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Predicting nitrogen mineralization from dairy manure and broadleaf residue in a semiarid cropping system

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Abstract

Approximately 37% of US milk production occurs in semiarid regions, providing an opportunity to recycle manure nutrients through a variety of cropping systems. Accurate prediction of nitrogen (N) mineralization is critical to determine manure application suitability in intensive irrigated agriculture as many crops in the region have quality parameters that are sensitive to N. Research was conducted in southcentral Idaho to evaluate N mineralization via a buried bag methodology to develop a predictive N-mineralization model. The study was arranged in a randomized complete block design with manure application rates of 18, 36, and 52 Mg·ha^{-1} (dry weight basis) both annually and biennially with synthetic fertilizer and untreated check treatments. The crop rotation included small-grain and broadleaf crops. In the final year of the study, preplant soil organic carbon, total nitrogen, and NO_3–N concentrations were positively linearly correlated with manure application rate. Nearly five times as much N was mineralized annually in the 0- to 30-cm depth as compared to the 30- to 60-cm depth. Increased rates of N mineralization for each kilogram of added N occurred in years when residue from broadleaf crops (slope = 0.17) was applied as compared to years with manure only application (slope = 0.07). Stepwise modeling determined that the most predictive model for seasonal N mineralization (R^2 = 0.79) included manure N, residue N, soil organic matter, and electrical conductivity. These results allow preplant N mineralization estimation and will prove critical for managing manure in semiarid regions for agronomic, economic, and environmentally sound crop production.

Abbreviations: EC, electrical conductivity; ET, evapotranspiration; GDD, growing degree days; IN, inorganic nitrogen; SOM, soil organic matter; TN, total nitrogen.

1 | INTRODUCTION

In intensive livestock producing regions, there is an opportunity to enhance recycling of manure nutrients through crop production, thereby improving the circularity of these systems. Depending on the source, handling, and storage, much of the nitrogen (N) found in manure may be in an organic form that will have to undergo mineralization before it can be utilized by crops. Manure N mineralization rates are affected by manure characteristics, soil characteristics, and climate, resulting in a wide range of measured values in the literature. These factors make accurate prediction of N mineralization challenging, which makes it difficult to provide producers with robust tools for estimating the N value of applied manures. High rates of N mineralization (up to 90% of total nitrogen [TN]) have been reported for poultry and pig manure in the first year following application, whereas solid cattle manures have lower first season N mineralization (up to 30%) but may continue to be a source of N for several growing seasons (Bhogal et al., 2016; Gilbertson et al., 1979). One of the determining factors reported to influence N mineralization is the C to N ratio of the manures where lower C:N ratio manures have greater N mineralization rates (Alizadeh et al., 2012; Antoniadis, 2013; Ige et al., 2015). However, the recalcitrance of organic N compounds in the organic amendment may have a larger impact than just the C:N ratio (Artur et al., 2021; Heijboer et al., 2016). Additionally, cattle manures tend to have higher lignin–cutin compounds than poultry and pig manures, which can decrease N mineralization due to resistance to degradation compared with these other manures (Aranguren et al., 2021).

Nitrogen mineralization, as it is driven by microorganisms, is influenced by several environmental factors such as soil characteristics, soil temperature, and water content (Cabrera et al., 2005; Uddin et al., 2021). Manure N mineralization has been shown to decrease with an increase in soil clay content (Bhogal et al., 2016; Bouajila et al., 2021; Ige et al., 2015). As soil temperature increases, microbial activity and therefore mineralization also increases (Cassity-Duffy et al., 2018; Whalen et al., 2019). The optimum soil moisture content for N mineralization has been reported to be between 80% and 100% of field capacity, with depressed N mineralization at higher or lower soil moisture contents (Basak & Biswas, 2014; Guntiñas et al., 2012; Ige et al., 2015). Microbial activity and community structure may also be affected by the properties of the organic amendment (Heijboer et al., 2016). These changes can affect N immobilization and mineralization. Long-term additions of manure also increase microbial abundances and enhance soil enzyme activities that impact cycling of C and N in soils (Ashraf et al., 2020; Dungan et al., 2022; Masunga et al., 2016; Wang et al., 2022). Many studies have evaluated the effects of a one-time application of manure; however, long-term application of manure may enhance the residual N pool that is available for mineralization in subsequent years, and therefore short-term studies may underestimate future plant-available N from manure (Mallory et al., 2010).

Core Ideas

- Tools are needed to estimate nitrogen (N) mineralization from applications of dairy manure in semiarid irrigated soils.
- N mineralization was affected by manure application rate, timing, and broadleaf residue N.
- Average manure N mineralization was 27% and 18% of N applied in the first and second years, respectively, following application.
- The incorporation of broadleaf residue with manure increased N mineralized to 41% of N applied.
- The best predictors of N mineralization were soil organic matter, soil electrical conductivity, manure N, and broadleaf N residue.

The south-central region of Idaho is the third largest dairy-producing region in the United States. Most dairies in the region house cattle in dry lots where the manure is scraped and piled in the lots for several months and then applied to cropland in the fall and/or spring. Approximately 16% of regional cropland receives manure, with average manure N application rates of 596 kg N·ha^{-1}·year^{-1} and average crop removal of 215 kg N·ha^{-1}·year^{-1}; additionally, many of these fields also receive fertilizer N (Leytem et al., 2021). Producer surveys indicate that 43% of respondents rated the nutrient value of manure as either “not important” or “somewhat important” (Leytem et al., 2021). Fertilizer management guides of the region typically account for N-mineralization in nonmanured soils by using an estimated mean or soil organic matter (SOM) content to determine relative magnitudes. Manure recommendations are generally separate from crop fertilizer guides. Sullivan (2008) provides guidance for predicting plant-available N from manure in humid regions west of the Cascade mountains in Oregon and Washington. However, direct guidance for estimating expected N from manure applications in Idaho and most of the semiarid western United States is unavailable.

While manure is typically used on farms for forage production, there are opportunities to utilize this valuable resource in a range of other crops produced in the region. Several high-value commodities are produced, namely, potato (*Solanum tuberosum*, L.), sugarbeet (*Beta vulgaris*, L.), malt barley (*Hordeum vulgare*, L.), and wheat (*Triticum aestivum*, L.). Widespread application of manure to these crops has not occurred in the past, partially due to the sensitivity of these crops to the N status of the soil over the growing season along with the fact that specific quality criteria of each crop are affected by N availability. A better understanding of N mineralization rates of manure will enable broader use of manure as a fertilizer source for these and other commodities as well as provide better crediting for manure N in all fertilizer guidelines. Therefore, the objective of this study was to (a) evaluate the long-term effects of dairy manure application rate and timing on seasonal N mineralization in irrigated cropping systems common to the region and (b) develop an empirical model to predict N mineralization rates.

2 | MATERIALS AND METHODS

2.1 | Site description

This study was conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, at 42°33′4.5″ N, 114°21′14.7″ W. The climate in the region is semiarid, receiving only 284 mm of precipitation annually, on average, with an average annual temperature of 8.7°C. Most of the precipitation occurs during the winter months and crops are produced with irrigation water sourced from ground water wells or diverted from the Snake River, as in the current study. Irrigation application rates each year were determined based on crop water use estimates using the Washington State University Irrigation Scheduler (http://irrigation.wsu.edu/index.php). Crop water use was estimated as evapotranspiration (ET) calculated based on the reference alfalfa ET based on the standardized ASCE Penman–Monteith method and mean crop coefficients for the crop being grown (Allen et al., 1998). Soils in the region are predominantly Portneuf silt loams (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids), with the study site having the following average properties in the top 30 cm determined 1 week prior to the first fall manure application in 2012: clay, 125 g·kg^{-1}; silt, 692 g·kg^{-1}; sand, 183 g·kg^{-1}; SOM, 11 g·kg^{-1}; pH, 8.0; and electrical conductivity (EC), 0.99 dS·m^{-1}. Prior to the start of the study (fall 2012), this field had a cropping history of corn silage (2011) and pinto beans (2012), with no history of manure application.

2.2 | Experimental design

The study was initiated in the fall of 2012 and consisted of the following crop rotation planted in the spring of each year: malt barley (2013), sugarbeet (2014), hard red wheat (2015), potato (2016), malt barley (2017), sugarbeet (2018), hard red wheat (2019), and sugarbeet (2020). The experimental design was a randomized complete block with eight treatments replicated four times for a total of 32 plots (18 × 12 m). The treatments included dairy manure applied annually (every year) or biennially (every other year starting in 2012) at target rates of 18, 36, and 52 Mg·ha^{-1} (dry weight basis) at each application event; synthetic fertilizer only; and a control that received no nutrient application. The manure used in the study was collected from lactating dairy cows housed in dry lots, with the manure being scraped and piled for storage (no turning of pile) for several months prior to application, which represents the main manure handling practice in the region. A schematic of the crop rotation as well as manure and residue applications is shown in Figure 1.

2.3 | Manure application and analyses

Manure additions were selected to reflect the range of manure application rates for the region, ranging from typical dry matter rates used farther from dairy operations (18 Mg·ha^{-1}) to those closer to dairy operations (52 Mg·ha^{-1}). The biennial manure treatments were included to evaluate the effects of taking a year off from manure application. This practice is common in rotations containing sugarbeet and potato, where manure is not applied immediately prior to these crops. Manure was applied in the fall (October or November) each year by weighing the appropriate amount of manure per plot on a dry weight basis and spreading with a small plot manure spreader. Manure was immediately incorporated through disking or moldboard plowing to a depth of 15 cm to minimize ammonia volatilization and phosphorus (P) runoff losses over the winter; the fertilizer and control plot tillage was handled the same as manured plots.

