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CULTAN Fertilization Contributes to Lower N Leaching While Maintaining Yield

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ABSTRACT

Background: The controlled uptake long-term ammonium nutrition (CULTAN) fertilization technique consists of injecting a concentrated ammonium solution into the soil and aims to positively impact crop physiology and N use efficiency.

Aims: This study assesses whether CULTAN can contribute to lower N leaching while maintaining yields in temperate regions with an annual precipitation of around 1000 mm or higher.

Methods: We analyzed a 12-year lysimeter experiment with two consecutive 6-crop rotations and a 3-year field experiment with winter wheat and maize in Switzerland. CULTAN was compared to a conventional surface application of ammonium nitrate fertilizer (ConvF).

Results: CULTAN achieved at least similar yields compared to ConvF in both studies and had a 38% lower yield-scaled N leaching in the lysimeters. In both studies, CULTAN displayed higher nitrogen recovery efficiency (NRE) compared to ConvF, with an increase ranging from 8% to 17% depending on crop type, although a statistical significance was only found for winter wheat in the field study. NRE and N leaching were only weakly correlated, indicating that other N pathways are affected in the CULTAN fertilization system. Finally, we suggest that the timing and placement of the CULTAN injection need to be better adapted to the plant physiology and pedoclimatic conditions for optimal nutrient use and crop yields.

Conclusion: In areas of high nitrate concentration in the groundwater, CULTAN can be an effective fertilization strategy complementing loss reduction measures.

1 | Introduction

Elevated concentrations of nitrate (NO_3^-) in groundwater are often found in regions with high-N fertilizer input with intensive agriculture including arable farming systems (European Commission 2021) and are associated with health risks for humans (Stayner et al. 2022) and with eutrophication of susceptible surface waters (Galloway et al. 2003). In the period 2016–2019, the nitrate concentration in groundwater exceeded 50 mg L^{-1}, the limit value for drinking water set by the EU and the WHO, in 14% of the monitoring stations in the EU27 + United Kingdom (European Commission 2021; WHO, 2022).

The controlled uptake long-term ammonium nutrition (CULTAN) fertilization technique implies a single injection of a highly concentrated ammonium (NH_4^+) solution into

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the soil resulting in an NH_4^+-dominated N uptake and slowly ongoing nitrification and nitrogen release during the season, with plants likely self-regulating N uptake based on their capacity to assimilate NH_4^+ (Sommer and Scherer 2007). The combination of the NH_4^+ with minor amounts of nitrate or urea can be considered for some crops, like sugar beet and maize. In contrast, other studies using highly concentrated NH_4^+ solutions injected into the soil have shown that the rate of nitrification varies depending on soil texture (Nabel et al. 2018) and that even CULTAN delivers nitrogen as a mix of NO_3^- and NH_4^+ rather than exclusively as NH_4^+ (Schittenhelm and Menge-Hartmann 2006).

Preferential N assimilation in the form of NH_4^+ causes a shift in the source–sink relationship of carbohydrates and amino acids in the plant, whereby the roots become the dominant sink for carbohydrates and the source for amino acids (Engels et al. 2012; Sommer and Scherer 2007). This offers three advantages for plant growth. First, it promotes a dense root system around the NH_4^+ depot and the initiation of lateral roots, enhancing the uptake of nutrients compared to surface application (Nabel et al. 2018; Nkebiwe et al. 2016, 2017). Second, NH_4^+ nutrition may increase plant resistance to drought (Ding et al. 2015; Huang et al. 2018) and defense against pathogens as demonstrated in the review by Marino and Moran (2019). Third, the root dominance may promote the phytohormone cytokinin, which supports the maintenance of the shoot apical meristems, leading to a stronger and shorter stem (Sommer and Scherer 2007). CULTAN was reported to produce similar or higher crop yields compared to surface application of ammonium nitrate fertilizer (Deppe et al. 2016; Kubešová et al. 2014; Nkebiwe et al. 2017; Schittenhelm and Menge-Hartmann 2006), increase the N use efficiency (Nkebiwe et al. 2016; Yokamo et al. 2023), and reduce N leaching.

However, CULTAN has been mostly studied in temperate areas with an annual precipitation of around 500–700 mm, such as parts of Germany and Eastern Europe (Albert et al. 2012; Deppe et al. 2016; Kubešová et al. 2014; Kücke 2003; Schwarz et al. 2013; Sedlář et al. 2011; Weimar 2001), whereas studies in more humid regions, such as parts of the Swiss midlands, where annual precipitation is above 1000 mm, yet facing increasing drought risks in summer, are still missing. Elevated NO_3^- concentrations in groundwater in regions with high shares of arable land indicate the necessity for a fertilization strategy able to reduce nitrate leaching risk while maintaining crop yields. We therefore used two existing experiments for a system comparison between CULTAN and a split surface application of granular ammonium nitrate, a common mineral fertilization strategy for arable crops in Switzerland.

