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Organic amendments tighten nitrogen cycling in agricultural soils: a meta-analysis on gross nitrogen flux

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Introduction: Understanding how nutrient inputs affect nitrogen (N) transformations and storage is vital for developing sustainable agroecosystems. Organic N inputs, such as crop residues (e.g., cover crop biomass and stover) and animal manures, can accelerate N cycling by increasing mineralization and immobilization rates to provide crops with more opportunities to intercept N as it moves through bioavailable pools. We aimed to understand how organic and synthetic soil amendments inhibit or promote N mineralization, immobilization, and nitrification rates.

Methods: We conducted a meta-analysis of peer-reviewed studies to assess N transformation rates in agroecosystems. Specifically, we targeted studies employing ¹⁵N pool dilution methods to quantify N mineralization, immobilization, and nitrification rates in response to organic and synthetic soil amendments.

Results and discussion: Our findings indicate that adding synthetic, manure, and crop derived residues as soil amendments increased mineralization by 60%, 135%, and 214%, respectively, relative to the unamended controls. While manure and residue produced similar mineralization rates, residue amendments induced significantly higher immobilization rates than synthetic and manure amendments – a sevenfold and fourfold increase, respectively. Furthermore, only residue N amendments enhanced the ammonium (NH₄⁺) pool size, while synthetic and manure amendments resulted in no change in NH₄⁺ pool size. These results suggest that residue amendments encourage tighter coupling of the carbon (C) and N cycles compared to manure or synthetic amendments by delivering C rich substrates (e.g., C:N ratio >20:1) to soil microbes. This tighter coupling with residue amendments leads to faster mineralization-immobilization processes and larger NH₄⁺ pools than those observed with manure or synthetic amendments. As such, residue amendments encourage soil N recycling between inorganic and organic forms, which is crucial to supporting crop N needs throughout the growing season while minimizing N losses.

KEYWORDS

gross nitrogen transformations, gross nitrogen mineralization, gross nitrogen immobilization, ¹⁵N, isotope pool dilution, organic amendment, synthetic amendment, meta-analysis

1 Introduction

Nitrogen (N) is a limiting resource for aboveground biomass production (Vitousek and Howarth, 1991; LeBauer and Treseder, 2008) and is essential for promoting crop yield (Xu et al., 2012; Lassaletta et al., 2014). Growers use N-rich fertilizers to supply bioavailable N and optimize yields. However, most crops only use roughly 50% of the N supplied via external inputs (Allison, 1955; Robertson and Vitousek, 2009; Yan et al., 2019), resulting in high environmental N losses (Drinkwater and Snapp, 2007; Robertson and Vitousek, 2009; Butterbach-bahl et al., 2013; Paustian et al., 2016). To address this issue, there is growing interest in using alternative N sources such as crop residues and animal manures that supplement organic N pools. This strategy aims to reduce dependence on inorganic N sources that are highly reactive and vulnerable to losses (Bodirsky et al., 2014).

Organic amendments are a promising means to regulate N availability and potentially improve long-term soil fertility. Organic amendments facilitate carbon (C) and N cycling by furnishing organic C and N to the system, providing an alternative N source that reengages the microbial community's role in N transformations. Most N in organic inputs must undergo microbial transformation to become bioavailable (Schimel and Bennett, 2004) with the balance between N mineralization and immobilization dependent on the stoichiometric ratio of both the microbial community and their substrate (Mooshammer et al., 2014b). Compost, and especially manure, often have low C:N (e.g., 5-20:1) and may thus provide microbes with excess N that is subsequently released in the process of N mineralization. In contrast, crop residues with high C:N (e.g., >30:1) may require additional N from the soil environment to maintain ideal stoichiometry resulting in N immobilization. However, crop residues can range from those with low C:N (e.g., clover) to others with high C:N (e.g., wheat chaff, corn stover). Therefore, the range in organic amendment quality, whether manure or crop residues, can cause high variability in N transformations in the soil (Trinsoutrot et al., 2000).

N mineralization and immobilization are key transformations affecting crop N availability and system-level crop N use efficiency (NUE) in agroecosystems. Thus, a deep understanding of how different organic and synthetic fertilizer amendments influence mineralization-immobilization dynamics will help inform the development of optimal fertilizer strategies. N isotope pool dilution may provide unique insights into both gross and net rates of N transformations and how they are impacted by organic and inorganic fertilizer inputs. Historically, researchers estimated N cycling rates by tracking changes in NH_4^+ or NO_3^- pools, which

only offers insight into net fluxes. Net transformation rates and pool sizes do not fully represent N availability, potentially obscuring rapid shifts between inorganic and organic forms of N. Rapid N transformations due to soil organic matter (SOM) turnover deliver frequent small doses of bioavailable N to the soil (Nguyen et al., 2016; Soldatova et al., 2024), which can support plant growth, create a more efficient N cycle, and minimize N loss in natural ecosystems (Robertson and Groffman, 2024). This continual turnover and supply of N provides an approach to managing agroecosystems that reduces reliance on large and inefficient inorganic N pools (Drinkwater et al., 2017; Drinkwater and Snapp, 2022). Isotope pool dilution techniques give a more detailed view by measuring rates of both N production and consumption, reflecting microbial activity's impact on N dynamics and providing additional insights into crop N availability.

