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Nitrogen mineralization from organic amendments is variable but predictable

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Abstract

To manage nitrogen (N) efficiently, organic growers must be able to predict the amount and timing of plant-available N from organic amendments. In this study, we measured N mineralization from a variety of organic amendments, including composted animal manures and plant material, pelleted and granular organic fertilizer formulations, slaughter waste products, and hydrolyzed liquid fertilizers. In a laboratory incubation, we measured net N mineralization from materials mixed with either organically or conventionally managed soil at 23°C and 60% water holding capacity after 0, 7, 21, 42, and 84 d. We found that net mineral N change in the amended soils after 84 d of incubation fell into four categories: immobilization to 5% of applied N for yard trimmings composts, 15–30% for poultry manure composts, 35–55% for granular fertilizers, and 60–90% for quick release products. However, across all amendments the amount of plant-available N after 84 d of incubation was well correlated with the carbon (C)/N ratio ($R^2 = 0.92$). Within amendment types, the C/N ratio predicted N mineralization for yard trimmings composts ($R^2 = 0.91$), manure composts ($R^2 = 0.81$), and specialty fertilizer and slaughter products ($R^2 = 0.88$) but not liquid products ($R^2 = 0.11$). Soil management history did not consistently affect net N mineralization but may have influenced timing.

1 | INTRODUCTION

Due to concerns about nitrate (NO_3) leaching into the groundwater, California growers are under increasing legislative pressure to match their N applications with crop demand. Among those are certified organic growers, who occupy over 400,000 ha of California farmland (USDA–NASS, 2017). Synchronizing timing of plant-available N with crop demand is especially challenging for organic growers, who use a wide variety of fertility sources from which N must be mineralized before it is plant available. These sources range from composted municipal yard trimmings to patented pelleted and liquid fertilizer formulations. Observing the "4Rs" of efficient nutrient management (right rate, right time, right type, and right placement) and managing irrigation practices appropriately for such a range of different materials requires good information about (i) how much of the amendment N is likely to become available to the current crop, (ii) the predicted timing of N mineralization, and (iii) how environmental and management factors affect amendment N mineralization dynamics. New formulations are continually developed; in particular, specialized pelleted and granular

Abbreviations: CONV, conventional; Food, unshaken food hydrolysate; FoodS, shaken food hydrolysate; GF, granular fertilizer; GF4%, granular fertilizer with 4% N; $N_{min}84$, plant-available N after 84 d of incubation; ORG, organic; PMC, poultry manure compost; SOC, soil organic carbon; WHC, water holding capacity; YTC, yard trimmings compost.

blends are increasingly popular. Little research has been done on these materials, in which many different types of organic materials are combined and processed according to proprietary recipes. In addition, compost properties vary depending on the composting process, which differs among facilities, and the feedstock quality and pile age, which may differ from batch to batch within a facility. Therefore, it would be useful to identify classes of materials that behave in similar ways or easily measurable characteristics that can predict an amendment's N mineralization behavior.

Results from prior studies show that N mineralization dynamics are complex and can be highly variable. A first-order kinetics model is often used to describe decomposition and N mineralization from composted amendments (Bernal, Navarro, Sánchez-Monedero, Roig, & Cegarra, 1998a; Hadas & Portnoy, 1994; Hadas, Kautsky, & Portnoy, 1996) or from both fresh and composted amendments (Agehara & Warncke, 2005; Gale et al., 2006). Other researchers have found that the decomposition of incompletely composted or heterogeneous amendments follows a two-pool model (e.g., linear mineralization during initial decomposition of the easily available material but first-order kinetics thereafter) (Bernal et al., 1998a). In addition, potentially mineralizable N from an amendment class can differ by an order of magnitude. For example, poultry manure compost studies from around the United States report that organic N mineralization plateaued at anywhere from 5% (Hartz, Mitchell, & Giannini, 2000; Preusch, Adler, Sikora, & Tworkoski, 2002) to over 40% of the applied N (Gale et al., 2006; Whitmore, 2007).

It is also uncertain whether the mineralization dynamics of an amendment applied to land transitioning to organic management will be the same as it would be applied to land under long-term organic management, where years of organic matter additions have built up a different microbial community (Fauci & Dick, 1994). Some studies found that net N mineralization from different amendments was unaffected by management history (Hadas et al., 1996; Sanchez, Willson, Kizilkaya, Parker, & Harwood, 2001) and concluded that N mineralization can be considered an intrinsic amendment property. Conversely, other studies have found that amendment N mineralization was significantly dampened where labile soil organic C (SOC) was high (Mallory & Griffin, 2007; Tyson & Cabrera, 1993). This dampening is attributed to immobilization by the larger and more active microbial community fostered by increased substrate in high-SOC soils (Mallory & Griffin, 2007). Several studies have examined whether simple biochemical properties can predict potential amendment N mineralization. The C/N ratio is one of the most commonly recommended properties, having been found by multiple studies to closely relate to N mineralization from a wide range of organic amendments (Delin, Stenberg, Nyberg, & Brohede, 2012; Gale et al., 2006). However, the quality of the C and the initial ammonium (NH_4) concentration can also be predictive, especially for noncomposted amendments, because a high concentration of labile C can stimulate microbial biomass growth and immobilization, and a high NH_4 concentration can indicate a less-decomposed material (Agehara & Warncke, 2005; Bernal, Paredes, Sánchez-Monedero, & Cegarra, 1998b; Burger & Venterea, 2008; Calderón, McCarty, & Reeves, 2005). Other measurements found to be correlated with potential N mineralization or immobilization include total N (Hartz et al., 2000) and short-term CO_2 release (Castellanos & Pratt, 1981).