The following hypothesis, derived from previous studies on CULTAN, and other subsurface fertilizer application techniques were tested: (1) CULTAN results in similar or higher crop yield levels compared to surface application of ammonium nitrate fertilizer, (2) the N use efficiency is improved, and (3) as a result, N leaching is reduced.

2 | Materials and Methods

2.1 | Lysimeter Study

The first study is based on a lysimeter experiment including a typical multi-year crop rotation for the Swiss midlands and treatments with different N fertilizer application rates and methods, including CULTAN.

The experiment was conducted at a lysimeter facility at Zürich–Reckenholz (47°25′41″ N, 8°31′05″ E; 444 masl) over 12 years (2009–2020). The lysimeters contain a column of monolithic soil (1 m^2 surface, depth of 1.35 m) taken in a small area of a farmer's field some months before the start of the experiment in 2009. Three quartz sand layers of 5 cm with different particle sizes (0.10–0.50, 0.71–1.25, and 3.15–5.60 mm) were placed between the soil and the bottom of the lysimeter to prevent waterlogging in the soil column and denitrifying conditions. The soil texture measured at the field site in the 0–27 cm horizon corresponded to a sandy loam texture (17% clay, 32% silt, and 51% sand). The facility is located outdoors, is not irrigated, and has a mean annual temperature of 10.2°C and a mean annual precipitation of 981 mm in the period 2009–2020.

A 6-year crop rotation was repeated twice and included silage maize (*Zea mays* L.), winter barley (*Hordeum vulgare* L. subsp. *vulgare*), sugar beet (*Beta vulgaris* subsp. *vulgaris* var. *altissima Döll*), winter wheat (*Triticum aestivum* L.), oilseed rape (*Brassica napus* L. var. *napus*) and Triticale (*X Triticosecale*). Phacelia (*Phacelia tanacetifolia* Benth.), and white mustard (*Sinapis alba* L.) were used as cover crops after winter barley and triticale, respectively.

CULTAN was compared to a conventional fertilization system (ConvF) in the form of granular surface-applied ammonium nitrate with an N supply corresponding to 100% of the recommendation by the Swiss fertilization guidelines (Sinaj et al. 2009). CULTAN solutions differed slightly between years, being bought as commercially available products containing varying amounts of ammonium sulfate and nitrate (Table S1). NH_4^+ was predominant with at least 84% of total N. All CULTAN solutions had a pH below 4.3 except for the second year where it was 6.6. A low pH is meant to support the nitrification slowdown, particularly in mixed ammonium nitrate solutions. N-fertilizer input via the CULTAN solution was mistakenly based on ammonium content only, ignoring the nitrate content. Consequently, the N-application rate of CULTAN varied between 100% and 120% of ConvF and averaged 115% over the 12-year period (Table S1).

To assess whether this higher N supply created a bias in the results, CULTAN and ConvF were compared to surface application of ammonium nitrate with an N supply set at 130% of the recommended fertilizer input for each crop, representing a surplus fertilization (SurF) treatment, which was only included during the first 7 years of the experiment. Lysimeters with zero N fertilization, but sufficient supply of other macro and micronutrients, were used to derive N use efficiency indicators.

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Knowing that long-term omission of N might decrease annual N release in later years, it is assumed that it still serves as a reliable indicator for soil N release and atmospheric N-input, although it might slightly underestimate the actual annual N release. The mentioned treatments, each replicated three times, were randomly allocated to the lysimeters and remained assigned to the same lysimeter throughout the experiment.

The conventional fertilizer was spread manually on the soil surface with the total N fertilizer input split into two or three applications depending on crop (Table S1). CULTAN was injected with a syringe at the beginning of the cropping period at about 10 cm depth and between crop rows with a density (number of injections m^{-2}) of 8 for sugar beet, 10 for silage maize, and 16 for cereals and oil seed rape (Table S1).

2.2 | Field Study

In the second study, a split broadcast surface application of ammonium nitrate (ConvF) was compared to a CULTAN application in a series of field trials with a randomized block design with four replicates performed in 2008, 2009, and 2010 with winter wheat and silage maize.

Each crop was sown at two sites each year on plots of 6 m × 20 m. The fields with different soil textures (sandy clay loam, clay loam, and loam) were located north of Zürich. The regional mean annual precipitation and temperatures were similar across sites (around 1050 mm and 8.3°C, respectively; Table S2).

N supply was determined by the respective farmers at the locations and ranged from 103 to 162 kg N ha^{-1} for wheat and from 102 to 142 kg N ha^{-1} for maize (Table S2). In the ConvF treatment, the fertilizer was applied using a pneumatic spreader in two and three applications for maize and winter wheat, respectively. The CULTAN fertilizer solution was injected at a depth of 5–7 cm at the same time as the first application in the ConvF treatment using a tractor-mounted wheels injector device, with wheel distances of 25 and 13 cm between injection points resulting in a density of about 30 injections m^{-2}.

2.3 | Evaluation Parameters

To evaluate the effects of CULTAN compared to ConvF across both studies, yield and N leaching were measured and N use efficiency was calculated.