Isotope pool dilution is a standard method used to quantify gross rates of N cycling based on the movement of a ^{15}N tracer through the soil (Kirkham and Bartholomew, 1954). At the beginning of the incubation (t_0), a known quantity of the ^{15}N label is added to the NH_4^+ or NO_3^- pool. Then after a defined incubation period at t_1 , after the production of new NH_4^+ or NO_3^- dilutes the ^{15}N pool with ^{14}N , the difference in isotope enrichment between t_0 and t_1 informs calculations that estimate gross rates of N immobilization and mineralization. Before the widespread use of this method, and still today in many studies, researchers estimated N mineralization and nitrification rates by determining the change in overall NH_4^+ or NO_3^- pool size, providing just an estimate of net flux. Pool dilution methods capture the combined influence of microbial consumptive and productive processes, accounting for gross N production (i.e., mineralization) and consumption (i.e., immobilization) (Murphy et al., 2003). Pool dilution methods thus link microbial communities to organic N dynamics and cycling rates of key bioavailable N species. In agricultural soils, pool dilution techniques reveal the impact of management on microbial activity and N cycling, aiding in understanding crop N availability. For example, some agroecosystems appear to maintain yields despite low standing inorganic N pools, likely due to increased NUE (Fageria and Baligar, 2005; Xu et al., 2012; Lassaletta et al., 2014). One explanation for this may be faster processes of mineralization and immobilization. Rapid N cycling (e.g., Osterholz et al., 2017) can help maintain small inorganic N pool sizes, boost crop NUE, and maintain adequate crop N uptake (Grandy et al., 2022).

Twenty years have passed since Booth et al. (2005) published a meta-analysis that examined controls on N cycling in global terrestrial ecosystems with studies that utilized pool dilution methods. The authors identified ecosystem type as a primary moderator and treated agricultural systems uniformly without considering local conditions or specific management factors. Then, Gardner and Drinkwater (2009) used ^{15}N crop recovery (via tracer experiments) to examine the efficiency of crop nutrient uptake from organic and inorganic N inputs to the soil. They found that organic inputs tended to have higher ^{15}N input recovery in crops than synthetic inputs, highlighting the potential for organic nutrient inputs to supply plant N more efficiently than inorganic fertilizer inputs. A more recent meta-analysis (Mahal et al., 2018)

Abbreviations: Amendment Effect, the natural-log transformed ratio of the means (i.e., response ratio; RR) quantifying the differences between amended and unamended soils; AE_{Δ} , Percent change in transformation rates (or NH_4^+ pool size) with respect to zero (i.e., back-transformed RR); AE_{min} , Amendment effect on mineralization rates; AE_{imb} , Amendment effect on immobilization rates; AE_{nit} , Amendment effect on nitrification rates; $AE_{\text{NH}_4^+}$, Amendment effect on NH_4^+ pool size.

showed that conservation agricultural practices like adding organic amendments can substantially increase potential net N mineralization but does not distinguish among types of N inputs. Understanding how different nutrient management practices affect microbial N processing and the balance of N production and consumption could inform practices that optimize crop yield, while minimizing environmental N losses.

To quantify broad patterns of N transformation rates in response to different soil N amendments, we conducted a meta-analysis that assessed 124-216 paired comparisons (depending on N transformation reported) from 18 studies that matched our criteria. We selected studies that exclusively employed ^{15}N pool dilution methods to measure gross N transformation rates under zero (control) N amendments and synthetic or organic N amendments (treatment). We aimed to determine whether organic inputs enhance gross rates of mineralization and immobilization, as these N recycling processes can support plant available N during the growing season and reduce inorganic N losses.

2 Materials and methods

2.1 Data collection

We collected data from peer-reviewed publications from 1984 up to February 2024. Our meta-analysis used the online databases ISI Web of Knowledge and Google Scholar to search for relevant studies. We performed four searches using the asterisk (*) as a wildcard to broaden the scope of our search terms, with “min” defining broad usage of the term “mineralization,” employing the following combinations: (i) [Nitrogen min* AND soil AND pool dilution] OR [Nitrogen min* AND soil AND isotop*] AND [agri*]; (ii) [Gross nitrogen min* AND isotop*] AND [Gross nitrogen min* AND pool dilution]; (iii) [Nitrogen min* AND soil AND pool dilution] OR [Nitrogen min* AND soil AND isotop*]; (iv) nitrogen mineralization AND agri* AND soil AND pool dilution. We also screened published reviews and meta-analyses for publications that the search engines may have missed. We collected 512 studies that matched our search terms. We implemented the following criteria to screen the final database of studies: (i) studies were performed in an agroecosystem; (ii) gross N mineralization rates were measured by pool dilution methods and reported for both the reference (control) and experimental treatment; (iii) studies manipulated N amendments (organic and/or synthetic); (iv) studies reported values for non-amended soils; (v) the means, standard deviations or standard errors, and sample sizes were reported in text, figures, or tables.

In total, there were 26 studies that fulfilled our criteria. A total of five studies were removed from the final pool because they did not specify an unamended control. Finally, three more studies were removed from the final pool because the field manipulations received a one-time basal application of fertilizer at the beginning of the growing season. Therefore, the final pool of studies was further reduced from 26 studies to 18 studies (Table 1; Supplementary Figure 1). All studies measured gross N mineralization rates, but N immobilization and nitrification rates

were not consistently reported across all studies. We considered N mineralization, immobilization, nitrification rates, and NH_4^+ pool size the target response variables measured in the control and treatment groups. Throughout this manuscript, we will refer to mineralization, immobilization, and nitrification rates collectively as “N transformation rates” when discussing the broader context of N cycling to highlight their interconnected roles in soil N dynamics.

The reference (control) group consisted of zero soil amendments and the experimental group consisted of soil amendments. There were three broad categories of amendment types that were applied as treatments in reference to the control: synthetic amendments, organic amendments, and in some cases, a combination of the two (referred to as a combination effect throughout this manuscript). Synthetic amendments were defined as inorganic mineral fertilizers, including urea, commonly applied to agricultural fields. Although urea’s chemical composition is technically organic, we classified it as a synthetic amendment due to its industrial production and similarities to some inorganic fertilizers, such as rapid N availability and high N loss potential (Kirova-Yordanova, 2017). Organic amendments were defined as N-containing crop residues, green manures, and animal-based manures and were pooled together to obtain an overall effect size for organic amendments. When considering soil amendment type as a moderating variable, we subdivided it into two categories, plant derived amendments (e.g., crop residues and green manures) and animal derived amendments (e.g., pig slurry, cow manure). Plant and animal derived amendments will be referred to as “crop residues” and “manure,” respectively, throughout the manuscript. Often, there were multiple comparisons derived from each study (e.g., no amendment vs low amendment, no amendment vs high amendment) and we treated these comparisons as distinct comparisons within studies. In addition, several studies in our database conducted incubations with destructive harvests at multiple time points. We also considered each of these comparisons as distinctive datapoints but accounted for their non independence in our analysis (Nakagawa and Santos, 2012) (see below).