The objectives of this study were (i) to determine potential net N mineralization amounts and timing for a wide range of amendments commonly used on California organic farms, (ii) to examine whether amount and timing of N mineralization differ between two soils with conventional and organic management histories, and (iii) to identify amendment biochemical characteristics that could be used to predict the behavior of amendments.

Core Ideas

- N availability from organic amendments ranged from immobilization to 90%.
- N mineralization from amendments was similar between conventionally and organically managed soils.
- The amendment C/N ratio predicted potential plant-available N well.

2 | MATERIALS AND METHODS

In 2017 and 2018, a set of controlled 84-d incubations were performed to determine the N mineralization potential of a range of organic amendments in two soils with different management histories. Both soils were mapped as Yolo silt loam (fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents). The CONV site (38°32′ N, 121°47′ W) was a conventionally managed research field near the University of California, Davis; the ORG site (38°53′ N, 122°14′ W) was a commercial field that had been organically managed for over 10 yr. Conventionally and organically managed soils were chosen to determine whether materials would behave similarly on newly transitioning land as on long-term organic land.

2.1 | Amendment analyses

A total of 22 amendments used by local organic vegetable growers were selected. All materials were approved for use in organic production by the Organic Materials Review

Institute. The amendments included yard trimmings–based and manure-based composts, a vermicompost, several commercial granular or pelleted products formulated with manures and slaughter wastes, slaughter products (blood and feather meal), a liquid fish emulsion designed for fertigation, and a hydrolyzed food waste liquid (Table 1). Because liquid organic fertilizers have components that settle out, the food-based liquid was incubated both with and without agitation to suspend particles immediately prior to decanting. Compost types included yard trimmings compost (YTC), poultry manure compost (PMC), and compost made from poultry and plant waste (PMC/YTC). The YTCs and PMCs were each obtained from manufacturers in different counties: Yolo and Solano for YTCs and Sutter and Merced for PMCs. From the Yolo YTC facility, samples from five batches were collected during 2017 and 2018 and incubated separately. From the Sutter PMC facility, samples collected from three batches were incubated separately. Fresh amendments were stored at 4°C in sealed bags until use.

Moisture content was determined by freeze-drying the liquid amendments and drying the solid amendments at 105°C until weights were stable. Total C and N were analyzed by dry combustion of finely ground samples on a Costech Elemental Analyzer (Costech Analytical) according to Nelson and Sommers (1996). To prevent N loss by ammonia (NH_3) volatilization, materials with a high initial NH_4 concentration were ground and analyzed at ambient moisture when possible or acidified with 3 M HCl and dried at 60°C (Derikx, Willers, & ten Have, 1994). Amendment C and N concentrations are hereafter reported on a dry-weight basis for all solid amendments and on a fresh-weight basis for liquids (Table 1).

2.2 | Soil collection and analyses

Amendments were incubated in three separate batches in spring and fall of 2017 and in fall of 2018. Shortly before each incubation, soils were obtained from the top 15 cm of the CONV and ORG sites. Spring samples were taken before planting but after cover crop incorporation in the ORG site and after spring tillage at the CONV site. Fall samples were taken just after the final hand harvest, while the tomato plants were still standing, in fall 2017 at both sites and in fall 2018 at the CONV site. In fall 2018 at the ORG site, soil was sampled after wheat grain had been harvested and the straw removed. Fresh soils were kept at 4°C until use, which was within 8 wk of collection. Although some mineralization occurred during storage, the inclusion of one test amendment (granular fertilizer [GF]4%) with every incubation ensured that different storage times did not affect the net mineralization from amendments.

Baseline soil properties were measured in spring 2017 on soils collected from the plow layer (top 30 cm) as part of a general site characterization at both the ORG and CONV sites (Table 2). Soils were analyzed for moisture by drying in an oven at 105°C for 24 h and for electrical conductivity and pH in a 2:1 deionized water–soil slurry (Smith & Doran, 1996).

Soil organic C, texture, and water holding capacity (WHC) were analyzed using dry combustion (Nelson & Sommers, 1996), the pipette method (Gee & Bauder, 1996), and the funnel method (Wade, Horwath, & Burger, 2016), respectively. To obtain initial mineral N concentrations of the soil and amendments, fresh ORG or CONV soil (sieved < 8 mm) equivalent to 100 g of oven-dry soil was mixed with the equivalent of 336 kg total N ha^{-1} (172 mg N kg^{-1} dry soil) of each amendment. This rate was chosen as the minimum at which all amendments could be uniformly mixed with the soil without pulverization. This is higher than a normal field application rate for most amendments, and at such a high rate some N may be lost by volatilization as NH_3 from the high N amendments. However, the loss is not likely to be substantial: Martin and Chapman (1951) found that 3% or less of the added N was volatilized from 500 mg N kg^{-1} as dried blood mixed with a Yolo sandy loam soil and incubated under similar moisture, temperature, and pH conditions. Additionally, Gale et al. (2006) observed a 1:1 correlation between mineralization potentials from amendments incorporated at rates up to 500 mg N kg^{-1} in a laboratory incubation and the same amendments incorporated at lower rates in the field.

Pieces of undecomposed plant matter in the composts weighing more than 10% of the total amount added were excluded. An unamended control was also included. Two 12-g subsamples were immediately extracted for NH_4–N and NO_3–N analysis as described by Geisseler, Horwath, and Doane (2009).

2.3 | Amendment incubations

Net amendment N mineralization was determined in three incubations, each of which was organized as a randomized complete block design with four replicates. One amendment, a granular fertilizer with 4% N (GF4%), was used in all incubations to ensure comparability. This amendment was reanalyzed immediately prior to each use to ensure no N loss had occurred during storage.