2.3.1 | Yield

Yield was recorded for both the main products (grain for the cereals and oilseed rape, beets for the sugar beets, and above-ground biomass for the silage maize) and the by-products (straw, sugar beet leaves) removed from the lysimeters and on a sample of 30 m^2 for the field trials. Yields are reported as fresh matter yield converted by applying the standard moisture level according to the Swiss fertilizer guidelines (Sinaj et al. 2017) or commercial norms to dry matter yield, which allows the comparison to reference yields. For silage maize, dry matter yields were reported following the Swiss fertilizer guidelines. The relative yield, defined as the ratio of the treatment yield to the Swiss reference yield (Sinaj et al. 2017), was used to compare performance across crops and over the 12 years.

2.3.2 | Nitrogen Use Efficiency Indicators

Nitrogen use efficiency indicators were based on the N content in harvested biomass and made use of the average N uptake in the unfertilized plots, as a proxy for soil N supply and N-input from the atmosphere. Total N content did not include the nitrogen in the biomass left on the lysimeters, such as sugar beet tops in the second rotation and cover crops. In both studies, the N concentration of plant products was measured using the Dumas method. N concentration of oilseed rape in the second rotation was unfortunately not measured before samples were discarded.

Nitrogen recovery efficiency (NRE) is the ratio of the difference in total N content in harvested biomass between the fertilized plots (N_{total}) and the unfertilized plots (N_{zero}) to the N fertilizer input (N_{input}):

$$\text{NRE} = \frac{N_{\text{total}} - N_{\text{zero}}}{N_{\text{input}}}. \quad (1)$$

N budget (N_{Bud}) is a proxy for N losses to the environment and the accumulation or depletion of N in the soil resulting from fertilization (N_{input}):

$$N_{\text{Bud}} \left(\text{kg ha}^{-1}\right) = N_{\text{zero}} + N_{\text{input}} - N_{\text{total}} . \quad (2)$$

2.3.3 | N Leaching

In the lysimeter study N leaching (on the basis of seepage volume and NO_3^- concentration) was calculated for the period from February 25, 2009 to March 25, 2021. Seepage volume was recorded with tipping buckets, with 1.5% of water sampled and analyzed biweekly colorimetrically for NO_3^- concentration by segment-flow injection analysis.

N leaching was calculated per unit of area (N kg ha^{-1} $year^{-1}$) and per unit of main harvested product (yield-scaled N leaching, N g kg^{-1}) to account for crop productivity.

Two reference periods were used to analyze annual N leaching. First, a 12-month hydrological year was defined from September 1 to August 31 of the following year. Second, a crop-specific reference period was defined, starting with the recording of the seepage volume following the first fertilizer application and ending when all treatments had reached 300 mm seepage water. The crop-specific reference periods ranged from 11 to 20.6 months and included the overwinter and, in some cases, a portion of the following main crop (Table S3).

In the field study, soil samples from the 0–90 cm horizon were taken to measure soil mineral nitrogen (SMN = NH_4^+–N + NO_3^-–N) before each N fertilization and after harvest, which was used as an indicator for N-leaching risk and for the stability of the CULTAN depot. Samples were pooled on site level before the first

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N-fertilizer application, and subsequently at the treatment level for each site. Before sowing, 5 and later, 12 soil cores were taken from each plot and pooled to represent the SMN distribution in the plot area. Sampling, sample handling, processing, and measurements were done according to the fertilization guidelines (Sinaj et al. 2017) imposing a 4-week period after the last fertilizer application for instance.

2.4 | Statistical Methods

We analyzed the data with R version 4.1.1 (R Core Team 2021). The statistical differences between CULTAN and ConvF were tested using the ANOVA function with the error term set at the lysimeter level and the trial level for the field experiment. In the absence of hierarchical data, a *t*-test was performed using the ANOVA function without error term. The level of statistical significance was set at 5%.

Normality and homoscedasticity of residuals were evaluated using the Shapiro test and the Levene test in the *rstatix* package (Kassambara 2021). Yield-scaled N leaching was log-transformed before the statistical analysis to obtain normality and homoscedasticity of residuals, but untransformed data are presented in the results. When assumptions for residuals were not met on non-hierarchical data, differences in means between treatments were compared using a permutation test in the *coin* package (Hothorn et al. 2008). When assumptions on residuals were not met on hierarchical data, no statistical test was performed.

When three treatments were compared (CULTAN, ConvF, and SurF), pairwise comparisons were statistically tested by adjusted *p* value according to the Tukey method with the *emmeans* package (Lenth 2022).

3 | Results

3.1 | Effects on Crop Performance

In the lysimeter experiment, yields of the main product were 9% higher for CULTAN than for ConvF, with the differences only being statistically significant for some cereals (winter wheat: +10%, winter barley: +20%; Table 1). In contrast, both fertilizer treatments performed similarly in the field study. Yields of the by-product were higher with CULTAN than with ConvF in both studies, with significant differences for winter wheat and triticale.

Yields of silage maize and oilseed rape showed no significant differences between treatments. In sugar beet, a tendency toward lower yields (−6%) was observed for CULTAN.