We extracted data presented in figure format with WebPlotDigitizer opensource software (Rohatgi, 2020). We converted N inputs (regardless of inorganic or organic species) to reflect a kg N ha^{-1} basis. If a study lacked the necessary information to calculate N contributions of residues (e.g., did not report the N content of residues or provide sufficient details on residue characteristics), we used C:N reported in the literature to fill information gaps and estimate N application rate via residue as accurately as possible. Specifically, three studies – Cookson et al. (2005) and Fisk et al. (2015a and 2015b) – did not provide enough information for precise calculations. In Cookson et al. (2005), the authors described the residue as “grass hay,” and given the wheat-based cropping system in this study, we referenced C:N values for wheat straw from the literature, which range from ~40-130:1 (Thomsen and Sørensen, 2006; Wu et al., 2010; Gan et al., 2011; Zhang et al., 2018). As a reasonable approximation for “grass hay” we assigned a C:N of 50:1 to this study to estimate N’s contribution from residues. For Fisk et al. (2015a, 2015b), residue applications

TABLE 1 Collection of studies included in the meta-analysis displaying amendment type and amendment species reported by each study.

Reference	Application Location	Amendment Type	Amendment Species	Soil Handling	Sampling Depth (cm)	Incubation Duration (hours)	Sampling Days
Schimel (1986)	Field	Synthetic	Unknown	Homogenized	0-10	48	1
Watkins and Barraclough (1996)	Lab	Organic	R	Homogenized	0-15	72	11
Coyne et al. (1998)	Field	Organic	M	Intact	0-10	24	10 June, 29 July, 25 Nov., 1993
Recous et al. (1999)	Field	Organic	R	Intact [†]	0-20	48	1, 25, 43, 88, 218, 253, 295, 378
Shi and Norton (2000)	Lab	Synthetic, Organic	(NH ₄) ₂ SO ₄ , M	Homogenized	0-15	24	7, 40, 70 112
Andersen and Jensen (2001)	Lab	Organic	R	Homogenized	0-20	24-72	4, 9, 15, 26, 37
Cookson et al. (2002)	Lab	Organic	R	Homogenized	0-10	72	5, 10, 12, 19, 26, 32, 40, 44, 54, 60, 80, 100, 120, 142, 162
Shi and Norton (2000)	Field	Synthetic	(NH ₄) ₂ SO ₄	Homogenized	0-15	24	1
Cookson et al. (2005)	Field	Synthetic, Organic	R	Homogenized	0-10	72	1
Flavel and Murphy (2006)	Lab	Organic	R, M	Homogenized	0-15	24, 72	3, 9, 16, 37, 82, 142
Griffin (2007)	Lab	Organic	M	Homogenized	0-10	48	7, 56
Murphy et al. (2007)	Field	Organic	M	Intact	0-15	48, 72	0, 21, 49, 83, 118, 146, 180, 202, 230, 251, 279, 315
Herrmann and Witter (2008)	Field	Combination, Organic, Synthetic	R, R + Ca(NO ₃) ₂	Homogenized	0-23	24	One day in 2002 and 2003
Bedard-Haughn et al. (2013)	Field	Synthetic	Unknown	Intact	0-7	24	1
Hu et al. (2014)	Field	Organic	R	Homogenized	0-15	24	1
Fisk et al. (2015a)	Field	Organic	R	Intact	0-15	24	1
Fisk et al. (2015b)	Field	Organic	R	Intact	0-10	48, 72, 96	1, 3, 7, 10, 14
Wang et al. (2023)	Field	Combination, Organic, Synthetic	M, U, M+U	Homogenized	0-10	24	1

R, residue; M, manure; U, Urea.

[†] Amendment incorporated by hand into core, then placed in field.

Soil status indicates whether the soil sample was homogenized into a bulk sample or left as an intact core. Sampling days is the number of days since cultivation (field) or initiation of the amendment incubation (lab).

occurred across multiple years with different crops in each year: barley straw in 2003, canola straw in 2006, and oat straw in 2010 – for both studies – and oat straw in 2012 for Fisk et al. (2015b). Barley straw C:N ranges from ~15-150:1 (Chantigny et al., 2001; Havstad et al., 2010; Naz et al., 2017; Reichel et al., 2022), canola straw C:N ranges from ~33-141:1 (Singh et al., 2006; Chico-Santamarta et al., 2011; Gan et al., 2011), and oat straw C:N ranges from 46-83:1 (Papavizas et al., 1962; Wu et al., 2010; Zhao et al., 2018). These wide ranges of C:N reflect variation due to crop

variety, maturity at harvest, and climatic factors (e.g., moisture and temperature). Therefore, to estimate a representative N contribution from the three crop inputs, we used a 60:1 C:N in our calculations. This ratio represents a midpoint value within the ranges reported in the literature and aligns more closely with the narrower and lower range of oat straw, the most recent crop in rotation. In addition to amendment types, we also collected data on sample- and site-level descriptors to understand how environmental and edaphic characteristics may influence N

transformation rates. These descriptors included total soil C and N, soil C:N, pH, sampling depth, incubation temperature, pool dilution incubation duration, and experimental duration.

The small sample size of some of our observations for synthetic and combined amendments may give more weight to organic amendments in the overall analysis. However, we reduced the number of publications examining the effects of synthetic amendments on N transformation rates due to the absence of a proper control group with no soil amendment. Consequently, we excluded these studies from our analysis, leading to a smaller sample size of paired observations. Furthermore, our extensive literature synthesis found limited studies investigating the combined effects of applying synthetic and organic amendments. Given that growers are likely to utilize a combination of synthetic and organic inputs to address soil fertility needs, more research is needed to assess gross N transformation rates under these input regimes.