Fresh soil equivalent to 300 g of oven-dry ORG or CONV soil was sieved to 8 mm and thoroughly mixed with an equivalent of 336 kg N ha^{-1} of each amendment by shaking in a large polyethylene bag. Unamended controls were similarly shaken. Pelleted and granular amendments were lightly crushed if necessary for adequate mixing. Soils were transferred to 473-mL plastic cups and packed to a bulk density of 1.3 g cm^{-3}, and moisture was uniformly adjusted

TABLE 1 Properties of amendments incubated in spring 2017, fall 2017, and fall 2018

Category	Amendment description	ID[a]	Incubation date	Moisture	Total N†	C/N ratio	$N_{min}0$[b]
				%	%		% of total N
Plant-based composts	yard trimmings compost, Yolo (batch 1; mixed with gypsum)	YTC-Y1	spring 2017	59.05	0.72	20.80	0.20
	yard trimmings compost, Yolo (batch 2)	YTC-Y2	spring 2017	69.29	1.35	18.42	0.45
	yard trimmings compost, Yolo (batch 3; larger chunks)	YTC-Y3	spring 2017	71.11	1.44	20.14	0.09
	yard trimmings compost, Yolo (batch 4)	YTC-Y4	spring 2017	57.88	0.89	19.61	0.61
	yard trimmings compost, Yolo (batch 5)	YTC-Y5	fall 2018	44.64	1.78	13.64	1.27
	yard trimmings compost, Solano	YTC-S	fall 2017	49.49	1.46	13.22	2.32
Manure-based composts	yard trimmings/poultry manure compost blend	YTC/PMC	fall 2018	60.07	2.64	12.05	9.91
	vermicompost (on cattle manure composted with rice hulls)	Verm	fall 2017	126.80	2.61	13.17	17.77
	poultry manure compost, Sutter (Apr. 2017 batch)	PMC-S1	spring 2017	46.24	5.27	7.87	15.90
	poultry manure compost, Sutter (Oct. 2017 batch)	PMC-S2	fall 2017	33.84	3.72	6.84	14.77
	poultry manure compost, Sutter (Apr. 2018 batch)	PMC-S3	fall 2018	41.11	4.69	7.52	16.24
	poultry manure compost, Merced	PMC-M	fall 2017	43.19	4.27	6.68	25.11
Pelleted/granular fertilizers	granular fertilizer, 2% N (poultry manure based)	GF2%	fall 2017	9.36	3.13	6.33	16.84
	granular fertilizer, 4% N (poultry manure and fish based)	GF4%	all	17.14	4.55	6.54	22.75
	pelleted fertilizer, 4% N (poultry manure, bone meal based)	PF4%	spring 2017	11.27	4.27	7.34	9.31
	pelleted fertilizer, 6% N (poultry manure, feather meal based)	PF6%	spring 2017	10.33	7.13	5.16	3.71
	pelleted seabird guano	guano	spring 2017	11.14	12.53	1.15	55.06
Slaughter products	blood meal	blood	fall 018	9.61	13.83	3.51	0.45
	feather meal	feather	fall 2017	7.75	15.64	3.83	0.79
Liquid products	food-based liquid fertilizer, poorly shaken	food	fall 2017	60.34	2.78	5.16	12.76
	food-based liquid fertilizer, well shaken	foods	fall 2018	60.34	3.13	4.58	11.64
	liquid fish emulsion	fish	fall 2017	68.69	2.03	5.19	14.49

[a]Amendment N concentration expressed on a dry weight basis for the solid amendments and on a fresh weight basis for liquid products.
[b]Proportion of the amendment total N initially present in mineral form.

TABLE 2 Initial properties of conventional (CONV) and organic (ORG) soils. Soils were collected from the top 30 cm prior to planting in spring of 2017

Properties [a]	CONV	ORG
Location	Davis, CA	Guinda, CA
Soil series	Yolo silt loam	Yolo silt loam
Rotation (summer 2016–2018)	barley/tomatoes/sweet corn; fallow over winter; conventional fertilizers	melons/tomatoes/wheat; oat-legume cover crop over winter; history of spring compost addition (withheld spring 2017)
Sand, %	21	53
Clay, %	32	19
EC (2:1 water slurry), mS m^{-1}	8.41 (0.29) [b]	18.66 (0.37)
pH (2:1 water slurry)	7.75 (0.02)	7.08 (0.01)
WHC, g g^{-1} dry soil	0.41 (0.006)	0.39 (0.005)
SOC, %	0.88 (0.006)	1.21 (0.035)
Total N, %	0.10 (0.01)	0.11 (0.002)
C/N ratio	8.94 (0.04)	10.86 (0.12)

[a]EC, electrical conductivity; SOC, soil organic carbon; WHC, water-holding capacity.
[b]Numbers in parentheses are SEM ($n = 3$).

to 60% WHC (0.23–0.25 g H_2O g oven-dry $soil^{-1}$) with deionized water using a syringe with a side-port needle. Soils receiving the liquid amendments were mixed and packed as described above and uniformly injected with the equivalent of 336 kg N ha^{-1} of amendment diluted in the water used to adjust the moisture. Cups were covered with perforated plastic film and kept in loosely covered bins at 23°C. The moisture content was chosen to provide optimum conditions for microbial activity, and the soil temperature is typical for summer-grown irrigated vegetable crops in Yolo County. Incubation studies performed at similar moisture and temperatures, although not necessarily representative of field conditions, have been generally found to be good proxies for mineral fertilizer equivalent in the field or greenhouse (Delin et al., 2012; Gale et al., 2006; Hartz et al., 2000; Spargo, Cavigelli, Mirsky, Meisinger, & Ackroyd, 2016).

Samples were periodically aerated by fanning, and moisture was maintained between 50 and 60% WHC. Cups were destructively harvested after 7, 21, 42, and 84 d of incubation, and subsamples were extracted for NH_4–N and NO_3–N analysis as described above.