CULTAN showed a trend toward higher NRE for all crops in both studies with a statistical significance in the field trial for winter wheat (Table 1). In the lysimeters, the NRE of CULTAN was 12% above that of ConvF, despite its 15% higher N supply, and CULTAN obtained a higher NRE in 8 out of 11 years, although not statistically significant (Table S5).

3.2 | Nitrate Leaching in the Lysimeters

3.2.1 | Yield- and Area-Scaled Nitrate Leaching

During crop-specific periods in the lysimeters, CULTAN had lower yield-scaled N leaching for all crops compared to ConvF, with a statistical significance for winter barley, oilseed rape, and triticale (Table 1). Over the 12 years, the amounts of N leached per area and per yield unit were lower under CULTAN, with the 38% difference in yield-scaled N leaching being significant. With a mean annual seepage volume of 305 mm, CULTAN had 7% less seepage water than ConvF, coherent with its higher yield (Table 2).

The lower N leaching under CULTAN predominantly resulted from the 32% lower NO_3^- concentration in seepage water. This was consistent across the 12 hydrological reference periods with CULTAN having lower NO_3^- concentration and lower N leaching in 10 and 11 periods, respectively (Table 3).

Over the study period, mean N leaching in CULTAN was 4.3 kg N ha^{-1} year^{-1} lower than in ConvF, whereas mean N budget over 11 years of available records was 2.8 kg N ha^{-1} year^{-1} lower in CULTAN than in ConvF.

3.2.2 | Seasonal Patterns of Area-Related Nitrate Leaching

Seepage volume and NO_3^- concentration, and the amount of nitrate leached showed a seasonal pattern, and so did the magnitude of difference between CULTAN and ConvF (Table 4).

In summer and fall, seepage volume was generally low. During winters, seepage volume ranged from 44% to 115% of precipitation, with an average of 85% in rotation 1 (R1) and 70% in rotation 2 (R2). The winters at the lowest range typically followed a dry fall. In spring, seepage varied from 11% to 77% of precipitation, reflecting the large variation of soil water saturation during winter but also the temporal distribution of spring precipitation and water uptake by early crop growth.

Mean annual precipitation decreased by 9% between R1 and R2 with fall precipitation reducing the most (−25%), creating a greater time lag in soil being refilled with water. As a result, fall seepage occurred only once during R2, and winter seepage decreased by 9% relative to R1 despite a 12% increase in winter precipitation. For both treatments, mean annual NO_3^- concentrations were higher in R2 than in R1, with the increase being larger in the CULTAN treatment.

Half of the total amount of N leached occurred in winter, caused by the high seepage volume and still high NO_3^- concentrations. During spring, fall, and summer, differences in N leaching between treatments were mostly influenced by NO_3^- concentration of seepage water and less by seepage volumes (Table 4).

3.3 | Soil Mineral Nitrogen in the Field Study

Before stem elongation of winter wheat, 4 weeks after CULTAN injection, SMN under CULTAN was 12 kg N ha^{-1}

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TABLE 1 | Mean yield, nitrogen recovery efficiency, and N leaching per crop, treatment across both studies.

	Lysimeter study							Field study	
	SM	WB	SB	WW	OR	Tr	Study[a]	SM	WW
Reference yield (Mg ha^{-1})									
Main yield	18.5	6.0	90.0	7.5	3.5	6.0		18.5	7.5
By-product yield	n.a.	6.0	47.5	7.5	9.0	7.5		n.a.	7.5
Relative main yield									
CULTAN	0.99a	1.82a	1.16a	1.31a	1.10_{Nt}	1.54_{Nt}	1.32a	1.29a	0.97a
ConvF	0.97a	1.52b	1.23a	1.19b	1.11_{Nt}	1.21_{Nt}	1.21b	1.24a	0.97a
Effect size (%)	2	20	−6	10	−1	27	9	4	0
Relative by-product yield									
CULTAN	n.a.	1.35a	*0.44a*	1.32a	n.a.	1.26a	n.a.	n.a.	1.08a
ConvF	n.a.	1.12a	*0.39a*	1.10b	n.a.	1.04b	n.a.	n.a.	0.99b
Effect size (%)		21	13	20		21			9
N recovery efficiency									
CULTAN	0.67a	0.88a	0.51a	0.80a	*0.42a*	0.56a	0.66a	0.35a	0.68a
ConvF	0.57a	0.78a	0.47a	0.72a	*0.37a*	0.52a	0.59a	0.30a	0.61b
Effect size (%)	18	13	9	7	*14*	8	12	17	12
Yield-scaled N leaching (N g kg^{-1})									
CULTAN	2.1a	4.6a	2.0a	8.3a	34.3a	1.9a	8.6a	n.a.	n.a.
ConvF	3.3a	10.2b	2.6a	15.7a	49.7b	4.1b	14.0b	n.a.	n.a.
Effect size (%)	−36	−55	−23	−47	−31	−54	−38		

Note: Results shown as average across both rotations for the lysimeter study and across all trials for the field study. Different letters within a crop or within total for each study indicate a significant difference between treatments ($p < 0.05$). "Nt" indicates that the differences were not tested statistically given non-normality of residuals (Tr) and heteroscedasticity of residuals (OR) on hierarchical data. Numbers in italic represent measures available for one rotation only. Yield-scaled N leaching per crop is based on N-leaching volume during the crop-specific period.