Because of the limited number of studies that used pool dilution techniques and matched our criteria, our analysis included lab and field studies where the researchers manipulated soil amendments, which allowed us to broaden our dataset. While lab-based studies do not fully represent N cycling dynamics in the field, they do provide insight into potential soil responses to synthetic and organic inputs and were thus included. Additionally, even though field studies tend to have higher variances in a meta-analysis than lab studies, the field studies only contribute to a small portion of the overall heterogeneity in the variances (Hillebrand and Gurevitch, 2014). Therefore, overall conclusions from a meta-analysis that includes both lab and field studies are unlikely to be impacted by the differences in variances (Hillebrand and Gurevitch, 2014).

2.2 Meta-data analysis

We used the natural-log transformed ratio of the means (RR) as the effect size metric to quantify differences between the unamended and amended samples in our target studies, which is a common approach to calculating effect size in meta-analyses of ecological research (Hedges et al., 1999; Lajeunesse, 2011; Koricheva et al., 2013)

$$RR = \ln\left(\frac{\bar{X}_t}{\bar{X}_c}\right)$$

where the natural log of the RR is the proportional change in the means of treatment group (\bar{X}_t) and control or reference, no amendment group (\bar{X}_c). The corresponding variances were calculated as:

$$v = \frac{SD_c^2}{n_c \bar{X}_c} + \frac{SD_t^2}{n_t \bar{X}_t}$$

where SD is the standard deviation and n are the standard deviations and sample size of X_t and X_c . This method of calculating variances down-weights studies with large variances (Hedges et al., 1999; Lajeunesse, 2011). In the instance where variance was not reported and could not be calculated based on available information

($n = 2$), standard deviations were imputed based on the ratio of standard deviations and means from all studies that reported both values (Lajeunesse, 2013; Bowles et al., 2016).

We used the metafor package (Viechtbauer, 2010) to compute RRs and the corresponding confidence intervals. To account for non-independence of multiple observations within a study, we assigned publication ID as a random effect in our random-effects and mixed-effects meta-regression models. All meta-analyses were performed with the rma function, and the models were fit by using restricted maximum likelihood estimation. To obtain an overall effect size for each N transformation and NH_4^+ pool size, we constructed random effects model with publication ID as the random effect.

To examine the influence of different amendment types on N transformation rates, we conducted a meta-regression by including amendment type as a moderator and publication ID as the random effect. Specifically, we tested different moderators including amendment type (synthetic, organic, or combination) and amendment species (amendment species: residue, manure, residue + manure, synthetic fertilizer, organic + synthetic fertilizer), to explore the influence of broad amendment categories (organic vs synthetic fertilizer) and their subcategories on N transformation rates. This approach allowed us to assess not only whether synthetic or organic amendments had a larger effect but also the extent that specific amendment species influenced N transformation rates and NH_4^+ pool size. We conducted an omnibus test for each moderator to test for between-group heterogeneity for moderator levels and moderators were considered to influence N transformation rates if the Q_m value was significant ($p < 0.05$) (Viechtbauer, 2010; Koricheva et al., 2013). For simplicity of interpretation, we transformed \ln RRs and 95% CIs to reflect percent change from zero:

$$\% \text{ change} = (e^{RR} - 1) \times 100$$

Transformed values of $RR > 0$ indicated a positive effect of soil amendments on N transformation rates in comparison to zero amendments, while values of transformed $RR < 0$ indicated a negative effect of soil amendments on N transformation rates in comparison to zero amendments. We assessed publication bias by visually inspecting the funnel plot for asymmetry and applying the trim-and-fill method to detect and adjust for any potentially missing studies (Koricheva et al., 2013). We evaluated the overall heterogeneity of the model by performing the meta-analysis without any moderators (Viechtbauer, 2010).

We computed Pearson rank correlation coefficients to describe the relationships between N transformation rates, NH_4^+ pool size, amendment application rate, and site level characteristics using the rstatix package (Kassambara, 2019). Correlations were computed using the non-back transformed RR values. To minimize the impact of skewness and outliers and improve linearity between the variables, we applied log-transformations on amendment application rate, soil C, and soil N. To visualize the relationships between amendment application rate, mineralization, immobilization, and NH_4^+ pool size by amendment category (i.e., organic, synthetic, combination), we plotted regressions fitted with linear models and kernel density plots of the distributions using the GGally package (Schloerke et al., 2024).

All figures were generated using the packages `ggplot2` (Wickham, 2016) and `Ggally` (Schloerke et al., 2024). All statistical analyses were performed in the statistical computing software R (version 4.3.3, R Core Team, 2020). Flow diagram of study selection (Supplementary Figure 1) was created using the PRISMA Flow Diagram tool (Haddaway et al., 2022).

3 Results

Eighteen studies measuring gross N mineralization rates with ^{15}N isotope pool dilution methods showed that soil amendments increased N mineralization, immobilization, and nitrification rates in agricultural soils. Overall, amendments enhanced N mineralization rates by 172% ($p < 0.001$), N immobilization rates by 147% ($p < 0.001$), and nitrification rates by over 200% ($p < 0.001$; Figure 1) relative to zero amendments. N transformation rates were generally low in the control group and high in the experimental group across all studies (Table 2).