2.4 | Modeling and statistical analysis

For each amendment, the following parameters were calculated. The proportion of the total added N (N_{tot}) initially in mineral form ($N_{min}0$) was calculated as

$$N_{min}0 = \frac{(NH_4\text{-N} + NO_3\text{-N})_{amended} - (NH_4\text{-N} + NO_3\text{-N})_{control}}{N_{tot}} \quad (1)$$

for amended and unamended control samples extracted directly after mixing. The proportion N_{tot} in mineral form at time t (in days) was calculated as

$$N_{min}t = \frac{(NH_4\text{-N} + NO_3\text{-N})_{amended} - (NH_4\text{-N} + NO_3\text{-N})_{control}}{N_{tot}} \quad (2)$$

The proportion of organic N ($N_{org}t$) mineralized with each amendment at time t was calculated as

$$N_{min}t - N_{min}0$$

The $N_{min}t$ values for each time t were compared using PROC MIXED in SAS (SAS Institute) such that each incubation date (spring 2017, fall 2017, and fall 2018) was analyzed as a separate randomized complete block design experiment with replicates as blocks. Means separation was performed with Tukey's test using an alpha of 0.05. Blocks were treated as random effects; treatment and soil type were fixed effects. One amendment, GF4%, was incubated at each date to ensure conditions were comparable. Incubation dates were compared by testing the GF4% date and date × soil interactions for the amount of plant-available N after 84 d of incubation ($N_{min}84$) using PROC MIXED in SAS.

Potential net N mineralization of the added organic N (N_0) and rate constant (k) were also calculated for each amendment as described in the Supplemental Materials.

3 | RESULTS AND DISCUSSION

None of the parameters tested for GF4% differed significantly ($p > 0.10$) among incubation dates for either soil type. Therefore, results were considered to be comparable for amendments incubated in different batches.

3.1 | Rate and timing of amendment nitrogen availability

The results demonstrate the wide range of N mineralization dynamics and potential crop availability from different amendment types used by California organic growers (Figure 1). Because overall mineralization patterns were very similar between the ORG and CONV soils, amendment curves in Figure 1 represent average values. Full data are given in Supplemental Table S1. The tested amendments fell generally into four classes: Class a, YTCs from which < 5% of N was in mineral form after 84 d of incubation; Class b, manure composts from which $N_{min}84$ = 15–30% of applied N; Class c, granular fertilizers from which $N_{min}84$ = 35–55%, most of which was already in mineral form within a few weeks of application; and Class d, quick-release liquids, slaughter products, and guano, from which $N_{min}84$ = 60–90%. The PMC/YTC compost and vermicompost fell intermediate of Class a and Class b.

Mineralization patterns followed three shapes (Figure 1). In the first pattern, which was observed for the vermicompost and most of the YTCs, mineral N remained fairly stable over 84 d (Figure 1a and 1b). The YTCs all started with low N concentrations and over the 84 d either immobilized N or mineralized < 5% of their total N. Similarly, Hartz et al. (2000) studied several California municipal yard waste composts and found that between −1.9 and 5.4% of the total N was available after 84 d of incubation at 25°C. The YTCs tested are therefore a negligible source of plant-available N during the growing season in which they are applied. At the measured N concentrations, a YTC application of 22 Mg ha^{-1} would add 100–200 kg N ha^{-1} to the soil. Even at the highest measured mineralization rate, only about 5–10 kg N ha^{-1} of that would be expected to be mineralized in warm and moist soil over a 3-mo period. However, over time their application may contribute to long-term soil fertility. In a 7-yr experiment with different green waste composts, Sullivan et al. (2003) found that in the first year after a large application (155 Mg ha^{-1}), composts either reduced or had no effect on grass yield compared with a no-compost control. Over the following 6 yr, however, grass yield, N uptake, and soil mineral N were increased in the amended plots.

Similar to the YTCs, vermicompost mineral N was relatively stable over the 84 d. However, unlike the YTCs, the vermicompost started with the relatively high $N_{min}0$ of 17.8%,