Abbreviations: ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition; OR, oilseed rape; SB, sugar beet; SM, silage maize; Tr, triticale followed by white mustard; WB, winter barley followed by phacelia; WW, winter wheat.

[a]Mean over the 12-year study period.

TABLE 2 | Mean annual seepage volume, NO_3^- concentration in seepage water, N leaching, and N budget for the 12-year lysimeter study.

	Seepage volume (mm)	NO_3^- concentration (mg L^{-1})	Area-scaled N leaching (kg N ha^{-1})	Yield-scaled N leached (N g kg^{-1})	N budget (kg N ha^{-1})
CULTAN	305a	11a	7.5a	8.6a	44.5a
ConvF	328b	16a	11.8a	14.0b	47.3a
Effect size (%)	−7	−32	−36	−38	−6

Note: Different letters indicate a significant difference between treatments ($p < 0.05$). The statistical tests for seepage and N leaching per unit area were performed on cumulated numbers for the period between February 25, 2009, and March 25, 2021. Results are shown as annualized based on 12.1 years. The mean annual yield-scaled N leached is based on the crop specific reference period. The N budget is only based on 11 years, as the N content was not measured for oilseed rape in the second rotation.

Abbreviations: ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition.

lower than the sum of SMN and the second mineral N-fertilizer application under ConvF. The difference increased to 20 kg N ha^{-1} before heading, 6–8 weeks after injection and just after the third N application in ConvF (Figure 1a).

At the 4–5 leaf stage of maize, 4 weeks after injection and right after the second N application in ConvF, SMN under CULTAN was higher than SMN and the second N supply in ConvF. Upon harvest, on average 22 weeks after the injection, SMN was 21 kg N ha^{-1} lower under CULTAN than under ConvF (Figure 1b).

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TABLE 3 | Seepage, nitrate, and N leached per hydrological period and treatment.

Hydrological period	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Crop		SM	WB	SB	WW	OR	TR	SM	WB	SB	WW	OR	TR
Precipitation (mm)		1087	792	1004	1114	1067	977	1048	797	903	959	930	478
Seepage (mm)													
CULTAN	172	328	245	145	508	258	463	318	260	235	215	323	213
ConvF	179	359	277	165	601	287	492	317	241	280	230	304	231
Seepage: precipitation (%)													
CULTAN		30	31	14	46	24	47	30	33	26	22	35	45
ConvF		33	35	16	54	27	50	30	30	31	24	33	48
NO_3^- concentration (mg L^{-1})													
CULTAN	1.8	2.7	12.5	30.8	3.7	7.1	8.0	4.5	9.5	43.0	5.7	25.0	2.5
ConvF	3.7	6.1	23.8	38.6	12.3	12.8	12.5	5.1	11.9	41.1	4.8	41.2	2.5
N leaching (kg N ha^{-1})													
CULTAN	0.7	2.0	6.9	10.1	4.2	4.1	8.4	3.2	5.6	22.8	2.7	18.3	1.2
ConvF	1.5	5.0	14.9	14.4	16.7	8.3	13.9	3.7	6.4	26.0	2.5	28.3	1.3

Note: Hydrological period runs from September 1 until August 31 of the following year. For the hydrological period 2008, measurement started on February 25, 2009 (6.1 months). For the hydrological period 2020, measurement was available until March 25, 2021 (6.8 months).
Abbreviations: ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition; OR, oilseed rape; SB, sugar beet; SM, silage maize; Tr, triticale followed by white mustard; WB, winter barley followed by phacelia; WW, winter wheat.

TABLE 4 | Mean seasonal precipitation and N leaching during rotation 1 (R1) and rotation 2 (R2) for the treatments CULTAN and ConvF.

	Spring (MAM)		Summer (JJA)		Fall (SON)		Winter (DJF)		Full year	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Precipitation (mm)	230	215	332	309	240	180	205	231	1007	935
Seepage volume (mm)										
CULTAN	90	79	26	19	48	7	170	156	335	261
ConvF	90	78	34	22	65	10	184	165	373	275
Seepage: precipitation (%)										
Mean	39	37	9	7	24	5	85	70	35%	29%
Range (low-high)	11–50	12–77	0–28	0–35	0–49	0–14	58–115	44–100		
NO_3^- concentration (mg L^{-1})										
CULTAN	5.7	14.5	11.7	5.3	11.0	19.2	7.1	16.4	7.5	15.3
ConvF	9.8	17.5	15.0	3.7	22.0	38.2	13.3	20.3	14.1	18.5
N leaching (kg N ha^{-1})										
CULTAN	1.1	2.6	0.7	0.2	1.2	0.4	2.7	5.8	5.7	9.0
ConvF	2.0	3.1	1.2	0.2	3.2	0.6	5.5	7.6	11.9	11.5

Abbreviations: ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition; DJF, December–January–February; JJA, June–July–August; MAM, March–April–May; SON, September–October–November.