During application events, manure samples were collected from each plot by placing three trays (0.5 × 0.6 m) within the plots during manure application, composited by plot, and then further composited over plots to obtain three representative samples. Manure water content was determined gravimetrically on a 100-g subsample by drying at 105°C for 24 h; total C and N contents were determined via combustion with a CHN 628 analyzer (LECO). Manure inorganic nitrogen (IN; ammonium [NH_4–N] + nitrate [NO_3–N]) concentration was determined with 2 mol·L^{-1} KCl extraction and analysis via an automated flow injection analyzer (Lachat Method 12–107–04–1-B and Lachat Method 12–107–06–2-A; Lachat Instruments). The percentage of organic N was calculated by subtracting the IN from TN. Manure pH and EC were measured in a 1:5 (manure to distilled water) slurry. Total elements (P, potassium [K], calcium [Ca], magnesium [Mg], sulfur [S], zinc [Zn], copper [Cu], and boron [B]) were determined by digesting 0.5 g of manure with nitric/perchloric acid (Method B-4.20; Miller et al., 2013) and measuring the elements using inductively coupled plasma optical emission spectrometry (Perkin Elmer Optima 7300 DV; Perkin Elmer). Manure properties measured over the study period are provided in Table 1.

The amount of manure N applied by treatment and year is shown in Table 2. The average manure TN application rate

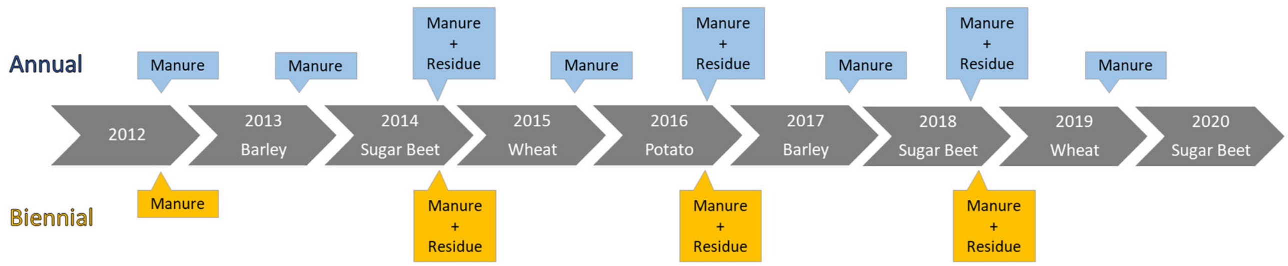

FIGURE 1 Schematic representation of the cropping system by annual and biennial applications of manure as well as the addition of manure and crop residue in relation to year and crop. Residue N is the N contribution from the broadleaf aboveground biomass left in the field in the fall following harvest of potato tubers and sugarbeet roots, and the N contribution from sugarbeet roots not harvested in 2014.

TABLE 1 Select physical and chemical properties of the fall-applied dairy manure sources, by year.

Properties	Units	2012	2013	2014	2015	2016	2017	2018	2019
Dry Matter	g·kg^{-1}	586 ± 155	357 ± 61	620 ± 113	515 ± 7	545 ± 33	539 ± 50	523.2 ± 2.7	568 ± 61
pH		9.0 ± 0.2	8.9 ± 0.1	8.7 ± 0.1	8.7 ± 0.1	8.3 ± 0.0	9.0 ± 0.1	9.0 ± 0.3	9.0 ± 0.1
EC	dS·m^{-1}	19.4 ± 1.8	23.0 ± 2.7	14.3 ± 2.5	12.6 ± 0.7	9.3 ± 0.1	6.5 ± 0.6	7.9 ± 0.4	7.2 ± 0.4
Total N	g·kg^{-1}	14.8 ± 1.2	18.3 ± 0.8	12.0 ± 1.5	15.0 ± 1.1	12.4 ± 1.5	11.7 ± 1.8	11.0 ± 0.1	10.6 ± 1.5
Total C	g·kg^{-1}	286 ± 24	319 ± 17	192 ± 27	220 ± 20	196 ± 27	175 ± 35	124.0 ± 1	137 ± 16
Total IN	g·kg^{-1}	2.3 ± 1.6	2.9 ± 1.4	3.6 ± 0.9	3.1 ± 0.6	3.6 ± 1.0	1.0 ± 0.2	0.3 ± 0.1	1.2 ± 0.8
Organic N	%	86.5	86.3	76.9	82.9	77.5	92.1	97.4	89.8
C/N		17	13	15	15	10	15	11	10
P	g·kg^{-1}	4.6 ± 0.5	6.2 ± 0.7	3.6 ± 0.8	6.7 ± 1.1	5.5 ± 0.7	4.7 ± 0.5	5.0 ± 0.2	6.6 ± 1.6
K	g·kg^{-1}	45 ± 6.2	46 ± 2.6	28 ± 7.2	27 ± 1.9	22 ± 2.4	24 ± 2.7	22 ± 1	23.9 ± 6.1
Ca	g·kg^{-1}	22.5 ± 8.8	11.7 ± 2.2	19.6 ± 3.2	15.7 ± 0.1	32.1 ± 2.9	47.6 ± 2.1	24.9 ± 0.2	30.7 ± 8.1
Mg	g·kg^{-1}	8.1 ± 3.5	3.9 ± 0.8	8.0 ± 1.9	6.1 ± 0.1	13.5 ± 1.4	12.3 ± 0.6	9.4 ± 0.1	12.0 ± 2.8
S	g·kg^{-1}	3.6 ± 1.6	3.1 ± 0.6	2.6 ± 0.7	2.1 ± 0.1	4.3 ± 0.4	3.9 ± 0.0	3.3 ± 0.1	4.9 ± 2.0
B	mg·kg^{-1}	37.0 ± 15.1	28.3 ± 5.9	19.5 ± 6.4	17.0 ± 0.0	22.0 ± 8.5	13.5 ± 2.1	16.8 ± 0.1	28.1 ± 19.5
Cu	mg·kg^{-1}	43.3 ± 34.2	34.0 ± 7.9	78.0 ± 28.3	63.5 ± 2.1	92.5 ± 13.4	33.0 ± 1.4	45.8 ± 2.8	136.5 ± 7.8
Zn	mg·kg^{-1}	94.3 ± 52.7	70.0 ± 22.6	175.0 ± 53.7	112.0 ± 0.0	159.0 ± 15.6	155.5 ± 10.6	176.5 ± 6.7	164.1 ± 28

Note: Concentrations are reported as the mean ± standard deviation on a dry weight basis.

for the annual manure 18, 36, and 52 Mg·ha^{-1} treatments were 258, 523, and 788 kg N·ha^{-1}, respectively, whereas the cumulative N application over the study for these treatments was 2063, 4188, and 6305 kg N·ha^{-1}, respectively. For the biennial manure 18, 36, and 52 Mg·ha^{-1} treatments, the average application rates were 237, 453, and 697 kg N·ha^{-1}, respectively, while the cumulative manure N applications were 948, 1812, and 2789 kg N·ha^{-1}, respectively. Fertilizer N application rates varied with crop and were determined based on regional university extension recommendations for the individual crop using spring soil test results. The amount of C applied annually with manure across all treatments ranged from 2.1 to 21.1 Mg C·ha^{-1} (Table 3). The cumulative amount of manure C added for the annual manure 18, 36, and 52 Mg·ha^{-1} treatments was 32.4, 65.0, and 98.6 Mg C·ha^{-1}, respectively. For the biennial treatments, the cumulative amount of manure C added for the 18, 36, and 52 Mg·ha^{-1} treatments was 15.2, 29.4, and 45.5 Mg C·ha^{-1}, respectively. The majority of manure N was in an organic form with a range of 76.9%–97.4% of TN, while the C:N ratio of the manures ranged from 10 to 17 (Table 1). Manure pH ranged from 8.3 to 9, while the EC ranged from 6.5 to 23.0 dS·m^{-1}.

2.4 | Soil collection and analyses

Preplant soil samples were collected in late March or early April each year, with approximately eight subsamples collected with a 5.7-cm-diameter bucket soil auger and composited by plot at depths of 0–30 and 30–60 cm. Soils were air dried, ground, and passed through a 2-mm stainless steel sieve prior to analysis. Soil pH was measured with a digital pH meter (Orion; Thermo Scientific) and soil EC was measured with a conductivity bridge (YSI Model 31; YSI Inc.)

TABLE 2 The addition of nitrogen from all sources (manure, broadleaf crop residue, fertilizer) by treatment and year.