The addition of soil amendments, regardless of amendment type, facilitated an overall increase in mineralization rates (Supplementary Table 2). Organic amendments increased N mineralization rates by 187% ($p < 0.0001$; CI lower = 151, CI upper = 229), and synthetic amendments increased N mineralization rates by 60% ($p = 0.05$; CI lower = 1, CI upper = 154). Combining organic and synthetic amendments increased N mineralization rates by 137% ($p < 0.001$; CI lower = 50, CI upper = 275). Organic amendments also increased N immobilization rates by 164% ($p < 0.0001$; CI lower = 127, CI upper = 208) and nitrification rates by 220% ($p < 0.0001$; CI lower = 171, CI upper = 277). Synthetic amendments did not affect N immobilization rates

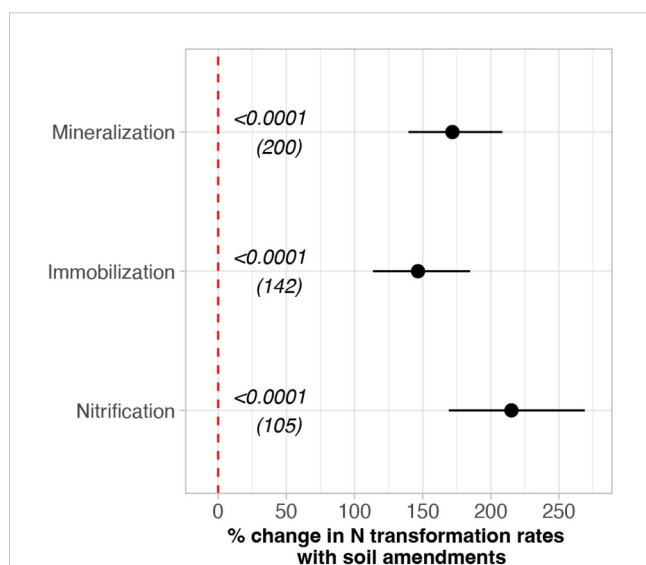


FIGURE 1

Overall amendment effects (% change) on N transformation rates in the soil. A separate meta-analysis was run for each N transformation rates. Amendment effects were calculated as the back-transformed response ratios (RR). Bars represent 95% confidence intervals. Effects are considered significant if the CIs do not overlap with zero. Numbers in parentheses indicate the number of paired comparisons.

but did increase nitrification rates by 204% ($p = 0.005$; CI lower = -13, CI upper = 106). Combined amendments increased immobilization rates by 129% ($p = 0.01$; CI lower = 22, CI upper = 330) but did not influence nitrification rates.

No differences in N mineralization rates were observed between the residue and manure amendments (Figure 2A). However, residue resulted in a 240% increase in immobilization rates ($p < 0.0001$; Figure 2B), while manure amendments resulted in a 57% increase in immobilization rates ($p < 0.001$; Figure 2B). Residue amendments also had a larger impact on nitrification rates than manure, with a 306% ($p < 0.0001$; Figure 2C) and 37% ($p = 0.05$; Figure 2C) change, respectively. Within the combination treatments, both residue + manure and organic + synthetic amendment categories resulted in significant increases in mineralization rates but were not different from each other (Figure 2A). While the organic + synthetic combination treatment increased immobilization rates ($p = 0.001$), it was not statistically different from the residue + manure treatment (Figure 2B).

Mostly, NH_4^+ pool size did not change with soil amendment treatment type. However, NH_4^+ increased by 83% under residue amendments relative to zero amendments ($p < 0.0001$; Figure 3). Additionally, the $AE_{\text{NH}_4^+}$ (i.e., amendment effect on NH_4^+ pool size) correlated weakly with the overall amendment application rate; specifically, organic amendments were weakly and negatively correlated with $AE_{\text{NH}_4^+}$, while synthetic and combination amendments had no relationship with the $AE_{\text{NH}_4^+}$ (Figure 4D). Organic amendments, on average, stimulated mineralization at a rate of nearly three times that of synthetic amendments (Table 2). However, neither organic nor synthetic amendment application rate significantly correlated with AE_{min} (i.e., amendment effect on mineralization rates) or AE_{imb} (i.e., amendment effect on immobilization rates) (Figures 4A, B). These findings imply that even though organic amendments often contributed more to the NH_4^+ pool than synthetic amendments, the overall quantity of N applied via amendment does not drive differences in N transformation rates.

However, Pearson correlations revealed strong relationships between the $AE_{\text{NH}_4^+}$ and AE_{min} (Figure 4E) and $AE_{\text{NH}_4^+}$ and AE_{imb} (Figure 4F). Additionally, there was a strong relationship between AE_{min} and AE_{imb} (Figure 4C). Unamended soil properties from each study, including soil C and N, C:N, and soil pH, showed minimal correlation with N transformation rate RRs (Supplementary Table 2). While AE_{min} correlated with AE_{imb} and $AE_{\text{NH}_4^+}$, its correlation with soil pH and C was weak and negative, and we found no significant correlation with soil N or the C:N. AE_{imb} demonstrated weak, negative correlations with soil pH and the C:N but not with soil C or N. Finally, AE_{nit} (i.e., amendment effect on nitrification rates) showed a moderate, negative correlation with soil pH and C:N, and weak correlations with soil C and N.

4 Discussion

Understanding the influence of soil amendments on N cycling dynamics within agroecosystems is vital for developing effective nutrient management strategies. These strategies rely on optimizing

TABLE 2 Overall and moderator level means and standard errors for N transformation rates, NH_4^+ pool size, and amendment application rate for control and experimental treatments across all studies.

	Control				Experimental			
	Overall	Synthetic	Organic	Combination	Overall	Synthetic	Organic	Combination
Mineralization	1.3 ± 0.1	1.8 ± 0.5	1.3 ± 0.1	0.9 ± 0.2	3.5 ± 0.3	2.5 ± 0.7	3.7 ± 0.3	1.8 ± 0.4
Immobilization	1.6 ± 0.2	1.7 ± 0.4	1.7 ± 0.2	0.4 ± 0.1	3.6 ± 0.2	2.4 ± 0.6	3.9 ± 0.3	0.9 ± 0.3
Nitrification	1.2 ± 0.1	2.3 ± 1.2	1.1 ± 0.1	1.4 ± 0.9	4 ± 0.4	5.7 ± 2.4	4 ± 0.4	2.9 ± 2
NH_4^+ Pool Size	6.4 ± 1.1	5.2 ± 2.6	6.8 ± 1.2	2.2 ± 1.2	10 ± 1.1	5.2 ± 2.2	10.6 ± 1.3	6.7 ± 2.1
Application Rate	–	0	0	0	–	81 ± 13	230 ± 20	230 ± 33

Transformation Rates: $\mu\text{g N kg}^{-1}$ soil day⁻¹.

