf Cren M, Orsel M. 2008. Leaf nitrogen remobilisation for plant development and grain filling. *Plant Biology* I: 23-36. https://doi.org/10.1111/j.1438-8677.2008.00097.x

MPI. 2021. Overseer whole model review. Ministry for Primary Industries, Wellington, New Zealand.

Mu X, Chen F, Wu Q, Chen Q, Wang J, Yuan L, Mi G. 2015. Genetic improvement of root growth increases maize yield via enhanced postsilking nitrogen uptake. *European Journal of Agronomy 63*: 55-61. https://doi.org/10.1016/j.eja.2014.11.009

Mueller SM, Vyn TJ. 2016. Maize plant resilience to N stress and postsilking N capacity changes over time: A review. *Frontiers in Plant Science 7*: 53. https://doi.org/10.3389/fpls.2016.00053

Myers RJK, Weier KL, Campbell CA. 1982. Quantitative relationship between net nitrogen mineralisation and soil moisture. *Canadian Journal of Soil Science 62*: 111-124. https://doi.org/10.4141/cjss82-013

Nafziger ED, Yoder B, Mathesius J, Carter P. 2021. Nitrogen deficiency and corn yield with delayed N application. *Agronomy Journal 113*: 3665-3674. https://doi.org/10.1002/agj2.20760

Nasielski J, Earl H, Deen B. 2019. Luxury vegetative nitrogen uptake in maize buffers grain yield under postsilking water and nitrogen stress: A Mechanistic understanding. *Frontiers in Plant Science 10*: 318. https://doi.org/10.3389/fpls.2019.00318

Ning P, Fritschi FB, Li C. 2017. Temporal dynamics of post-silking nitrogen fluxes and their effects on grain yield in maize under low to high nitrogen inputs. *Field Crops Research 204*: 249-259. https://doi.org/10.1016/j.fcr.2017.01.022

NIWA. 2024. CliFlo: NIWA's National Climate Database. National Institute of Water and Atmospheric Research, Wellington, New Zealand. Available from: https://cliflo.niwa.co.nz. Accessed 13 August 2026.

Quemada M, Cabrera ML. 1997. Temperature and moisture effects on C and N mineralization from surface applied clover residue. *Plant and Soil 189*: 127-137. https://doi.org/10.1023/A:1004281804058

Rajcan I, Tollenaar M. 1999. Source:sink ratio and leaf senescence in maize: II. Nitrogen metabolism during grain filling. *Field Crops Research 60*: 255-265. https://doi.org/10.1016/S0378-4290(98)00143-9

Raun WR, Johnson GV. 1999. Improving nitrogen use efficiency for cereal production. *Agronomy Journal 91*: 357-363. https://doi.org/10.2134/agronj1999.00021962009100030001x

Reyes A, Messina CD, Hammer GL, Liu L, van Oosterom E, Lafitte R, Cooper M. 2015. Soil water capture trends over 50 years of single-cross maize (*Zea mays* L.) breeding in the US corn-belt. *Journal of Experimental Botany 66*: 7339-7346. https://doi.org/10.1093/jxb/erv430

Shearer G, Kohl D. 1986. N_2fixation in field settings: estimations based on natural ^{15}N abundance. *Australian Journal of Plant Physiology 13*: 699-708. https://doi.org/10.1071/PP9860699

Ta CT, Weiland RT. 1992. Nitrogen partitioning in maize during ear development. *Crop Science 32*: 443-451. https://doi.org/10.2135/cropsci1992.0011183X003200020032x

Tsimba R, Gunn TD, Densley RJ, Williams ID, Edmeades GO, Millar JA. 2021. Quantification and mitigation of nitrogen leaching in a maize silage cropping system. *Journal of New Zealand Grasslands 83*: 163-170. https://doi.org/10.33584/jnzg.2021.83.3506

Udvardi M, Below FE, Castellano MJ, Eagle AJ, Giller KE, Ladha JK, Liu X, Maaz TM, NovaFranco B, Raghuram N, Robertson GP, Roy S, Saha M, Schmidt S, Tegeder M, York LM, Peters JW. 2021. A research roadmap for responsible use of agricultural nitrogen. *Frontiers in Sustainable Food Systems 5*: 660155. https://doi.org/10.3389/fsufs.2021.660155

VSN International. 2022. Genstat for Windows, release 22. VSN International Ltd, Hemel Hempstead, UK.

Wheeler DM. 2016. Overseer technical manual. Overseer Ltd, Wellington, New Zealand.

Yan S, Weng B, Jing L, Bi W, Yan D. 2022. Adaptive pathway of summer maize under drought stress: transformation of root morphology and water absorption law. *Frontiers in Earth Science 10*: 1020553. https://doi.org/10.3389/feart.2022.1020553

Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. 2015. Managing nitrogen for sustainable development. *Nature 528*: 51-59. https://doi.org/10.1038/nature15743.