	Treatments							
	18A[a]	36A	52A	18B	36B	52B	Fertilizer	Control
	Manure N applied (kg·ha^{-1})							
Year								
2012	285	548	864	297	527	858	–	–
2013	417	788	1234	–	–	–	–	–
2014	211	471	677	233	458	675	–	–
2015	288	582	871	–	–	–	–	–
2016	222	450	659	227	437	689	–	–
2017	232	477	684	–	–	–	–	–
2018	196	386	581	191	390	568	–	–
2019	213	486	735	–	–	–	–	–
Cumulative	2063	4188	6305	948	1812	2789	–	–
	Residue N (kg·ha^{-1})[b]							
2014	341	408	463	280	294	370	202	137
2016	78	90	149	88	89	91	143	34
2018	113	129	198	117	118	183	79	20
Cumulative	531	627	811	484	500	644	425	191
	Fertilizer N (kg·ha^{-1})							
2013	62	62	62	62	62	62	81	–
2014	75	–	–	75	45	–	75	–
2015	11	–	–	53	–	–	107	–
2016	96	45	45	208	153	94	365	–
2017	124	53	38	117	79	72	136	–
2018	35	–	–	90	69	24	115	–
2019	112	25	–	124	82	22	147	–
2020	–	–	–	–	–	–	89	–
Cumulative	514	184	144	729	490	273	1026	–
Total (M + R + F)	3108	4999	7260	2161	2802	3707	1450	191

[a]18A = manure applied annually at a rate of 18 Mg·ha^{-1}; 36A = manure applied annually at a rate of 36 Mg·ha^{-1}; 52A = manure applied annually at a rate of 52 Mg·ha^{-1}; 18B = manure applied every other year starting in 2012 at a rate of 18 Mg·ha^{-1}; 36B = manure applied every other year starting in 2012 at a rate of 36 Mg·ha^{-1}; 52B = manure applied every other year starting in 2012 at a rate of 52 Mg·ha^{-1}. All rates on a dry weight basis.

[b]Residue N is the N contribution from the broadleaf aboveground biomass left in the field in the fall following harvest of potato tubers and sugarbeet roots, and the N contribution from sugarbeet roots not harvested in 2014.

in a 1:1 soil and deionized water suspension. SOM content was determined by the Sims/Haby colorimetric method (Sims & Haby, 1971) using a spectrometer (Spectronic 301; Milton Roy Co.). Soil IN, total C, N, P, K, Zn, Cu, and B were determined as described above for manure analyses. Olsen P was determined as bicarbonate-extractable P following Olsen et al. (1954).

2.5 | Fertilizer application

Synthetic fertilizer applications (N, P, K) were determined for each crop based on preplant soil nutrient concentrations and average yield goals for the region, following the University of Idaho Fertilizer Guidelines for each crop (Moore et al., 2009; Robertson & Stark, 2003; Stark & Kephart, 1989; Stark et al., 2004). The goal was to meet all necessary nutrient requirements, as would be done by a commercial grower, which resulted in application of synthetic fertilizer to some of the manure plots in specific years. Fertilizer N, P, and K rates are provided in Tables 2 and S1 and discussed below.

2.6 | Field operations

All fertilizer applications consisted of monoammonium phosphate, urea, and potassium chloride (KCl) unless otherwise stated. Following application, fertilizer was immediately incorporated on the same day via roller harrow with all plots receiving the same tillage for consistency.

TABLE 3 The addition of carbon from all sources (manure and broadleaf crop residue) by treatment and year.

	Treatments							
	18A[a]	36A	52A	18B	36B	52B	Fertilizer	Control
	Manure C applied ($Mg{\cdot}ha^{-1}$)							
Year								
2012	5.6	10.6	16.6	5.6	10.2	16.8	–	–
2013	7.3	13.7	21.1	–	–	–	–	–
2014	3.4	7.5	10.9	3.7	7.3	10.8	–	–
2015	4.2	8.5	12.7	–	–	–	–	–
2016	3.3	6.9	10.3	3.6	7.1	10.9	–	–
2017	3.4	7.1	10.4	–	–	–	–	–
2018	2.1	4.6	7.3	2.3	4.8	7.0	–	–
2019	3.1	6.1	9.3	–	–	–	–	–
Cumulative	32.4	65	98.6	15.2	29.4	45.5	–	–
	Residue C ($Mg{\cdot}ha^{-1}$)[b]							
2014	10.5	10.4	10.0	10.6	10.2	10.6	8.9	6.7
2016	1.3	1.4	1.9	1.5	1.5	1.5	1.7	0.8
2018	1.6	1.6	2.4	1.7	1.8	2.3	1.3	0.4
Cumulative	13.4	13.4	14.3	13.8	13.5	14.4	11.9	7.9
Total (M + R)	45.8	78.4	112.9	29.0	42.9	59.9	11.9	7.9

[a] 18A = manure applied annually at a rate of 18 $Mg{\cdot}ha^{-1}$; 36A = manure applied annually at a rate of 36 $Mg{\cdot}ha^{-1}$; 52A = manure applied annually at a rate of 52 $Mg{\cdot}ha^{-1}$; 18B = manure applied every other year starting in 2012 at a rate of 18 $Mg{\cdot}ha^{-1}$; 36B = manure applied every other year starting in 2012 at a rate of 36 $Mg{\cdot}ha^{-1}$; 52B = manure applied every other year starting in 2012 at a rate of 52 $Mg{\cdot}ha^{-1}$. All rates on a dry weight basis.

[b] Residue C is the C contribution from the broadleaf aboveground biomass left in the field in the fall following harvest of potato tubers and sugarbeet roots, and the C contribution from sugarbeet roots not harvested in 2014.

In 2013 and 2017, malt barley (Moravian 69) was planted on April 4 and April 6, respectively, at a seeding rate of 123 $kg{\cdot}ha^{-1}$. Preplant fertilizer was applied on April 2, 2013 and April 4, 2017, with application rates of N and P ranging from 38 to 136 kg $N{\cdot}ha^{-1}$ and 16 to 39 kg $P{\cdot}ha^{-1}$, respectively (Tables 2 and S1). Plot harvest for yield (26 m^2) was done on August 6, 2013 and August 8, 2017 using an Almaco plot harvester (1.5-m head). The field was bulk harvested within a week of plot harvest and residue was baled and removed as is common practice in the region.

In 2014, 2018, and 2020, sugarbeets (BTS-21RR25) were planted on May 5, May 1, and May 7, respectively, at a rate of 128,097 $seeds{\cdot}ha^{-1}$. The field was moldboard plowed the previous fall and roller harrowed prior to planting. Preplant fertilizer was applied on April 16, 2014, April 18, 2018, and May 5, 2020 with application rates of N, P, and K ranging from 24 to 115 kg $N{\cdot}ha^{-1}$, 37 to 66 kg $P{\cdot}ha^{-1}$, and 37 to 69 kg $K{\cdot}ha^{-1}$, respectively (Tables 2 and S1). Plots were mechanically harvested for yield (21 m of row) with a two-row beet harvester on October 3, 2014 and October 1, 2018; there was no plot harvest completed in 2020 due to field conditions. Bulk harvest of the field was done on October 9, 2018 and October 12, 2020. In 2014, due to field conditions, bulk harvest of the sugarbeets was not possible.

In 2015 and 2019, a hard red spring wheat (Jefferson) was planted on April 2 and April 13, respectively, at a seeding rate of 118 $kg{\cdot}ha^{-1}$. Preplant fertilizer was applied April 2, 2015 and April 12, 2019 with application rates of N and P ranging from 10 to 147 kg $N{\cdot}ha^{-1}$ and 20 kg $P{\cdot}ha^{-1}$, respectively (Tables 2 and S1). Plot harvest occurred on August 13, 2015 and August 16, 2019, followed by bulk harvest in the same manner as for barley, with residue baled and removed.

In 2016, potato (Russet Burbank) was planted on May 2. The field was moldboard plowed the previous fall following manure application and roller harrowed on April 21. Seed potatoes were planted at a rate of 2153 $kg{\cdot}ha^{-1}$. Preplant fertilizer (N, P, K) was applied on April 20 with two additional in-season applications of N being applied as polymer-coated urea (May 25) and urea (July 12), resulting in application rates of N, P, and K ranging from 45 to 365 kg $N{\cdot}ha^{-1}$, 20 to 98 kg $P{\cdot}ha^{-1}$, and 89 to 255 kg $K{\cdot}ha^{-1}$, respectively (Tables 2 and S1). In-season application of polymer-coated urea was incorporated immediately with a rolling cultivator (Lilliston by Bigham). In-season application of urea was watered into the soil with irrigation. Tuber yield was determined on October 3 for each plot using a single row potato digger (Grimme) with 33.5 m of row harvested within each plot. The field was bulk harvested on October 15 by a commercial operator.

2.7 | Residue sampling and analyses

As potato and sugarbeet are grown for their roots, only the belowground biomass is removed from the field. The aboveground biomass is returned to the field and recycled through the soil. Sugarbeets were not harvested in 2014 and were tilled into the soil due to poor field conditions. To account for the N and C added back into the soil as residue, both belowground (sugarbeets in 2014) and aboveground crop biomass were destructively harvested on September 30, 2014, September 26, 2016, and September 25, 2018. Plants were sampled from a single transect per plot that was 152 cm in length and 56 cm in width (row width). Plant foliage (both potato and sugarbeet) was cut near the soil surface with wet weights determined within 2 h. Sugarbeet roots were dug by hand using shovels, and adhering soil was manually removed from the beets prior to weighing. Sugarbeet roots were cut in half, with one half retained, and then chopped into 2.5-cm cubes. Approximately one quarter of the cubes were dried to determine moisture content, while the remaining cubes were pureed and spread on parchment paper for drying. All harvested foliage and root samples were dried at 60°C for 72 h and reweighed for dry weight. Dried samples were ground to pass a 2-mm sieve using a Wiley Mill (Thomas Scientific). Total C and N contents were determined as described above. Aboveground biomass dry matter production and beet root dry matter production along with TN and total C concentrations were used to determine the amount of residue N and C left in the field postharvest that would be available for mineralization the following growing season.