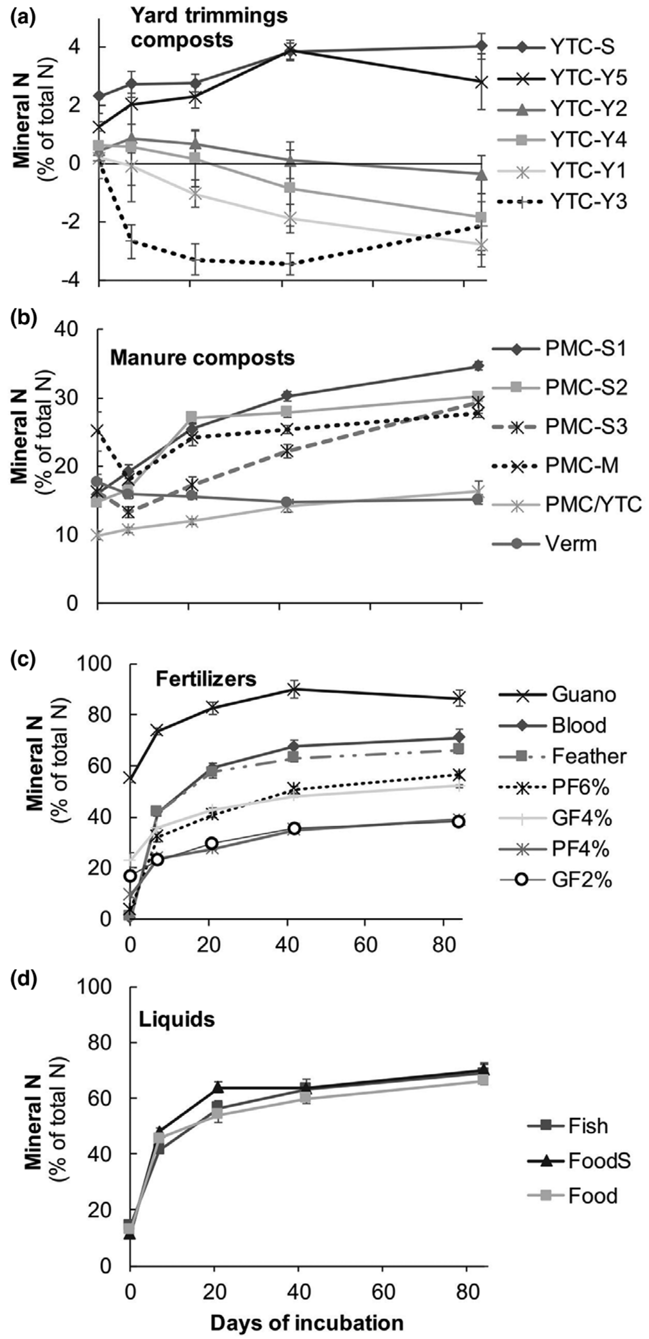

FIGURE 1 Changes in soil mineral N concentrations associated with organic amendments incubated at 23°C for 84 d, with reference to unamended control soils. Values are averages of amendments incubated in conventional (CONV) and organic (ORG) soils. (a) Yard trimmings compost. YTC-Y and YTC-S, yard trimmings compost from Yolo and Solano facilities, respectively. (b) Manure composts. PMC-S and PMC-M, poultry manure composts from Sutter and Merced facilities, respectively; PMC/YTC, blend of poultry and yard wastes; Verm, vermicompost. (c) Fertilizers. Blood and Feather, blood and feather meal, respectively; GF, granular fertilizer; PF, pelleted fertilizer. (d) Liquids. Fish, fish emulsion; FoodS and Food, shaken and unshaken food hydrolysate, respectively. Bars represent SEM (n = 4)

and, unlike all the other tested amendments, the majority of this was in the form of NO_3–N. A low ratio of NH_4–N to NO_3–N is generally considered an indicator of compost stability (Bernal et al., 1998b). The lack of further N mineralization during the incubation also suggests a very stable product. Flavel and Murphy (2006) also report vermicompost to be highly stable.

In the second pattern, which included PMC from the Merced facility (PMC-M), the third PMC batch from the Sutter facility (PMC-S3), and the third YTC batch from the Yolo facility (YTC-Y3), N was initially immobilized and then slowly increased (Figure 1a and 1b). The pattern of quick net immobilization followed by gradual net mineralization is characteristic of non- or incompletely composted complex organic substrates (Bernal et al., 1998a; CCQC, 2001). These materials still contain relatively undecomposed and labile C that stimulates soil microbes to immobilize N, which is then slowly re-mineralized as the microbial biomass turns over (Bernal et al., 1998a; Burger & Venterea, 2008; Calderón et al., 2005). For YTC-Y3, which had negligible $N_{min}0$, this immobilization caused mineral N to be well below the control ($N_{min}t < 0$) throughout the incubation (Figure 1a). Our results show that PMC from the Merced facility and PMC-S3 had the highest initial NH_4–N concentrations and NH_4/NO_3 ratios and were the only two PMCs to follow this pattern. They also had less additional N mineralization over 84 d compared with PMC-S1 and PMC-S2. Although microbial biomass was not measured, this result is in line with Calderón et al. (2005), who found that the initial NH_4 concentration in manure was positively correlated with microbial N immobilization. Another possible explanation for the decline is volatilization as NH_3, which can occur under high NH_4 concentrations at a high pH (Hadas, Bar-Yosef, Davidov, & Sofer, 1983). However, this is unlikely to have been the major cause because similar declines were observed for both the alkaline CONV soil and the neutral ORG soil (Supplemental Table S1).

In the third pattern, N mineralization followed first-order kinetics. This pattern was observed for pelleted/granular, slaughter, and liquid products as well as PMC-S1, PMC-S2, and to some extent PMC/YTC. In these amendments, N was rapidly mineralized during the first few weeks. Mineralization slowed between 21 and 42 d and tended to plateau thereafter. Within this broad pattern, the $N_{min}0$ and the proportion of N mineralized varied widely for different materials. Average $N_{min}84$ from amendments following first-order kinetics ranged from 38 to 87% of added N, with higher proportions mineralized from low C/N ratio amendments (see below). Average guano $N_{min}0$ was 55%. The guano $N_{min}0$ in this study was high compared with values observed by other studies, which range from 5 to about 20% (Hadas & Rosenberg, 1992; Hartz & Johnstone, 2006; Manojlović, Čabilovski, & Bavec, 2010); however, the potential plant-available N in those studies was similar to observed $N_{min}84$ values. In contrast, the slaughter products' $N_{min}0$ was <1%, but 40% of their N was mineralized within 7 d. The N in these products consists almost entirely of protein, which is hydrolyzed by proteases when incorporated into soil (Ciavatta, Govi, Sitti, & Gessa, 1997; Hadas & Kautsky, 1994; Jan, Roberts, Tonheim, & Jones, 2009). The potentially plant-available N observed from slaughter and liquid amendments was similar to that observed in other studies (Delin et al., 2012; Hadas & Kautsky, 1994; Hadas & Rosenberg, 1992; Hartz & Johnstone, 2006; Hartz, Smith, & Gaskell, 2010; Manojlović et al., 2010), which found that mineral N plateaued at 60 to 80% of added N. Most of this was mineralized within the first 2 wk. Curves for the pelleted and granular blends tended to resemble combinations of the amendments from which they were made, suggesting that processing did not notably change their release properties.