3.4 | Higher N-Fertilizer Input in CULTAN

In the first 7 years of the lysimeter study, the relative yield of the treatment with ammonium nitrate at 130% of the recommended N-fertilizer input (SurF) did not differ significantly from either ConvF or CULTAN (Table 5). Yields of the main product were 10% higher for CULTAN than for ConvF during the 7-year period, which is similar to the 9% higher yield observed for CULTAN over the full 12 years (Table 1). This indicates that the elevated N supply alone does not explain the slightly higher yield achieved by CULTAN in the lysimeters.

ConvF and SurF reached similar N recovery efficiency, but the N budget in SurF was 10 kg N ha^{-1} higher compared to

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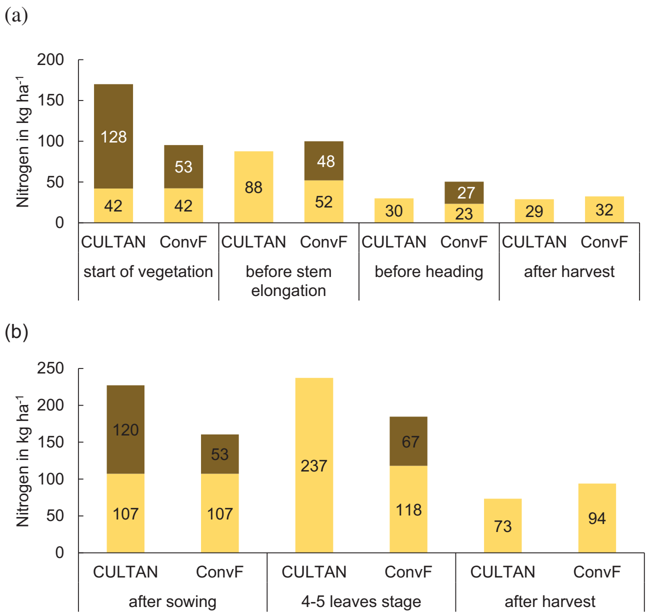

FIGURE 1 | Sum of soil mineral nitrogen (SMN) measured in the 0–90 cm horizon (light beige) and the N-fertilizer input at each stage (dark beige) in both treatments (CULTAN, ConvF) after each N-fertilizer application and after harvest of winter wheat (a) and maize (b). The difference between treatments in SMN after harvest is not statistically significant ($p > 0.05$). ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition; SMN: soil mineral nitrogen.

ConvF, without statistical significance. The comparison between CULTAN and ConvF for NRE and N budget showed similar trends as observed over 12 years (Table 2).

N leaching and NO_3^- concentration of seepage water were in a similar range for ConvF and SurF. The N leaching under CULTAN was 54% lower than under ConvF, which was a larger difference than the 36% lower N leaching measured over 12 years. The statistical significance could not be shown over 7 years either.

4 | Discussion

4.1 | CULTAN Can Lower N Leaching While Maintaining Yield

The lysimeter study provides valuable long-term observations of CULTAN. However, the experimental design left some uncertainties, related to the use of a slightly higher N-input for CULTAN versus ConvF as well as changing ratios between NH_4^+ and NO_3^- in the ammonium sulfate nitrate solution used for the CULTAN treatments. In addition, baseline seepage and N-leaching values prior to the study are missing making it difficult to elucidate the effect of fertilization in general. The comparison of the CULTAN and the ConvF treatments with SurF at 130% N-input did not show a significant influence of higher N supply on yield or N leaching (Table 4). Solutions used for the CULTAN system at practical farms often vary and can include ammonium, urea ammonium sulfate, or urea ammonium nitrate although originally only ammonium was used in the CULTAN system (Sommer and Scherer 2007). Although the lysimeter study used a less common but commercially available fertilizer solution made of ammonium sulfate nitrate, solution properties inducing low microbial activity in the depot were respected, including a high concentration of NH_4^+ in total N (>84%) and a low pH (<4.3) in 11 out of 12 years. The latter was assumed to reduce bacterial microbial activity. Though sulfur supply is often found in excess to plant demand in fertilization systems with frequent and high sulfate-based fertilizer input (Loide et al. 2020), as was the case in our study (Table S1), no symptoms of toxicity were observed. Excess sulfur supply is related to several detrimental effects on soil, plants, and groundwater (Boxberger et al. 2020; Bergmann 1993).

The lack of baseline data for seepage and nitrogen (N) leaching in the lysimeters before the experiment, which Brown et al. (2021) used to characterize the spatial variability of water budget components, is partially addressed in our study through replication. In addition, no systematic variation in seepage volumes between lysimeters was detected with largest differences occurring in summer and fall and being consistent with yield variations (Table 4). Although one ConvF lysimeter generated notably

TABLE 5 | Comparison of main variable (N-input, Relative main yield, NRE, N budget, Seepage volume, NO_3^- concentration, N leaching) by treatment averaged over 7 years (2009–2015).