2.8 | Nitrogen mineralization estimation

In situ N mineralization was determined via a buried bag method (Lentz et al., 2011; Meek et al., 1994; Westermann & Crothers, 1980). This method consists of obtaining a representative soil sample from each plot and placing it in a polyethylene bag (10-µm thick, 5-cm diameter) that allows gas exchange but does not allow movement of water into or out of the bag to conserve N within the bag. The bags were buried at the depth that they were collected in the field, and removed over time to determine the amount of IN released between the start of the study and when the bag was retrieved. By placing the bags within the plots, soil temperature (which is one of the main drivers of N mineralization) is reflective of that of the individual plots throughout the growing season. In each plot, soil was collected with a 5.7-cm-diameter soil auger at two depths (0–30 and 30–60 cm). There were approximately 10 cores collected at the 0- to 30-cm depth and six cores collected at the 30- to 60-cm depth; soil cores were composited, passed through a 6-mm screen, and thoroughly mixed. A subsample of the composited soil was collected to determine IN at the date of installation (T_0). Composited soils were then placed in the polyethylene bags that were sealed on one end (or in the middle for samples bags containing both soil depths). The final bags were 5 × 30 or 60 cm depending on whether they had both soil depths included. The soil was settled using a vertical shaking action, and the open end was then sealed. The soil bags were then inserted (in the same orientation for the 60-cm bags) into one of the sample holes created previously. Soil was placed in the hole around the bag as needed to fill the cavity, thus ensuring representative soil temperatures in the bagged soil. Bags were removed over the course of the growing season (eight to 12 sampling events for the depth of 0–30 cm and four to seven sampling events for the depth of 30–60 cm) to determine soil IN. The buried bags were typically deployed mid-April to early May and removed in October of each year depending on the field operations associated with the cropping season. Dates of buried bag installation and final retrieval along with average air temperature and cumulative growing degree days (GDD) over the course of the installation are listed in Table 4. All climatic data (average air temperature, soil temperature measured at 10.2 cm, cumulative GDD each year over the study time period, and precipitation) were obtained from the Twin Falls (Kimberly) Idaho AgriMet Weather Station 7E (twfi; https://www.usbr.gov/pn/agrimet/agrimetmap/twfida.html) located 0.85 km from the field site.

The net IN mineralization (Net IN) during the period between burial and retrieval was calculated as follows:

$$\text{Net IN mg} \cdot \text{kg}^{-1} = \text{IN}_{t_x}\ \text{mg N} \cdot \text{kg}^{-1} - \text{IN}_{t_0}\ \text{mg N} \cdot \text{kg}^{-1}, \quad (1)$$

where IN_{t_x} is the total IN determined for each soil depth (0–30 and 30–60 cm) at each sampling interval (x) and IN_{t_0} is the total IN measured when the bags were installed (T_0). A positive difference indicated net N mineralization, while a negative value indicated net N immobilization during the period. The rate of N mineralization over the season was determined by regressing the Net IN (mg N·kg^{-1}) at each time interval versus week or cumulative GDD at collection and fitting a linear regression over the season, with the slope of the regression representing the rate of N mineralization (mg N·kg^{-1}·week^{-1} or GDD^{-1}).

Net seasonal IN mineralization (Net IN_s) was determined as follows:

$$\text{Net IN}_\text{s}\ \text{mg} \cdot \text{kg}^{-1} = \text{IN}_{t_f}\ \text{mg N} \cdot \text{kg}^{-1} - \text{IN}_{t_0}\ \text{mg N} \cdot \text{kg}^{-1}, \quad (2)$$

where IN_{t_f} is the final IN (mg N·kg^{-1}) in the last buried bag at the end of the season. Net IN_s (mg N·kg^{-1}) was also converted to Net IN_s (kg N·ha^{-1}) by multiplying the 0- to 30-cm depth by a bulk density of 1.28 g·cm^{-3} and the 30- to 60-cm depth by a bulk density of 1.37 g·cm^{-3} (bulk density values represented

TABLE 4 Dates for buried bag deployment, average air temperature over deployment and the cumulative growing degree days (GDD) over deployment.

Year	Date in	Date out[a]	Average temperature (˚C)	Cumulative GDD[b]
2013	April 12	September 12 (August 16)	18.3	2414
2014	May 1	October 9 (September 25)	17.9	2458
2015	April 13	October 12	17.6	2753
2016	May 5	November 11	17.6	2316
2017	May 3	October 11	17.9	2452
2018	May 8	October 9 (September 18)	18.1	2336
2019	April 18	October 10	16.5	2355
2020	June 12	October 6 (September 1)	19.5	2007

[a]Values in parenthesis are for times when the 30- to 60-cm bags ended on a different date.

[b]GDD = [(Max Air Temp ˚C + Min Air Temp ˚C)/2] – 10˚C, where max air temp is capped at 30˚C and min air temp is capped at 10˚C.

averages for samples that had been collected within the field at various time points over the 8 years). The 0- to 30-cm and 30- to 60-cm depths (kg N·ha^{-1}) were then summed in order to determine the net seasonal IN mineralization in the upper plant root zone where the majority of N mineralization occurs.

The percent N mineralization (% N_{min}) was calculated as follows:

$$\%N_{min} = \left(\text{Net}IN_s \text{ kg N} \cdot \text{ha}^{-1}/\text{total N added, kg N} \cdot \text{ha}^{-1}\right) 100, \quad (3)$$

where the TN added was either the manure N + residue N from previous year, manure N only previous year, or the manure N and/or manure N + residue N from 2 previous years (for the biennial treatments).

The net percent N mineralization (% Net N_{min}) was calculated as follows:

$$\%\text{Net } N_{min} = \left[\frac{\left(\text{Net } IN_{s,t} \text{ kg N} \cdot \text{ha}^{-1} - \text{Net } IN_{s,c} \text{ kg N} \cdot \text{ha}^{-1}\right)}{\text{total N added kg N} \cdot \text{ha}^{-1}}\right] 100, \quad (4)$$

where Net $IN_{s,t}$ is the net seasonal N mineralized for the different treatments and Net $IN_{s,c}$ is the net seasonal N mineralized in the control.

Cumulative N_{min} and Net N_{min} were calculated by summing the Net IN_s (with and without control subtracted) over the 8 years and dividing by the total amount of N applied over the same period.

2.9 | Statistics

All data were statistically analyzed using SAS (SAS Institute Inc., 2013). Statements of statistical significance were based on a p-value of <0.05. Preplant soil properties (0–60 cm) in 2020 were statistically analyzed using a generalized linear mixed model (GLIMMIX) procedure including treatment as a main effect and block as a random effect with treatment effects determined via contrast statements. Linear regressions were performed with PROC REG to determine the rate of IN release over the season. Net IN release rates over time and Net IN_s were analyzed with GLIMMIX including year, depth, and treatment as fixed effects and block as a random effect. Net IN_s combined over the 0- to 60-cm depth was analyzed with GLIMMIX including year and treatment as fixed effects and block as a random effect. The protected least significant difference (LSD) method was used to determine significant differences between treatment means. Correlations among and between soil nutrients and Net IN_s were determined using Spearman's rank correlation (Proc CORR, Spearman) procedure. Forward stepwise regression (PROC REG) was used to develop models to predict seasonal Net IN_s. Net IN_s did not differ between the fertilizer and control treatments; therefore, we excluded the fertilizer treatment from this regression analysis. An initial analysis was performed to estimate Net IN_s using the following preplant soil variables TN, total C, SOM, NO_3–N, NH_4–N, EC, and pH along with the amount of manure N applied, residue N applied, air temperature, and GDD using the Mallows' C_p selection method. Multicollinearity issues was assessed and deemed acceptable when variance inflation factor (VIF) was <10 and a tolerance >0.1 (Montgomery et al., 2001)

3 | RESULTS

3.1 | Environmental conditions

The annual (January 1 to December 31) cumulative precipitation from 2013 to 2020 was 134, 368, 252, 358, 270, 243, 266, and 167 mm·year^{-1}, respectively. Total irrigation water applied each growing season over this time period was 385, 538, 419, 776, 574, 788, 289, and 772 mm, respectively (Figure 2). Soil temperature measured at 10.2 cm as well as cumulative annual GDD over the study period obtained from