NH_4^+ Pool Size: g $\text{NH}_4^+\text{-N kg}^{-1}$ soil.

Application Rate: kg N ha⁻¹.

internal N cycling and require balancing external inorganic and organic N inputs to the system. Our meta-analysis examined the change in N transformation rates via pool dilution methods in response to different organic and synthetic soil amendments (i.e., AE_{Δ}) and highlights the role that organic amendments, such as cow manure and crop residues, play in enhancing N cycling rates. Specifically, residue-based amendments increased mineralization (AE_{min}) rates more than synthetic amendments and increased immobilization (AE_{imb}) rates more than both synthetic and manure amendments (Figure 2). In contrast, neither manure nor synthetic amendments induced a significant AE_{imb} .

We found that manure and inorganic fertilizer contribute to an overall increase in mineralization rates of organic N to inorganic forms, increasing plant available N. However, high mineralization rates and large inorganic N pools also lead to environmental N losses (Galloway et al., 2008; Erisman et al., 2013). Our meta-analysis indicates that crop residue amendments produced higher N mineralization and immobilization rates than manure and synthetic N sources. Mineralization (i.e., microbial N production) releases NH_4^+ making it available for plant uptake or susceptible to volatilization (i.e., NH_3 release) or nitrification, which is prone to leaching NO_3^- (Erisman et al., 2013). Immobilization (i.e., microbial N consumption) reduces plant-accessible N but lowers the risk of N losses from the system. Thus, boosting immobilization and mineralization provides a potential means to increase soil N storage and plant N uptake (Schimel and Bennett, 2004; Daly et al., 2021). Ultimately, strategically combining crop residues, manure, and inorganic fertilizers may help optimize the opportunities for crop N uptake without excess soil N vulnerable to offsite losses (Vanlauwe and Giller, 2006; Drinkwater and Snapp, 2022; Grandy et al. 2024).

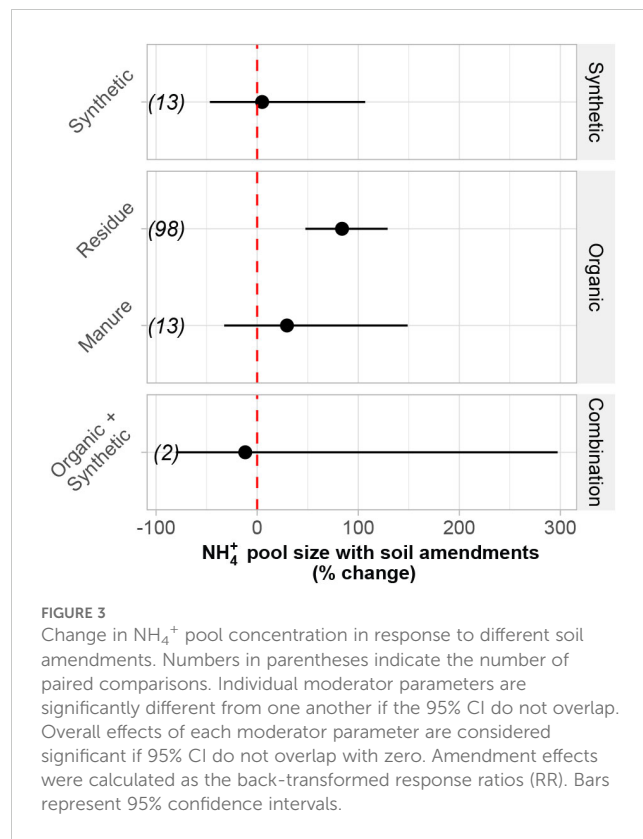
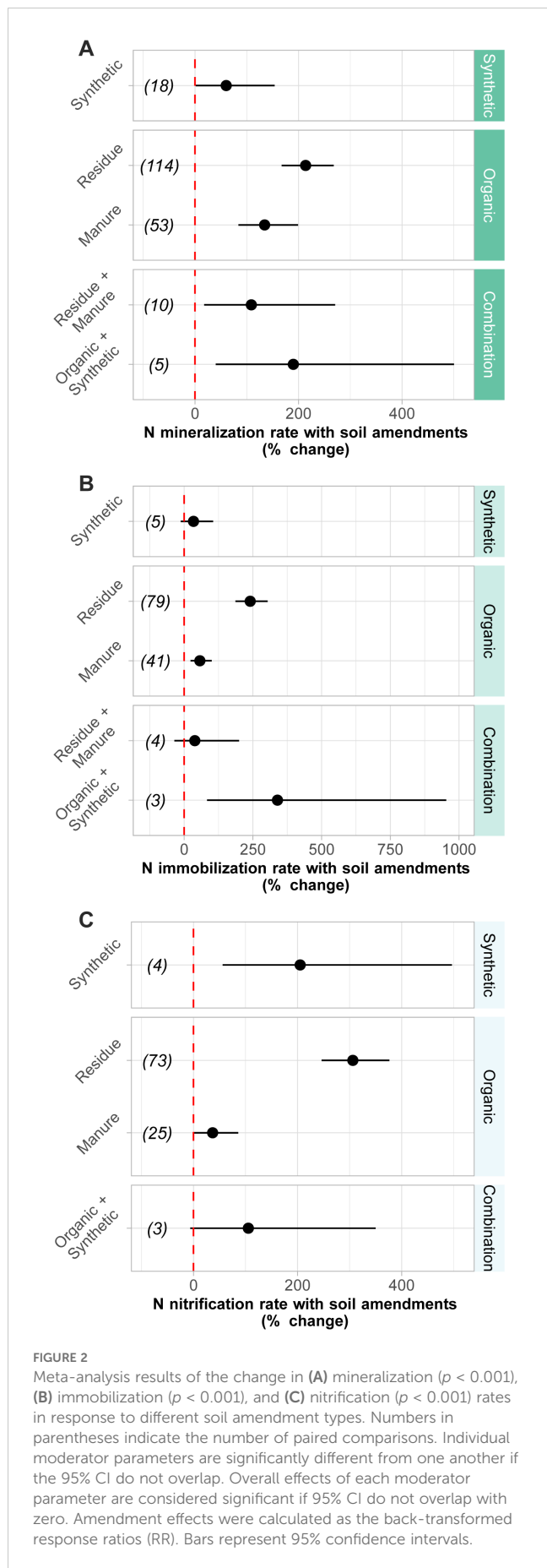
N amendments – synthetic, organic, or a combination – increased mineralization rates by roughly 60–215%, while residue was the only N amendment to substantially increase immobilization and nitrification rates. Our results contradict the findings of (Booth et al., 2005), who found that the overall effect of fertilizer treatments (inorganic and organic) did not affect mineralization rates, immobilization rates, or nitrification rates. However, the authors did not distinguish between organic and inorganic amendments in the determination of the overall effect size, therefore it is not possible to ascertain whether organic