The N mineralization rates of unshaken food hydrolysate (Food) and shaken food hydrolysate (FoodS) were not compared statistically because they were incubated at different dates; however, mineralization from FoodS appeared to be slightly faster (Figure 1d), suggesting a greater lability of the components that had fallen out of suspension. The N_{tot} of FoodS was 12% higher than that of Food (Table 1). Similarly, Hartz et al. (2010) found that about 8–21% of N contained in liquid fertilizers resided in particulate materials, which may be lost during filtration. Although values for $N_{min}84$ were similar between FoodS and Food, FoodS had greater N_{tot}, indicating a higher absolute net mineral N concentration after 84 d of incubation.

Despite the different shapes of their mineralization curves, $N_{min}84$ values were similar among PMCs from different batches and facilities. However, comparison with other studies suggests the material is more variable. The composition of a PMC varies depending on type of poultry, composting method and duration, bedding material, and storage method (Bernal et al., 1998a; Gale et al., 2006; Leconte, Mazzarino, Satti, & Crego, 2011; Preusch et al., 2002; Tyson & Cabrera, 1993). Both facilities in this study used rice hulls as the bedding material, which is a common agricultural waste in California but not in most of the United States. The $N_{min}0$ values in these PMCs are greater than those reported by Hartz et al. (2000), who collected seven PMCs from around California and found initial inorganic N concentrations ranging from 0–8% of the amendment's total N, with an additional 3–15% of the organic N mineralized over 84 d of incubation at 25°C. Other studies with PMCs have found $N_{min}0$ values of < 5%, with additional mineralization potentials of < 10% (Leconte et al., 2011; Preusch et al., 2002; Tyson & Cabrera, 1993). In contrast, $N_{min}0$ from PMCs in the current study ranged from 15–25% of their total N content (Table 1), and N_0 plateaued at around 20% of organic N (Supplemental Table S2). The $N_{min}84$ values were similar to potentially plant-available N measured in uncomposted or incompletely composted poultry litters (Gale et al., 2006; Sims, 1986). As discussed above,

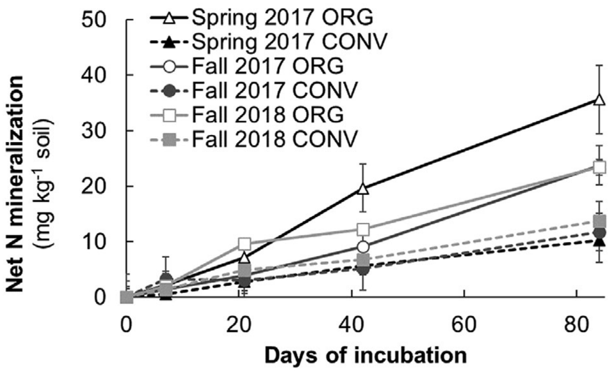

FIGURE 2 Nitrogen mineralized from organic (ORG) and conventional (CONV) control soils over 84 d of incubation at 23°C and 60% water holding capacity. Soils were collected from the same fields in spring and fall of 2017 and fall of 2018. Bars represent SEM ($n = 4$)

it is possible that the PMCs in our study had not completed the composting process.

The N mineralization amount and timing reported here are more accurate for warm and moist soils; mineralization may be slower in drier soils or under cool conditions. Where N release follows first-order kinetics, temperature affects the rate constant k more than the mineralization potential N_0 (De Neve, Pannier, & Hofman, 1996; Griffin & Honeycutt, 2000). For high-N materials, temperature differences would mainly be important during the first few days after incorporation, and therefore differences may not be on a scale relevant to growers. Hartz and Johnstone (2006) observed that, for four high-N amendments at 4 wk of incubation, a temperature decrease from 25 to 10°C decreased mineralization by 20% or less. A similar effect was observed for liquid amendments incubated at 15 and 25°C (Hartz et al., 2010). For low-N materials and those that do not follow first-order kinetics, the mineralization potential is more likely to be affected for a longer period (Agehara & Warncke, 2005).

3.2 | Soil effect on amendment nitrogen mineralization

Net N mineralization was higher in the unamended ORG soils than in the CONV soils at all dates (Figure 2). This is expected given the ORG site's long-term history of compost and cover crop addition; samples taken in spring from the plow layer of both sites show that SOC was 38% greater in the ORG soil than in the CONV soil (Table 2). For the CONV site, which received neither winter cover crop nor compost, N mineralization was similar from soils collected at all dates. Conversely, the ORG soils mineralized more N in spring than at either fall date, suggesting that the recently incorporated cover crop, which was the only amendment applied to the ORG soil in that year, contributed a large pool of labile organic matter relative to the fall soils. These were collected at the end of the season and had received no residue inputs (i.e., tomato plants were still standing in fall 2017 and fall 2018 CONV soil, and in fall 2018 ORG soil wheat straw had been removed).

Despite the soil differences, $N_{min}84$ did not differ significantly between the two soil types for any of the amendments (Table 3). A significant soil effect was observed during the first week of the spring incubation, where available N after 7 d of incubation in the CONV soils was significantly higher than in the ORG soils (Table 3; Supplemental Table S1). At that date, all ORG amendments had lower available N after 7 d of incubation than their CONV counterparts (Supplemental Table S1), suggesting that the significant soil effects were similar across all amendments. A significant main effect of soil and interaction with amendment was observed at 42 d of incubation in the Fall 2018 incubation (Table 3). Two amendments (the GF4% and YTC/PMC blend) had lower available N after 42 d of incubation in the CONV soil than in the ORG soil at this date. We do not have a plausible explanation for this temporary difference.

Our results are in line with many studies that observed that soil management history has only a transitory effect on net N mineralization from recently added amendments (Hadas et al., 1996; Nett, Ruppel, Ruehlmann, George, & Fink, 2012; Stark, Condron, O'Callaghan, Stewart, & Di, 2008). However, the difference in the first week of the spring incubation has implications for the shape of the mineralization curve. Modeling the rate constant and mineralization potential for amendments that followed first-order kinetics shows a higher mineralization rate constant but a lower mineralization potential for the CONV soil in spring—that is, in the spring CONV soil amendment N mineralized more quickly than in the ORG soil but plateaued at a lower value (Supplemental Table S2). The temporary dampening of net N mineralization from amendments incubated in the ORG soil in spring is consistent with the observation that, when a soil has a high concentration of readily available C, more of its N will be immobilized into the microbial biomass, from which it is later slowly mineralized (Burger & Venterea, 2008; Mallory & Griffin, 2007).