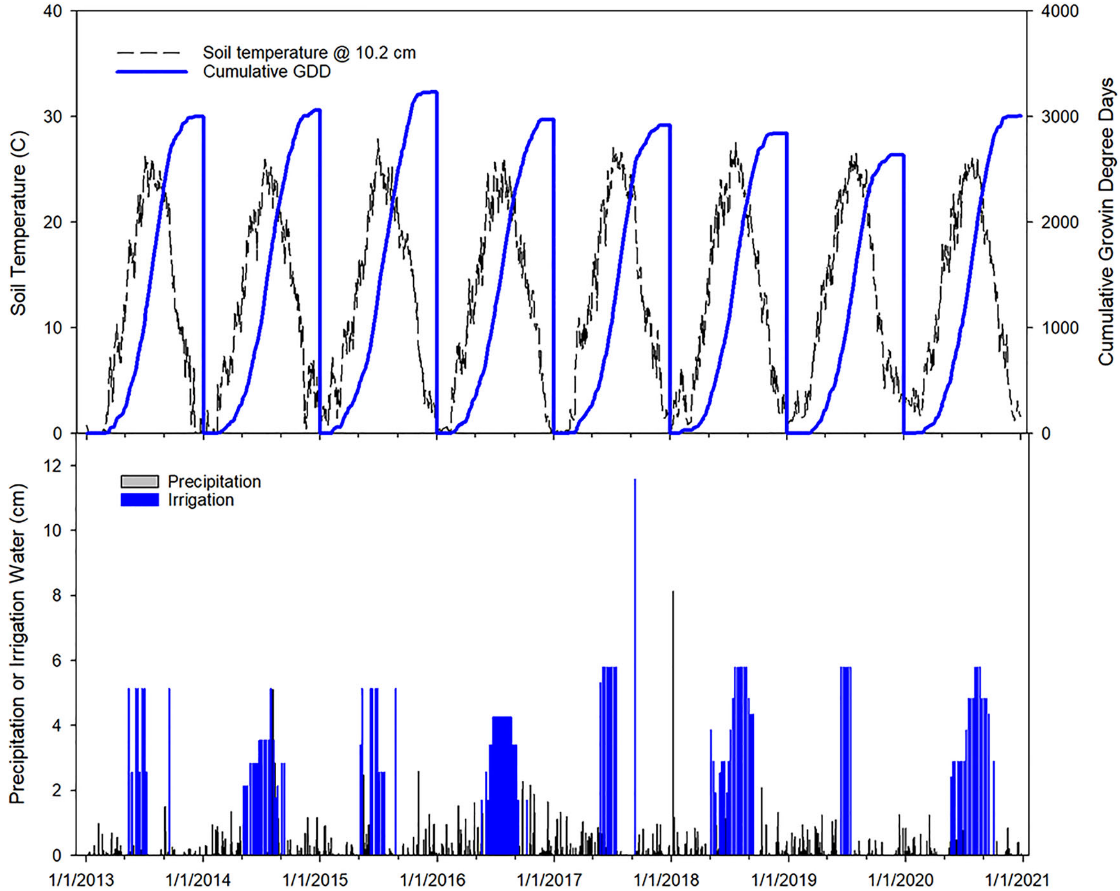

FIGURE 2 Soil temperature measured at 10.2 cm and cumulative growing degree days (GDD) each year over the study time period, precipitation, and cumulative irrigation water applied over study period. Data obtained from Twin Falls (Kimberly) Idaho AgriMet Weather Station 7E.

the local Agrimet weather station (<1 km from field site; US Bureau of Reclamation) is shown in Figure 2. Soil temperature ranged from −3.5 to 27.9˚C across years with annual averages ranging from 11.1 to 12.9˚C. Cumulative annual GDD ranged from 2842 to 3232 over the course of the study. During deployment of the buried bags, the average air temperature ranged from 16.5 to 19.5˚C and cumulative GDD ranged from 2007 to 2753 (Table 4).

3.2 | Soil properties

Soil samples were collected each year in the spring and analyzed for a variety of parameters that influence in-season N mineralization. Soil characteristics in the spring of the eighth and final year of the study (2020) are reported in Table 5. Eight years of manure application resulted in linear increases in SOM for both annual and biennial manure application rates. At the highest application rates, SOM increased by 116% and 47%, over the control, for the annual and biennial applications, respectively. All manure treatments had a greater SOM than fertilizer and control at the culmination of the study period.

Total soil N was greater in manure-treated plots than control and fertilizer plots reaching a maximum of 2.7 g·kg^{-1} in the 52A treatment, representing an 80% increase over the control. Soil NO_3–N concentrations were greater in manure treatments than control and fertilizer treatments and had a linear increase within the annual manure application rates with a maximum of 124 mg·kg^{-1} for the 52A treatment. Soil EC was greater in manure versus control and fertilizer plots and the annual manure application rate had a linear increase in EC with a maximum of 2.7 dS·m^{-1} for the 52A treatment.

In addition to supplying N and C, manure is also a good source of both macro- and micronutrients that are essential for plant growth and may also affect microbial activity and hence N mineralization in soils. As cumulative manure applications (on a dry matter basis) increased over the course of the study, total soil N as well as bicarbonate extractable P and K also increased linearly with r^2 values of 0.76, 0.88, and 0.86, respectively (Figure 3). Some soil micronutrients, namely, B, Cu, and Zn, also had a somewhat linear response to manure

TABLE 5 Preplant soil properties in spring of 2020 by treatment, combined over the 0- to 60-cm depth.

Soil properties	18A[a]	36A	52A	18B	36B	52B	Fertilizer	Control
Year	2020							
SOM, g·kg^{-1}	26 ± 2	33 ± 3	41 ± 4	23 ± 2	24 ± 2	28 ± 4	21 ± 1	19 ± 1
N, g·kg^{-1}	1.9 ± 0.2	2.4 ± 0.2	2.7 ± 0.3	1.9 ± 0.5	1.8 ± 0.1	2.0 ± 0.3	1.7 ± 0.2	1.5 ± 0.1
NO_3–N, mg·kg^{-1}	65.1 ± 14.7	74.9 ± 10.8	124.0 ± 21.8	43.0 ± 4.6	41.6 ± 9.8	47.6 ± 7.1	36.2 ± 3.2	14.9 ± 1.5
NH_4–N, mg·kg^{-1}	5.1 ± 2.4	7.0 ± 4.8	7.7 ± 3.9	6.1 ± 2.9	3.4 ± 1.7	4.2 ± 2.8	5.6 ± 2.5	6.5 ± 2.8
pH	7.8 ± < 0.1	7.8 ± 0.1	7.7 ± 0.1	7.9 ± 0.0	7.9 ± < 0.1	7.9 ± 0.1	7.9 ± 0.0	7.9 ± 0.0
EC, dS·m^{-1}	1.4 ± 0.2	1.6 ± 0.1	2.7 ± 0.1	0.9 ± 0.07	1.1 ± 0.1	1.1 ± 0.1	0.9 ± 0.11	0.6 ± 0.07

Note: pH and electrical conductivity are averages of the top 60 cm.

Abbreviations: EC, electrical conductivity; SOM, soil organic matter.

[a] 18A = manure applied annually at a rate of 18 Mg·ha^{-1}; 36A = manure applied annually at a rate of 36 Mg·ha^{-1}; 52A = manure applied annually at a rate of 52 Mg·ha^{-1}; 18B = manure applied every other year starting in 2012 at a rate of 18 Mg·ha^{-1}; 36B = manure applied every other year starting in 2012 at a rate of 36 Mg·ha^{-1}; 52B = manure applied every other year starting in 2012 at a rate of 52 Mg·ha^{-1}. All rates on a dry weight basis.

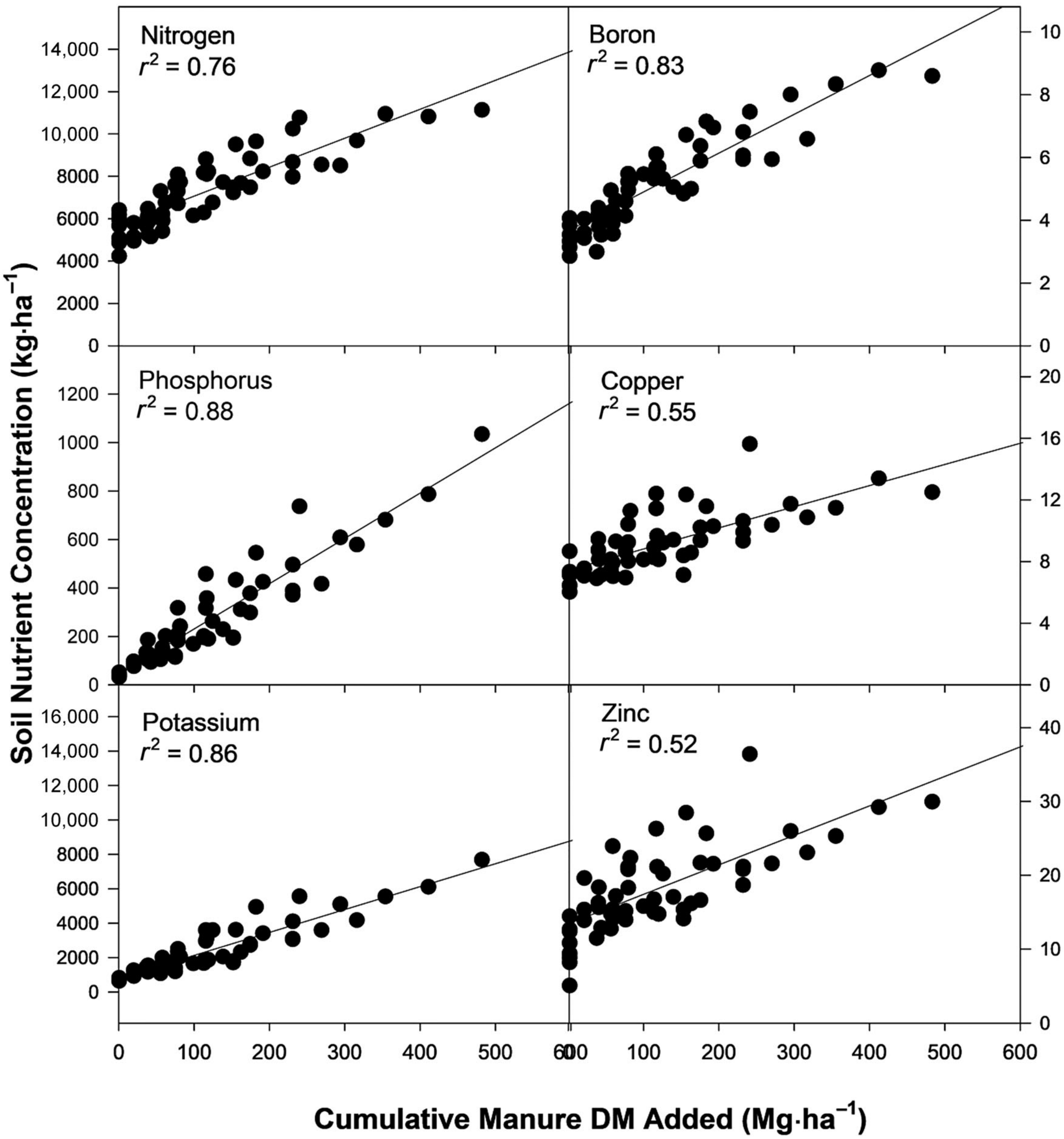

FIGURE 3 The relationship between the amount of manure added and soil accumulation of nitrogen, phosphorus, potassium, boron, copper, and zinc.

additions with r^2 values of 0.83, 0.55, and 0.52, respectively (Figure 3).