amendments indeed increased N transformation rates in their analysis. Furthermore, the authors reported that individual studies using organic fertilizer sources resulted in significant increases in mineralization rates. Our study parsed apart the amendment effect (i.e., synthetic vs. organic amendment) on N transformations and, consistent with existing research (e.g., Kumar and Goh, 2003; Diacono and Montemurro, 2010; Chen et al., 2014a), found that organic matter incorporation into agricultural soils can stimulate mineralization rates, as reflected in our findings of a strong organic amendment effect.

A recent meta-analysis conducted by Mahal et al. (2018) found that, on average, cropping systems that received N amendments – regardless of form – had higher potentially mineralizable N (PMN) relative to the non-amended controls. Specifically, the authors found that compost and manure amendments increased PMN by 52% and 78%, respectively, while inorganic amendments did not induce changes in PMN. We found a slight increase in mineralization rates with added synthetic amendments but a much larger one with crop residues and manure. Our findings and those from Mahal et al. (2018) suggest that the contribution of synthetic fertilizer N enhances the inorganic N pool but has relatively less or no impact on N mineralization.

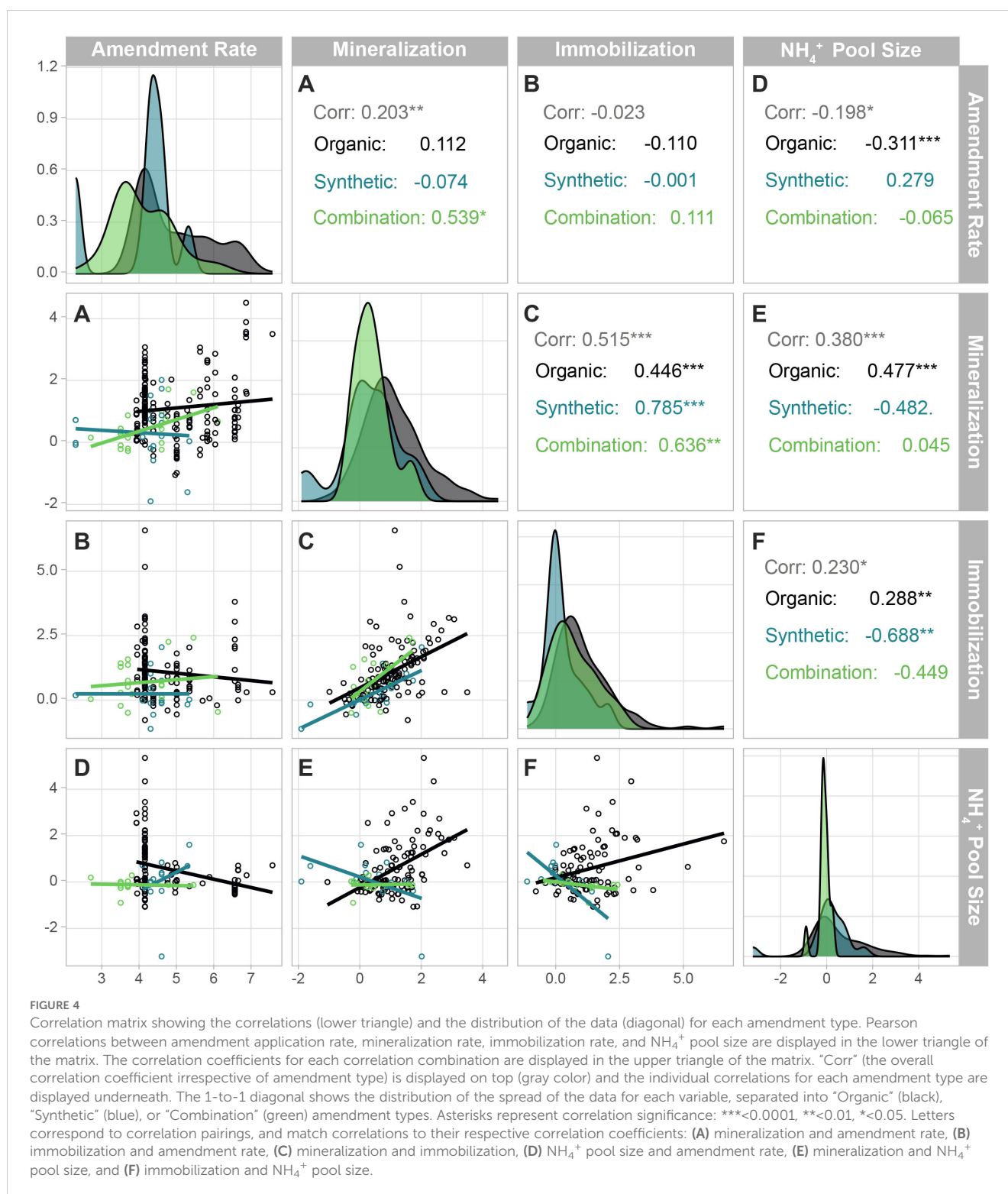
Synthetic amendments significantly increased both N mineralization and nitrification rates but had no detectable effect on immobilization rates. This finding suggests that, from a microbial perspective, there is an excess of available N with respect to C. Applying synthetic fertilizers often enhances crop productivity, resulting in increased crop residue inputs to soil and higher microbial biomass than crops receiving low or no fertilizer (Geisseler and Scow, 2014). This potentially high rate of residue inputs coupled with an active microbial community in a strongly N-enriched environment will induce microbial N spillover (Mooshammer et al., 2014a). Even if N fertilization has no effect or inhibits decomposition rates (Grandy et al., 2013), microbes may still release inorganic N during decomposition (Breza et al., 2023).