Although the two soils were mapped as the same series, the ORG soil had a sandier texture than the CONV soil, such that management and texture were confounded (Table 1). Several studies have observed greater net mineralization from coarse-textured soils than from fine-textured soils (Castellanos & Pratt, 1981; Gordillo & Cabrera, 1997; Sørenson & Jensen, 1995), an effect often attributed to increased microbial biomass due to a more protected habitat in higher-clay soils (Amato & Ladd, 1992). However, the fact that differences between ORG and CONV soils occurred in spring but not fall suggests they were related to management more than to texture. In this case it was the finer-textured CONV soil that had temporarily higher mineralization.

TABLE 3 Significance of the simple and interactive effects of amendment type and soil on available N after 7 ($N_{min}7$), 21 ($N_{min}21$), 42 ($N_{min}42$), and 84 ($N_{min}84$) days of incubation at 23°C and 60% water holding capacity. Comparisons were only made within an incubation date

Date	Effect	$N_{min}7$	$N_{min}21$	$N_{min}42$	$N_{min}84$
Spring 2017	amend	<0.0001	<0.0001	<0.0001	<0.0001
	soil	0.0007	0.4601	0.0765	0.5744
	amend × soil	0.4419	0.9936	0.1403	0.1746
Fall 2017	amend	<0.0001	<0.0001	<0.0001	<0.0001
	soil	0.4132	0.9625	0.7287	0.1207
	amend × soil	0.5909	0.5217	0.8427	0.7164
Fall 2018	amend	<0.0001	<0.0001	<0.0001	<0.0001
	soil	0.8224	0.8055	0.0137	0.0627
	amend × soil	0.0967	0.4264	0.0276	0.1131

3.3 | Amendment biochemical characteristics

The N concentrations in the incubated amendments ranged from 0.72 to 15.6% of their dry weight (Table 1). The C/N ratios ranged from a low of near 1:1 in the pelleted seabird guano to over 20:1 in some batches of YTC-Y. As expected, the manure composts as well as the pelleted, slaughter, and liquid amendments had higher N concentrations than the plant-based composts. Expressed as they are marketed (i.e., on a liquid basis), the 2–3% N concentrations for the liquid amendments were low compared with other fertilizers designed as sources of quickly available N to growing plants. When calculated on a dry-weight basis, the values were more comparable (6–8% N). The C/N ratios for the liquid amendments were similar to those of higher-N amendments (i.e., around 5:1).

Across the dataset, the C/N ratio was a good indicator of an amendment's $N_{min}84$ (Figure 3a). The $N_{min}84$ was also strongly related to the N concentration when the latter was expressed on a dry-weight basis for all amendments (Figure 3b). This relationship broke down if the fresh weight N concentration of the liquid amendments was used ($R^2 = 0.46$). Liquid amendment N concentrations are always guaranteed and are reported on a fresh-weight basis; therefore, the fact that the C/N ratio is independent of the amendment's moisture content makes it a more useful parameter for comparing liquid and solid amendments. The C/N ratio was a better predictor of $N_{min}84$ than N concentration for the fertilizers (pelleted and slaughter products; $R^2 = 0.88$ and 0.70, respectively) and YTCs ($R^2 = 0.90$ and 0.51, respectively). The N concentration, however, was a better predictor for the manure composts ($R^2 = 0.81$ and 0.92, respectively). Neither parameter was a good predictor of $N_{min}84$ within the liquid products ($R^2 = 0.11$ and 0.05, respectively).

The shape of the observed relationship between C/N ratio and mineralized N agreed well with those observed by Gale et al. (2006) and Delin et al. (2012). Both of these studies measured a wide range of composted, noncomposted, and specialty amendments; however, the former study reports mineralization in terms of plant-available N from field-applied amendments, and the latter reports mineralization in terms of mineral fertilizer equivalent in a pot study. In both these studies, the predicted potential N release tended to be slightly (on average around 7%) higher than the $N_{min}84$ we measured at equivalent C/N ratios. This may be due to

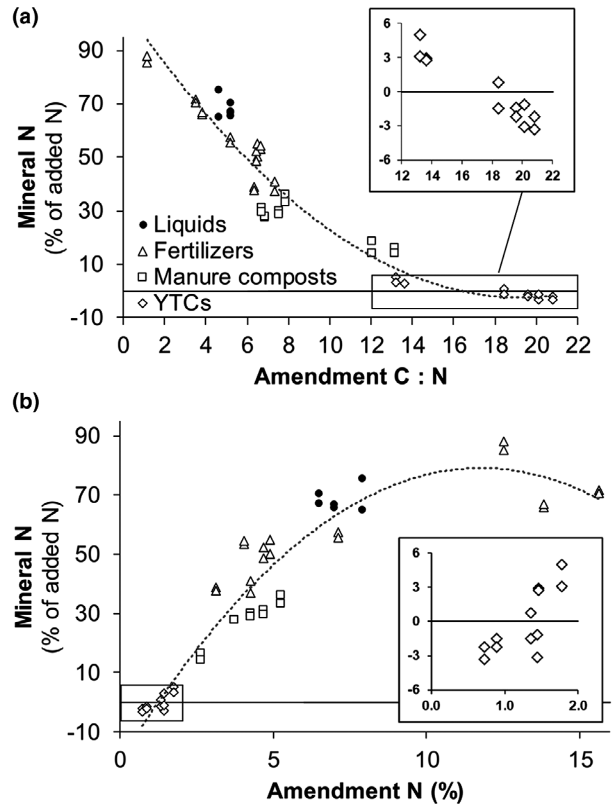

FIGURE 3 Relationship between the proportion of N in the mineral form after 84 d of incubation at 23°C in conventional (CONV) or organic (ORG) soil and (a) amendment C/N ratio and (b) amendment N concentration on a dry-weight basis. Insets represent the yard trimmings composts (YTCs). The R^2 value for the trendline in graph (a) is 0.927. The trendline in graph (b) has an R^2 value of 0.915

a variety of factors, including the presence of living plants, differences in application method, rate, experiment duration, and conditions, and method of calculating N availability.