3.3 | Plant residue N and C returned to soil

When sugarbeet and potato were harvested, the top biomass was chopped and left in the field as residue. Additionally, in 2014, sugarbeets were not bulk harvested due to the dry conditions in the field. The residue N returned to the soil from sugarbeets ranged from 137 to 463 kg N·ha^{-1} in 2014 (tops + roots) and 20 to 198 kg N·ha^{-1} in 2018 (tops only; Table 2). The residue N returned to the soil following potatoes in 2016 ranged from 34 to 149 kg N·ha^{-1}. The C returned to the soil from sugarbeet residue in 2014 and 2018 ranged from 0.4 to 11 Mg C·ha^{-1}, whereas the C returned to the soil from potato residue in 2016 ranged from 0.8 to 2 Mg C·ha^{-1} (Table 3). The C:N ratio of residue returned as sugarbeets in 2014 ranged from 11 to 17 for the tops and 41 to 122 for the roots. The C:N ratio of residue returned as sugarbeet tops in 2018 ranged from 12 to 20, while the C:N ratio of residue returned as potato tops in 2016 ranged from 12 to 23. In all instances, the C:N ratio of the residue decreased as the amount of manure N applied increased (due to increased tissue N concentration with manure application), with the controls having the highest C:N ratio (data not shown).

3.4 | Net IN release rates

The rate of Net IN release over the growing season ranged from 0.33 to 2.95 mg N·kg^{-1}·week^{-1} in the 0- to 30-cm soil depths and 0.01 to 0.76 mg N·kg^{-1}·week^{-1} in the 30- to 60-cm soil depths (Table 6). There was a significant effect of year, depth, treatment, year × depth, and depth × treatment on the rate of Net IN release over time. The average Net IN rate in the 0- to 30-cm depth (1.37 mg N·kg^{-1}·week^{-1}) was 4.5 times greater than in the 30- to 60-cm depth (0.25 mg N·kg^{-1}·week^{-1}). The greatest rate of Net IN release (combined over treatment and depth) occurred in 2017 and 2019 (1.13 mg N·kg^{-1}·week^{-1}), followed by 2015 and 2016 (0.83 mg N·kg^{-1}·week^{-1}) with few differences between the remaining years (0.55–0.74 mg N·kg^{-1}·week^{-1}). The highest manure application rate 52A (1.22 mg N·kg^{-1}·week^{-1}) had the greatest Net IN release rate, while the fertilizer and control (0.46–0.53 mg N·kg^{-1}·week^{-1}) had the smallest rate (combined over depth and year). The rate of Net IN (mg N·kg^{-1}) release versus GDD was determined for the 0-to 30-cm depth, as this depth generated the greatest amount of IN over the season. Combined over treatments, the years 2015, 2017, and 2019 had the greatest rate of Net IN release (0.019–0.021 mg N·kg^{-1}·GDD^{-1}), while the remaining years had few differences. There were few differences between treatments (combined over year); however, the annual manure applications had the greatest rates of Net IN release (0.015–0.022 mg N·kg^{-1}·GDD^{-1}) followed by the biennial applications and the control, and fertilizer had the lowest rates (0.006–0.008 mg N·kg^{-1}·GDD^{-1}).

3.5 | Net seasonal IN mineralization

Average Net IN$_s$ ranged from –6.3 to 297.4 kg N·ha^{-1}, with only one negative value (2013, 52A, 30–60 cm) representing N fixation (Figure 4). There was a significant effect of year, depth, treatment, treatment × depth, and year × depth on Net IN$_s$ ($p < .0001$). Net IN$_s$ in the top 30 cm (35.7–297.4 kg N·ha^{-1}) was nearly five times greater than that in the 30- to 60-cm depth (–6.3 to 87.9 kg N·ha^{-1}) and represented >83% of total N_{min} over the 0- to 60-cm depth (averaged across year and treatment). Net IN$_s$ followed the trend 2019 > 2015 = 2017 > 2016 > 2013, 2018, 2020, 2014 (2013 > 2014 only). Averaged across years and depth, there was a significant effect of treatment on Net IN$_s$ following the trend 52A > 52B = 36A = 36B = 18A > 18B = fertilizer = control. Net IN$_s$ did not differ between the control and synthetic fertilizer plots and ranged from 45 to 150 kg N·ha^{-1}, suggesting that addition of synthetic fertilizer alone did not enhance N mineralization. The greatest N mineralization rate from the control/synthetic fertilizer occurred in 2019 followed by 2015, 2016, and 2017 (average 112 kg N·ha^{-1}), indicating that residue N affected mineralization in the control plots. On average, excluding years following residue N contributions, Net IN$_s$ was 72 kg N·ha^{-1} from control/synthetic fertilizer plots.

The years 2015, 2017, and 2019 followed sugarbeet or potato crops where the aboveground biomass (and roots from sugarbeets in 2014) was left in the field after harvest the previous fall. In these years, both the rate of Net IN release over time and GDD (0- to 30-cm depth) and the Net IN$_s$ were greater than the other years, suggesting that crop residue was accelerating N mineralization. Years where both manure and residue N were added the previous fall (annual and biennial applications in years 2015, 2017, and 2019) were significantly different than the remaining years; therefore, these were grouped for further analyses. We also grouped treatments that had manure N only the previous fall and treatments where no manure and residue were added the previous year (representing second-year mineralization rates; biennial application in years 2014, 2016, 2018, and 2020) for further analyses.

TABLE 6 The average rate of inorganic nitrogen release over the course of the growing season by year, treatment, and soil depth.

Year	Treatments							
	18A[a]	36A	52A	18B	36B	52B	Fertilizer	Control
	mg N·kg^{-1}·week^{-1}							
0–30 cm								
2013	1.08	1.27	1.73	1.03	1.13	1.46	0.78	0.77
2014	1.05	1.41	1.31	0.55	0.91	0.91	0.41	0.54
2015	1.45	2.01	2.95	0.67	1.98	1.95	0.33	0.83
2016	1.14	1.31	1.88	0.78	1.38	1.36	0.79	1.06
2017	1.77	2.29	2.73	1.41	2.01	2.87	0.99	1.03
2018	1.07	1.48	1.49	0.75	0.92	1.40	0.52	0.61
2019	2.03	2.55	2.71	1.63	2.33	2.20	1.29	1.38
2020	1.23	1.63	2.12	1.09	1.45	1.35	0.68	0.75
30–60 cm								
2013	0.20	0.19	0.27	0.20	0.16	0.21	0.27	0.09
2014	0.13	0.26	0.24	0.15	0.16	0.37	0.16	0.18
2015	0.16	0.21	0.14	0.06	0.08	0.25	0.06	0.01
2016	0.69	0.50	0.37	0.35	0.46	0.45	0.44	0.32
2017	0.43	0.47	0.55	0.31	0.39	0.45	0.23	0.27
2018	0.22	0.05	0.76	0.19	0.29	0.32	0.14	0.17
2019	0.23	0.35	0.38	0.21	0.33	0.21	0.08	0.26
2020	0.25	0.14	0.33	0.19	0.11	0.21	0.14	0.23

[a]18A = manure applied annually at a rate of 18 Mg·ha^{-1}; 36A = manure applied annually at a rate of 36 Mg·ha^{-1}; 52A = manure applied annually at a rate of 52 Mg·ha^{-1}; 18B = manure applied every other year starting in 2012 at a rate of 18 Mg·ha^{-1}; 36B = manure applied every other year starting in 2012 at a rate of 36 Mg·ha^{-1}; 52B = manure applied every other year starting in 2012 at a rate of 52 Mg·ha^{-1}. All rates on a dry weight basis.