	N-fertilizer input rate (%)	Relative main yield	NRE	N budget (kg N ha^{-1})	Seepage volume (mm)	NO_3^- concentration (mg L^{-1})	N leaching (kg N ha^{-1})
CULTAN	113	1.36 a	0.64a	48a	322a	7.5a	5a
ConvF	100	1.23 b	0.58a	50a	356b	13.7a	11a
SurF	130	1.33ab	0.61a	60a	331a	14.2a	11a
Effect size							
CULTAN vs. ConvF		7%	10%	−4%	−9%	−45%	−54%
ConvF vs. SurF		2%	−6%	−17%	7%	−4%	0%

Note: Different letters indicate significant differences between treatments ($p < 0.05$). The period for seepage volume, N leaching and nitrate concentration runs from February 25, 2009, to March 2, 2016, which is the last seepage available for SurF.
Abbreviations: ConvF, conventional surface application of ammonium nitrate fertilizer; CULTAN, controlled uptake long-term ammonium nutrition; NRE, nitrogen recovery efficiency.

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higher N leaching than the others, the difference was most pronounced in the second rotation, suggesting that it was not attributable to baseline variations.

Finally, N leaching for both treatments remained low compared to average values calculated for Swiss arable land (38 N kg ha^{-1} $year^{-1}$) using the MODIFFUS model (Hutchings, Spiess, and Prasuhn 2023). Mean NO_3^- concentrations, ranging from 9.5 to 21.5 mg L^{-1} across lysimeters, could be considered relatively low, given that 40% of the Swiss monitoring stations in arable farming areas report values above 25 mg L^{-1} (FOEN 2019).

Although lysimeters may not fully represent field conditions, the area-scaled N leaching was lower under CULTAN compared to ConvF in 11 out of 12 years (Table 3) with slightly higher yields. The yield-scaled N leaching, combining the effect of reduced N leaching and higher yield, was statistically lower over the 12 years for CULTAN compared to ConvF with the difference ranging from −23% to −54% at the crop level (Table 1).

The field study is consistent with these results: CULTAN achieved similar yields with statistically better NRE for winter wheat and a tendency toward lower SMN at maize harvest, indicating a reduced N-leaching risk per unit area (Table 1).

4.2 | Timinlyg and Rate for CULTAN Application

The high NH_4^+ content and partly the low pH value in the CULTAN depot were expected to lower microbial activity and reduce the nitrification of ammonium. However, there is limited knowledge on the temporal evolution of the depot's depletion. Our study highlighted that the synchronization in the CULTAN treatment between N uptake and the crop N demand may have been sub-optimal for some crops at certain growth stages shown by SMN and the treatment differences between CULTAN, ConvF, and SurF.

In the field study, SMN data indicated that the ammonium depot under winter wheat depleted quickly, leading to high-N assimilation early in the growing season and less during the later grain-filling period. In another field study on winter wheat, Deppe et al. (2016) found a strong depletion of the ammonium depot 4 weeks after injection and full depletion after 10 weeks. For the CULTAN treatment in the lysimeters, higher straw yields and higher ear densities in cereals were found (Table S4), also pointing to a different temporal dynamic of N uptake between the treatments. Higher N uptake during early wheat development in CULTAN fosters tillering and consequently ear density and straw production. Higher N uptake during later stages as observed in ConvF might improve grain filling.

Whether a later injection could improve N contents and grain filling for cereals is unclear, as preliminary studies examining the effect of varied injection timing on winter cereal yield brought inconsistent results with a strong dependency on pedoclimatic conditions (Albert et al. 2012; Sedlář et al. 2011). However, the other studies found that temporary N deficiency following a late CULTAN application was overcome, particularly with adequate total N supply (Schittenhelm and Menge-Hartmann 2006; Schulz et al. 2015). The physiology of some crops may also call for a later CULTAN injection to maximize yield. It is noteworthy that CULTAN achieved relatively higher yields for sugar beet and oilseed rape in the first rotation when the injection was applied later (by 4 and 3 weeks, respectively) than the first N application in ConvF. For oilseed rape, an early N deficiency can usually be compensated later, but a high amount of N assimilated too early may lead to excessive vegetative growth at the detriment of grain yield (Avice and Etienne 2014). A later injection may be recommended for sugar beet because their roots grow slowly at the beginning of the season and may not reach the depot timely (Weimar 2001) and early ammonium nutrition can negatively affect sucrose formation (Varga et al. 2022). In a field study, where CULTAN was injected at the 6–8 leaf stage of sugar beets, higher yields and higher sugar contents were found compared to a surface application of ammonium nitrate (Weimar 2001). The timing of the injection may also influence N leaching. In a study on winter wheat and oilseed rape, a CULTAN injection delayed by 2 or 4 weeks, resulted in lower N leaching in spring with similar SMN levels in the following winter (Kücke 2003).