These overall relationships on N availability with C/N ratio or N concentration are more useful for obtaining a general estimate of an amendment's N mineralization potential than for predicting exact values within a group of similar amendments, because the R^2 value is partly a function of the range of C/N ratios or N concentrations under consideration (Hartz et al., 2000). For example, the good correlation for the manure composts is due to the inclusion of the vermicompost and the YTC/PMC blend, which had C/N ratios nearly double those of the PMCs. Within the PMCs, which occurred over a narrow range of C/N ratios, there was no relationship with $N_{min}84$.

The C/N ratio was a more reliable predictor than the N concentration of whether a compost would immobilize N. Several studies have reported organic amendment C/N ratio threshold values above which N is immobilized, including 15:1 (Gale et al., 2006), between 16:1 and 19:1 (Calderón et al., 2005), and 21:1 (van Kessel, Reeves, & Meisinger, 2000). In the present study, amendments with C/N ratios > 19:1 always immobilized N, whereas amendments with C/N ratios < 14:1 always mineralized N. All YTCs with a total N concentration < 1.3% (dry weight) immobilized N. However, some of the strongest immobilization occurred in YTC-Y3, which had a relatively high N concentration (1.4% dry weight) but was less decomposed.

No raw manures were included in this study because they are rarely applied to organic vegetables in California due to food safety concerns. With these materials, the initial quality of the C is extremely variable and is likely to have more of an effect on N mineralization potential than in composted amendments, and thus the C/N ratio may be a less reliable indicator (Calderón et al., 2005; Sims, 1986). Composting reduces some of this variability (Preusch et al., 2002).

3.4 | Implications for 4R management of organic fertilizers

The results of this study have implications for efficient rate, type, timing, and placement of organic fertilizers. The amount of N that will become available from a given fertilizer application rate can be broadly predicted by amendment type and C/N ratio, regardless of soil management. In addition, low rates of guano, liquids, and slaughter products are likely more efficient than high rates, especially on alkaline soils, because amendments that mineralize N quickly can increase salinity and NH_3 concentrations, reducing microbial activity and decreasing the total proportion of N mineralized (Cayuela, Sinicco, & Mondini, 2009; Hadas et al., 1983).

Because of compost's slow mineralization, the annual N applications may far exceed plant uptake, raising concerns about potential groundwater pollution if unused N, building up over time, is mineralized and leached when no crop is present. Although the experiment was not designed to assess this issue, long-term field research suggests that over time, the N mineralization rate from YTCs remains low enough (< 2.5% per year after initial application) that it is unlikely to be a serious risk, especially if cropped year-round (Horrocks, Curtin, Tregurtha, & Meenken, 2016; Sullivan et al., 2003). A greater proportion of manure-based compost N becomes plant available, and buildup from annual applications may result in leaching in the absence of winter crops (Evanylo et al., 2008).

Efficient timing for applying organic amendments depends on amendment type. Amendments varied in their degrees of maturity among compost batches and facilities, and immature composts may cause N or oxygen limitations for growing seedlings (Bernal, Alburquerque, & Moral, 2009). Individual batches therefore should be tested for maturity (CCQC, 2001), and incorporating immature composts less than a week before planting may be risky. For yard trimmings composts, for which N mineralization is likely slow enough that significant N leaching over winter is less of a risk, application during the previous fall for spring-planted crops may be safest. Conversely, the quick mineralization from almost all the fertilizer products suggests that, under warm and moist conditions, applications should be synchronized with plant demand to avoid leaching losses. Preliminary work by our laboratory and studies with similar amendments suggest that significant mineralization can occur within a few weeks even under cooler temperatures (< 5°C) (Agehara & Warncke, 2005; Hartz et al., 2010; Sims, 1986).

Initial NH_4 concentration and N mineralization rate have implications for amendment placement. A considerable amount of N may be lost through NH_3 volatilization when amendments with a high NH_4 concentration are surface applied. In manure-based composts, liquid fertilizers, and most granular and pelleted fertilizers, at least 10% of the total N was NH_4–N and would be susceptible to volatilization if not incorporated (Derikx et al., 1994; Hadas et al., 1983). Concentrated bands of fast-releasing materials such as the guano or slaughter products should be applied at a safe distance from the seedling because fast mineralization rates are associated with high NH_3 concentrations, which may inhibit germination or injure seedlings of sensitive species (Diaz-Perez, Jenkins, Pitchay, & Gunawan, 2017). The low concentrations applied through fertigation, typically 10–20 kg N ha^{-1} in an application, are less likely to be a risk.

4 | CONCLUSIONS

The results of this study can inform the 4Rs of efficient N management for organic fertilizers. The organic amendments tested have a wide range of potentially crop-available N ranging from immobilization by some yard trimmings composts to 80–90% of the N applied as seabird guano. However, across all materials the proportion of total N that was in the mineral form after 84 d of incubation was closely related to the C/N ratio. The timing of potential N mineralization may have been somewhat slowed by the high concentration of labile C present in the organically managed soil in spring, but otherwise N mineralization from all amendments was generally similar between two soils with different textures and management histories.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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