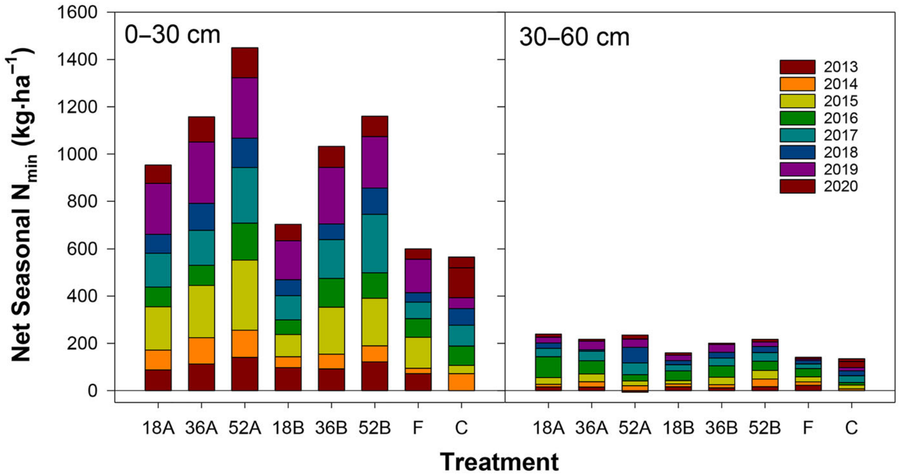

FIGURE 4 Measured net seasonal nitrogen mineralization (N = NO_3–N + NH_4–N) from 2013 to 2020 by treatment for the 0- to 30-cm depth (left panel) and 30- to 60-cm depth (right panel).

Net IN_s from the combined 0- to 60-cm depths ranged from 52 to 317 kg·ha^{-1} (Figure 5). There was a positive linear relationship between the amount of N added as manure + residue (kg N·ha^{-1}) and Net IN_s in the 0- to 60-cm depth with a slope of 0.17 (r^2 = 0.57). When there was only manure N applied the previous fall, there was a weaker linear relationship (r^2 = 0.49) and the slope decreased to 0.07. This relationship improved if 2016 was dropped (r^2 = 0.56, slope = 0.08). The Net IN_s in 2016 was greater than the other years when only manure N was applied the previous fall, although it is unclear why this trend occurred. Second-year Net IN_s had a similar slope (0.08) as treatments receiving

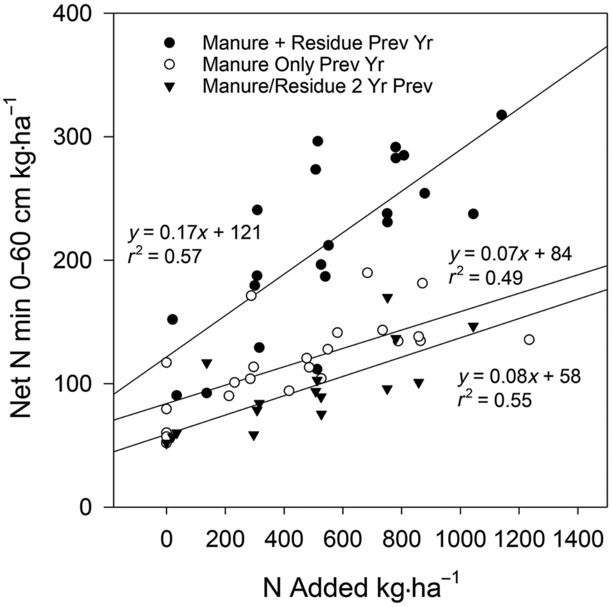

FIGURE 5 Net seasonal nitrogen mineralized in the top 60 cm of soil versus nitrogen added with manure and broadleaf crop residue. Data were broken out into three groups representing years and treatments where manure plus plant residue was incorporated the previous fall, manure only was incorporated the previous fall, and manure and/or residue was incorporated in the fall 2 years previously.

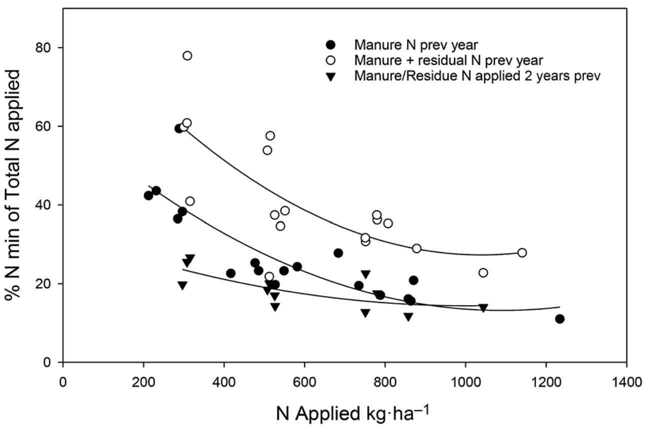

FIGURE 6 The percent nitrogen mineralization (of total N applied) in the top 60 cm of soil versus nitrogen added with manure and broadleaf crop residue. Data were broken out into three groups representing years and treatments where manure plus plant residue was incorporated the previous fall, manure only was incorporated the previous fall, and manure and/or residue was incorporated in the fall 2 years previously.

only manure the previous year ($r^2 = 0.55$). The % N_{min} each year was greater for plots that had both manure and residue N additions and ranged from 21% to 78% (Figure 6). When only manure was added the previous year, the % N_{min} ranged from 11% to 59%. Second-year % N_{min} rates ranged from 12% to 27% of the N applied 2 years prior. In all instances, there was a decrease in the % N mineralized of TN added as N applications increased.

The cumulative N_{min} versus the cumulative amount of N applied over the 8 years for annual manure treatments (including years with crop residue) ranged from 24% at the highest manure application rate (52A) to 46% for the lowest rate (18A) with an average of 33%. Biennial application of manure resulted in a greater cumulative N_{min} as a percentage of N applied and ranged from 40% at the highest manure application rate (52B) to 60% at the lowest manure application rate (18B), with an average of 51%. When adjusted for the IN released by the control plots, the seasonal % Net N_{min} in the years with manure + residue was greatest, averaging 20%, followed by years with previous manure application only (10.5%) and second-year N mineralization (4.6%).

3.6 | Predicting N mineralization with soil, manure, and plant residue parameters

Net IN_s in the 0- to 60-cm depth was correlated ($p < 0.01$) to preplant soil TN ($r = 0.55$), SOM ($r = 0.53$), EC ($r = 0.41$), and average ambient air temperature ($r = -0.64$; Table 7). These variables, as well as soil TN, total C, SOM, NO_3–N, NH_4–N, pH, cumulative GDD, and the amount of N added with manure and residue remaining in the field the previous fall, were used as predictor variables to estimate Net IN_s. The best fit model selected based on Mallows' C_p selection method included manure N, residue N, SOM, and EC (Table 8). Other models were investigated that would be valuable for estimating N mineralization based on commonly measured parameters. Both manure N and residue N were included in all models as they represent the N inputs to the system in any given year. The initial TN or SOM status of the soil were included to represent pools of N available for mineralization. The soil EC was included as continued application of manure can create a potential salt problem, which could negatively impact microbial activity. We also included GDD in two models to account for potential regional climatic differences. Five empirical models were selected that included (1) manure N, residue N, SOM, and soil EC; (2) manure N, residue N, SOM, soil EC, and GDD; (3) manure N, residue N, soil TN, soil EC, and GDD; (4) manure N, residue N, soil TN, and soil EC; and (5) manure N, residue N, and soil TN (Table 8). Models were all significant ($p < 0.0001$) with adjusted R^2 ranging from 0.67 to 0.76. The best model fit was with Equation (1) (manure N, residue N, SOM, EC), with a Mallows' C_p of 3.7 and Akaike information criteria (AIC) of 377.4. The poorest predictive model only included soil TN in addition to added N from manure and residue and had a Mallows' C_p of 26.6 and AIC of 417.5. The VIF for all model variables in all equations was 6 or less, with tolerance values ≥0.17.

TABLE 7 Correlations ($N = 56$) between net seasonal nitrogen mineralization, preplant soil properties, average air temperature over the growing season, and growing degree days (GDD) over buried bag installation.

	Net IN_s	TN	SOM	NO_3–N	NH_4–N	EC	pH	Air temperature	GDD
Net IN_s	1	0.55***	0.53***	0.33*	0.19 NS[†]	0.41**	–0.19 NS	–0.64***	0.19 NS
TN		1	0.77***	0.54***	0.13 NS	0.35**	–0.05 NS	–0.20 NS	–0.34**
SOM			1	0.68***	0.13 NS	0.72***	–0.46**	–0.14 NS	0.01 NS
NO_3–N				1	0.24 NS	0.79***	–0.69***	0.18 NS	–0.18 NS
NH_4–N					1	0.005[NS]	–0.03 NS	–0.41**	–0.16 NS
EC						1	–0.86***	0.11 NS	0.26 NS
pH							1	–0.21 NS	–0.32*
Air temperature								1	–0.38**
GDD									1

Abbreviations: EC, electrical conductivity; SOM, soil organic matter; TN, total nitrogen.
*Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significnat at the 0.001 probability level. †NS, not significant.

TABLE 8 Equations derived from forward stepwise regression to predict net seasonal nitrogen mineralization based on nitrogen additions (manure and residue), preplant soil properties, and growing degree days (GDD) ($N = 56$).