A single nitrogen application is often viewed as less favorable than a split application, which enables adjustments on the basis of environmental conditions and plant development (Johnston and Bruulsema 2014). However, a study by Schulz (2015) found that a single-N application after tillering in winter wheat can achieve yields comparable to split applications without increased N-leaching risks, supporting the case for a single late CULTAN application. Nevertheless, in our study, we observed reduced grain filling in winter wheat in CULTAN compared to a three split surface application indicating that in wheat production even in CULTAN a second fertilizer application, on the basis of soil or plant N status, could be necessary to optimize plant N nutrition. Further optimization of the CULTAN system, involving an initial N dose followed by a later top dressing for instance, or other fertilization management or technical approaches (Snyder 2017) should be investigated for different crops in the future.

The spatial distribution of NH_4^+ and NO_3^- is more heterogeneous under CULTAN, which requires adapting the placement of the injection to the structural development of the roots (Deppe et al. 2016; Nkebiwe et al. 2017). It has been shown that yield and above-ground N content increased when NH_4^+ was point-injected at or below 10 cm depth compared to shallower injection, especially under dry conditions (Nkebiwe et al. 2016; Su et al. 2015). In the lysimeters, CULTAN solution was injected at different distances from the rows, respectively 5 cm for cereals, 10 cm for maize and oilseed rape, and 17 cm for sugar beet, which may have influenced accessibility and thereby yield. According to Nkebiwe et al. (2016), crops benefit more from fertilizer placement rather close to the seedling.

4.3 | Lower N Leaching Is Not Only Caused by Higher N Use Efficiency

We found only a weak relation between N budget and N leaching in the lysimeter experiment. This could have been partly biased by

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the missing N content record for oilseed rape in second rotation, when we observed large-N leaching during the 2017 hydrological period from September to August of the following year (Table 3) showing a significant event that could not be integrated in the cumulated N budget. Furthermore, N budget does not consider non-harvested crop residues and cover crops, even though they can influence N leaching. A weak relation was also found in the analysis of various long-term experiments (Buczko et al. 2010). A lysimeter study with ^{15}N-labeled mineral fertilizer (Sebilo et al. 2013) showed that the unused N fertilizer is largely incorporated into soil organic matter and remineralized only slowly over the following years and decades. Thus, a 12-year study period may not be expected to show a strong correlation between N leaching and N budget.

Nevertheless, the weak relation could also indicate that other N fluxes differed among treatments. Possibly more N was immobilized in the soil under CULTAN, as CULTAN induces higher root biomass according to Sommer and Scherer (2007). Denitrification, which generates nitrous oxide (N_2O) emissions, is another pathway possibly affected by CULTAN, but its impact remains uncertain. Deppe et al. (2016) found similar N_2O emissions between conventional fertilization and CULTAN but noted N_2O hotspots near CULTAN depots in loamy soils.

Finally, the studied treatments are considered to pose a low risk of N loss via ammonia volatilization to the atmosphere, with low pH and injection reducing volatilization for CULTAN and a low official emission factor for surface-applied ammonium nitrate as reported by the European Environment Agency (2023). Thus, we assume no relevant difference between treatments.

4.4 | Opportunity for a More Sustainable Use of N Fertilizers

The production of mineral N fertilizers consumes 3%–5% of global natural gas (European Commission 2019) and long-term energy costs are expected to remain high. In this context, CULTAN offers an opportunity to mitigate economic and environmental costs associated with nitrogen fertilizers use for two reasons. First, consistent higher NRE with CULTAN across years and studies suggests its potential to reduce N-input, supported by research showing improved N use efficiency of placed fertilizers compared to broadcast fertilization (Nkebiwe et al. 2016, 2017; Sharma et al. 2017; Yokamo et al. 2023). Second, CULTAN can utilize recycled NH_4^+ from wastewater and manure. In Switzerland, some wastewater treatment stations extract NH_4^+ to produce a liquid ammonium sulfate fertilizer free of pollutants (Pürro and Gindroz 2018). Though this process requires investment and is economically linked to sulfuric acid costs, CULTAN offers an interesting channel for this recycled NH_4^+ and can, thus, contribute to closing the nitrogen cycle.

5 | Conclusion

This study shows that CULTAN can significantly reduce yield-scaled N leaching compared to surface-applied ammonium nitrate, consistently having lower leaching and higher N recovery efficiency at area scale while maintaining similar yields.

On the basis of these results and considering the opportunity to recycle NH_4^+ from organic sources, it seems reasonable to foster the CULTAN fertilization concept to complement other measures to reduce N use and consequently losses in areas of high NO_3^- concentration in aquifers. Our study must be seen as a system comparison, which leaves room for further research to address the separate effects of placed versus broadcast, single versus split fertilization, and ammonium nitrate versus ammonium nitrate sulfate. In addition, research is needed to investigate the effects of CULTAN on nitrate leaching as related to other N flux pathways, specifically on N immobilization in the soil and N_2O emission. Finally, further research should focus on crop-specific placement especially in broad row crops and on injection timing as a function of crop physiology and used fertilizer N source. Such research should include considerations of pedoclimatic conditions and measures of the temporal evolution of the depot nitrification.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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