Soil amendment stoichiometry is a major driver of microbial decomposition processes and N cycling and governs how organic inputs influence soil nutrient dynamics (Keiblinger et al., 2010; Chen et al., 2014b). Substrates with low C:N (e.g., manure and green manure) fuel the microbial community by providing easily accessible forms of C balanced with available N, thereby increasing



mineralization rates and short-term N release into the soil (Flavel and Murphy, 2006; Myrold and Bottomley, 2015). In contrast, high C:N inputs like crop residues contribute to the SOM pool both in the short and long term, providing C resources over extended periods and sustaining bioavailable N through mineralization-immobilization (Nguyen et al., 2016). Incorporating high quality crop residues with low to medium C:N (e.g., 20-30:1) may enhance SOM content in the short term (Ding et al., 2006; Tiemann et al., 2015), creating a fresh pool of substrates that can immediately stimulate microbial activity (Wang et al., 2015). For example, a study from our database (Herrmann and Witter, 2008) tested the immobilization potential of various N inputs to quantify the contribution of amendments to net NH_4^+ availability. The authors found a linear relationship between immobilization rates and microbial respiration rates irrespective of amendment C:N, suggesting the background SOM pool of their soils contained enough C to facilitate NH_4^+ immobilization. Over the long term, residue inputs contribute toward building the stable SOM pool that may ultimately drive immobilization rates (Yan et al., 2019). However, substrate quality is a key component in dictating N transformation rates, and distinguishing between whether the N input itself, the long-term accumulation of inputs, or an interaction of the two is a stronger driving force remains uncertain.

The existing organic N pool is an essential source of NH_4^+ , and implementing management strategies that build this pool (e.g., crop residue inputs) can contribute to increased N transformation rates and soil NH_4^+ concentrations (Farzadfar et al., 2021). While growers typically rely on inorganic N application rates to supply most or all plant-available N, the turnover of *in situ* organic matter can also be a significant N source (Näsholm et al., 2000; Snapp and



Fortuna, 2003; Geisseler et al., 2009). We found that synthetic N inputs and manure amendments did not alter NH₄⁺ pool size relative to the unamended control. Yet, we found that residue inputs increased the NH₄⁺ pool size by roughly 75% compared to no inputs. Moreover, there was a weak negative relationship between N application rate and NH₄⁺ pool size, but only for organic amendments. These results suggest that amendment type

facilitates changes in NH₄⁺ pool size rather than the quantity of N applied, *per se*, via external N inputs. As such, more N amendments do not necessarily mean an increase in the NH₄⁺ pool. Local edaphic factors like clay content (Vogel et al., 2015), soil temperature and moisture levels (Gutiérrez et al., 2012; Robertson and Groffman, 2024), and pH (Averill and Waring, 2018) can all influence N transformations rates and NH₄⁺ storage in the soil.

However, within the context of our analysis, the increase in mineralization rates indicates greater NH_4^+ production, but high immobilization rates under residue amendments suggest that microbial metabolic requirements may restrict the persistence of the NH_4^+ pool. Therefore, with residue amendments, C and N cycling may remain more tightly coupled (Gardner and Drinkwater, 2009; King and Hofmockel, 2017; Stella et al., 2019) where microbes assimilate NH_4^+ based on greater C availability (Mooshammer et al., 2014a).

While this meta-analysis detected compelling patterns in N transformation rates in response to different N amendments, there are limitations and considerations, primarily due to the number of studies included in the analysis. Although we initially identified about 40 viable studies, our selection criteria reduced the final number to 18 studies (see PRISMA flow diagram, Supplementary Figure 1). As such, the number of studies that manipulated synthetic or organic amendments was imbalanced, with six of the studies manipulating synthetic amendments and 12 manipulating organic amendments. Additionally, of the six studies on synthetic N, only two used the same fertilizer type, while the others did not report the chemical composition. The under-reporting of synthetic amendments limits our ability to fully understand their impact. Altogether, we conducted the amendment comparisons at a very high level (e.g., organic vs. synthetic), with organic amendments separated into plant residues or animal-derived manures and synthetic amendments as a single category, reflecting the minimal available data. These aspects of our study suggest some caution in generalizing the findings, particularly for synthetic amendments. Nonetheless, there is value in understanding how broad patterns of soil respond to inputs, even if specific responses vary depending on the context.

5 Conclusions

This meta-analysis demonstrated that organic-based soil amendments, especially crop residues, enhanced N mineralization, immobilization, and nitrification rates and increase the NH_4^+ pool size. While manure and synthetic N fertilizers also increased N mineralization rates, neither amendment altered immobilization or nitrification rates. This suggests that these amendments result in high N bioavailability, prompting microbial release of excess N, which can support crop production but also might increase potential N offsite movement. Applying N amendments that allow for slower N release and balance mineralization-immobilization dynamics over longer periods of time may help support production goals and reduce excess N and microbial spillover, thereby improving N retention within the agroecosystem. The effect of combining organic and synthetic amendments on N transformation rates remains ambiguous. However, future research could expand on these findings by examining gross N mineralization rates under different agricultural contexts and investigating how interactions between synthetic and organic nutrients influence these transformations. These insights have the potential to deepen our understanding of N cycling dynamics and help refine input strategies, contributing to climate smart solutions that maintain agricultural productivity and increase sustainability.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. AG: Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2025.1472749/full#supplementary-material>

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