Equation	Regression	*p*-value	Adjusted R^2	Mallows' C_p	AIC
1	0.22MN + 0.39RN[a] + 1.4SOM – 104EC + 45.8	<0.0001	0.76	3.7	377.4
2	0.22MN + 0.41RN + 1.3SOM – 102EC – 0.02GDD + 90.0	<0.0001	0.77	4.2	377.6
3	0.20MN + 0.38RN + 12.0TN – 80.0EC + 0.008GDD + 59.0	<0.0001	0.76	5.1	378.6
4	0.20MN + 0.38RN + 11.6TN – 75.6EC + 79.5	<0.0001	0.75	7.1	381.0
5	0.06MN + 0.34RN + 11.0STN + 27.8	<0.001	0.67	26.6	417.5

Abbreviations: AIC, Akaike information criteria; EC, electrical conductivity; GDD, growing degree days; MN, manure nitrogen ($kg·ha^{-1}$); RN, residue nitrogen ($kg·ha^{-1}$); SOM, soil organic matter ($MT·ha^{-1}$); STN, soil total nitrogen ($MT·ha^{-1}$); TN, total nitrogen.
[a]Residue N is the N contribution from the broadleaf aboveground biomass left in the field in the fall following harvest of potato tubers and sugarbeet roots, and the N contribution from sugarbeet roots not harvested in 2014.

4 | DISCUSSION

Fall-applied solid dairy manure provided a steady supply of N over the course of the growing season. Average cumulative % N_{min} for annual manure applications (33% of TN applied) was similar to N mineralization rates (32%–41%) from cattle manure on a calcareous soil with low soil organic carbon content in Greece (0.55%–1.8%; Antoniadis, 2013). The 0- to 30-cm depth was the driver of TN mineralization in the soil, similar to other work in the region (Rogers et al., 2018). Average cumulative % Net N_{min} (control subtracted) from treatments with fall-applied manure only (10.5%) was within the range (4%–28%) of that reported in other field studies (Alizadeh et al.;, 2012; Ige et al., 2015; Lehrsch et al., 2016; Moe et al., 2020).

Mineralization rates are driven by manure composition, C:N ratio of the manure, N content of the manure, texture of the soil, soil temperature, and soil moisture (Antoniadis et al., 2013; Ige et al., 2015; Moe et al., 2020; Pedersen et al., 2020). The N compounds found in dairy manure are a combination of endogenous N from within the digestive tract of the animal and fiber N, with the endogenous N being more quickly mineralized (Powell & Broderick, 2011). Cattle manure tends to have higher amounts of lignin–cutin compounds compared to poultry or swine as well as other N fractions with a high level of recalcitrance that are more resistant to degradation and subsequently provide a long-term supply of N (Aranguren et al., 2021; Artur et al., 2021). Several studies have reported that as the C:N ratio of the manure increases, mineralization decreases (Alizadeh et al., 2012; Antoniadis et al., 2013; Bhogal et al., 2016; Heijboer et al., 2016; Ige et al., 2015). In the present study, dairy cattle manure that had been handled as a solid and stacked for a few months prior to application may have had more recalcitrant N than other types of cattle manure (slurry, liquid) or fresh solid manure, which may explain why the % N mineralization was at the lower end of the range reported in the literature, even though the C:N ratio was somewhat low (~15 on average).

The addition of potato and sugarbeet crop residue with manure application the previous fall increased N mineralization by up to 50% having an average % N_{min} of 41% and % Net N_{min} of 20%. Several studies have reported enhanced N mineralization (39%–54%) of a variety of plant residues (clover, rapeseed waste, alfalfa silage) versus manure that was attributed to the characteristics of the residue such as the lignin content and C:N ratio (Hossain et al, 2021; Masunga et al., 2016; Tamele et al., 2020). Alternatively, residues with high C:N ratio (e.g., barley and wheat straw) can force microbial communities to immobilize N and thus, the source and characteristics of the residue are important (Cleveland & Liptzin, 2007; Reichel et al., 2018; Scheller & Joergensen, 2008).

De Neve and Hofman (1996) reported that 25%–86% of total organic N added to soil as vegetable crop residues (leaves and stems from bean, broccoli, celery, turnip, endive, cabbage, lettuce, fennel, cauliflower, and endive root) was mineralized over a 3- to 4-month period, with N mineralization related to the characteristics of the vegetation. The highest mineralization rates in the study by De Neve and Hofman (1996) were from plant leaves, which mineralized 56%–78% of TN added. Leaf decomposition and N mineralization are faster than other plant tissues due to the lower C:N ratio and reduced lignin contents, and the process is sped up by incorporation of the plant residues, as was done in the present study (Cherr et al., 2006; Radicetti et al., 2017). Radicetti et al. (2017) reported that 67%–83% of TN was mineralized from crop residue (hairy vetch, oat, and oilseed rape) within 120 days following incorporation in the spring. In the present study, sugarbeet leaves were incorporated into the soil in the fall after harvest in 2014 (C:N of 14) and 2018 (C:N of 15), while potato tops (leaves + vines, C:N of 16) were incorporated in the fall of 2016. In addition, beet roots (average C:N of 76) were left in the field in the fall of 2014. The addition of these residues likely affected microbial activity and possibly the microbial community composition, enhancing the overall N mineralization the following year. Heijboer et al. (2016) reported that the C:N ratio and lignin contents of organic amendments (cattle manure, maize silage, lucerne silage, and wheat straw) affected the microbial biomass, microbial activity, and microbial community composition and therefore N mineralization in amended soils. Although the C:N ratio of the manure and silage residue was similar, the effects on the soil microbial communities were different resulting in more recalcitrance of manure N as compared to silage residue N (Heijboer et al., 2016).

The second-year % N_{min} (18%) and % Net N_{min} (4.6%) were 47% and 70% lower, respectively, than when manure + residue or manure only was applied the previous fall. A decaying rate of N mineralization over time following a one-time application of manure has been reported previously, with reductions in N min from 2% to 91% in the second year compared to the first (Lentz & Lehrsch, 2012; Lentz et al., 2011; Pedersen et al., 2020). For all treatments in the present study, there was a decreasing rate of % N_{min} with increasing rate of N application. As more N is added into the system, the efficiency of conversion from organic N to IN is reduced. Therefore, N mineralization is not strictly a function of the quantity of manure and residue applied, and smaller applications may be more effective at supplying N on a per unit mass of manure/residue applied. Lentz and Lehrsch (2012) reported that the efficacy of N mineralization processes decreased as manure applications increased and therefore suggested that using a single decay series to predict N mineralization could lead to substantial errors. The use of a single decay series based only on characteristics of the amendment also overlooks the critical impact of soil characteristics and climate on N mineralization.

Microbial processes that drive N mineralization are affected by a variety of factors associated with the substrate, soil, and climate. The Net IN_s in the present study was correlated to preplant soil characteristics such as soil TN, SOM, and EC. Ashraf et al. (2020) reported that N mineralization was enhanced by soil-dissolved organic C, bicarbonate-extractable P, and soil N availability, which enhance the size of the microbial biomass and enzyme activities. In the present study, as manure application rates increased, there was a concurrent increase in soil N and P potentially enhancing microbial processes. In 2019, Dungan et al. (2022) evaluated a variety of soil health indicators in soils from the present study. They reported that potentially mineralizable N, microbial biomass N, and potential ammonia oxidation rates, as well as a variety of other biological indicators, increased with increasing manure application rates with both annual and biennial applications. Wang et al. (2022) also reported that long-term application of organic amendments increased microbial abundances as well as enhanced soil enzyme activities affecting N mineralization. Cassity-Duffy et al. (2018) utilized soils in the present study to determine the effects of temperature on N mineralization and determined that GDD provided a good predictor of net N mineralization.

In an effort to provide producers with a reliable method to estimate N mineralization over the growing season, we derived five empirical models using routinely measured parameters to predict N mineralization based on the amount of N being added (either as manure or broadleaf crop residue) along with preplant soil measurements (soil TN, SOM, and EC) and effect of climate (as GDD). The model with the best prediction included manure N, residue N, soil OM, and soil EC ($R^2 = 0.76$, $p < 0.0001$). The positive effects of SOM on microbial activity and organic N source were captured, along with the potential negative effects of elevated salt loading

(EC) that can occur under continual manure application. We feel this is an improvement over use of a single decay series to predict N mineralization as it captures not only the amount of N added but other soil variables that influence N mineralization rates. This model allows producers to utilize simple preplant soil characteristics along with N amendment rates to estimate seasonal N availability, thereby enabling better N management and overall N use efficiency.

In summary, manure management will continue to be a critical part of dairy operations, and detailed understanding of N mineralization will allow improved strategies for use on a range of crops. This is particularly important in crops with quality parameters that are sensitive to N and thus, this research will potentially increase the land area on which manure can be applied. Results from the study provide evidence of the relative contribution of manure, residue, and soil parameters in determining N mineralization amounts seasonally. While manure application rates, specifically N content, are an important factor for estimation of N mineralization, additions of broadleaf residues, such as sugarbeet leaves and potato tops, must be considered in manure-amended systems as these additions alter N mineralization. The SOM and soil EC were also important parameters for determining the best-fit model representing a source of both C and N as well as an understanding that enhanced soil salinity through high rates of manure applications over long time periods is important as it alters microbial community function. Further, our research on N mineralization from dairy manure in semiarid production areas and crop data will provide greater understanding of specific crop response under a range of manured conditions in calcareous soils. Finally, the developed model for N mineralization from dairy manure and broadleaf crop residue is a substantial improvement, as estimation tools are currently unavailable in the region and should be incorporated into manure fertilizer recommendations for cropping systems.

AUTHOR CONTRIBUTIONS

April B. Leytem: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Amber D. Moore**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; writing—review and editing. **Christopher W. Rogers**: Formal analysis; writing—review and editing. **Robert S. Dungan**: Investigation; resources; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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