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REVIEW

Post-harvest crop residue contribution to soil N availability or unavailability in North Dakota

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Abstract
North Dakota producers have adopted conservation tillage practices to conserve soil moisture and reduce wind and water erosion. As a result, an accumulation of crop residue has been observed but current recommendations encourage a fertilizer N credit in fields under no-till for more than 6 yr. Producers are concerned that post-harvest crop residues are not contributing to N needs of subsequent crops during the growing season. This study was established to assess N mineralization from common crop residue in conventional tillage systems using long-term incubation studies in order to establish a baseline for future studies on no-till systems. Three commonly cultivated North Dakota soil series were selected for study with seven residue treatments (varying C/N ratios) including corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], flax (*Linum usitatissimum* L.), forage radish (*Raphanus sativus* L.), winter pea (*Pisum sativum* L.), spring and winter wheat (*Triticum aestivum* L.), and a soil-only control. Biweekly leachings were collected for nine incubation periods and analyzed for nitrate-nitrogen (NO_3–N). Soils with higher organic matter (OM) resulted in increased soil N mineralization (Fargo [1.63 mg kg^{-1} N] > Forman [0.65 mg kg^{-1} N] > Heimdal–Emrick [0.38 mg kg^{-1} N]). Radish and pea residues (narrow C/N ratios) were the only treatments showing N mineralization potential compared with the soil only controls. However, post-harvest residues with wide C/N ratios (>25:1) promote N immobilization when compared with mineralization by the soil alone. These findings raise the question of whether the N credits for >6 yr of no-till management are appropriate in the northern Great Plains.

Abbreviations: EC, electrical conductivity; FL, flax; NH_4^+–N, ammonium-nitrogen; NO_3^-–N, nitrate-nitrogen; OM, organic matter; WP, winter pea; R, forage radish; SB, soybean; SW, spring wheat; WW, winter wheat.

1 | INTRODUCTION

North Dakota, a top U.S. producer of spring wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and forage crops, has more than 11 million hectares of cropland (USDA, 2018). Approximately 5.7 million hectares of this cropland is managed under no-till or conservation tillage management practices (USDA, 2015), and in many instances, these practices have been utilized for more than three decades. In these long-term no-till systems, accumulation of up to 8–10 Mg ha^{-1} of post-harvest residue has been observed (Aher et al., 2016). Because of the region's frigid climate, residue decomposition and nutrient mineralization from these residues can be limited by a short frost-free growing period of 100–135 d (NOAA, 2020). In addition, post-harvest crop residues generally have high C/N ratios (low N content) which can deter rapid decomposition (Lynch et al., 2016). Recent changes in fertilizer N recommendations for North Dakota have included a 56 kg ha^{-1} N credit (reduction) when fields are continuously under no-till management for more than 6 yr. In contrast, fields under no-till management for less than 6 yr have a requirement of an additional 22 kg N ha^{-1} (Franzen, 2018). In light of the work of Aher et al. (2016), it is unclear whether adequate N is being mineralized from the residue for use by subsequent crops, or if additional N fertilizer is needed to compensate for the residue. Information on N mineralization from crop residues with conventional tillage in the northern Great Plains is scant and this information is needed in order to evaluate these current recommendations. Crop residue on the soil surface can lower soil temperature and increase soil moisture by itself, but residue contact with the soil when remaining on the surface is also limited (Lynch et al., 2016). This slows the residue decomposition and N mineralization process impacting N availability for crops. Earlier studies examining this same topic have concluded that in a no-till system, effective N fertilizer management strategies are critical and fertilizer N additions may be required to compensate for an N supply shortage deeper in the soil profile (Bakermans & deWit, 1970; Bandel, 1979; Bandel et al., 1975).

By understanding the decomposition and N release of common crop residues, producers in the northern Great Plains environment can better determine fertilizer management strategies. Franzen et al. (2011) examined wheat yields from conventional and no-till systems and concluded that similar yields could be achieved with a ≥56 kg N ha^{-1} reduction in no-till systems over conventionally tilled systems. However, factors such as differences in stored soil moisture between cropping systems and residue load were not evaluated. In 2016, this recommendation was revised to take into consideration the length of time since a field had been under no-till management (Franzen et al., 2016). Further revisions were made in 2018 to integrate a more systematic approach to take into consideration gross optimal available N, soil test NO_3–N, previous crop residue type, time under no-till implementation, and soil organic matter (Franzen et al., 2018). In contrast, several states in the northern United States have recommended that N should be added in long-term no-till systems when heavy crop residues are present (Bundy, 1998; Clark, 2019; Jokela et al., 2004; Ketterings et al., 2003; Pariera Dinkins & Jones, 2019).

Currently, most N management recommendations in the northern United States do not take into consideration temporal residue decomposition and N mineralization and immobilization effects of varying crop residues, but instead cite standardized recommendations. The decomposition rate of different crop residues is directly affected by multiple factors, two of them being the quality and source of residue (Aher et al., 2016; Chatterjee et al., 2016; Johnson et al., 2007). Soil pH, soil moisture, and soil temperature have a direct impact crop residue decomposition due to its effect on the microbial community and its activity (Haynes, 1986; Miller & Johnson, 1964; Sabey, 1969). The C/N ratio is one measurement that has been utilized to assess decomposability of crop residue. Previous research (Li et al., 2015; Lynch et al., 2016) determined that a narrow C/N ratio improves residue decomposition and N mineralization, useful for subsequent crop growth, as compared with other crop residues with a wide C/N ratio (>25:1). The study by Aher et al. (2016) examined the C/N ratio in both fresh and aged crop residue, finding a narrower C/N ratio (less than or equal to 25:1) in the aged residue, due to higher C content in fresh residue, some of which is lost due to oxidation, decomposition, or leaching due to exposure to weathering between cropping seasons. This study also indicated that additional fertilizer N may be needed to compensate for the high C levels in the residues. Additionally, Alghamdi et al. (2021) examined the soil temperature and moisture regime among various conservation tillage practices in North Dakota and Minnesota and found an inconsistent relationship between crop yield and soil moisture, but noted

Core Ideas

- Common crop residues of North Dakota were evaluated for N availability under controlled conditions.
- High organic matter soils showed greater potential for N mineralization from high C/N crop residues.
- Residue decomposition did not affect soil pH during incubation due to cation buffering.
- Nitrogen from crop residue accumulated in North Dakota field is generally unavailable to subsequent crops.

that proper fertilizer application was shown to have greater influence than the tillage implements used.

Economics and environmental considerations driving precise nutrient application to crops require nutrient application adjustments based on actual crop needs. Standardized recommendations are useful in warmer and more moist climates which allow for optimum and more consistent N mineralization from crop residue. However, in cooler climates with highly variable precipitation, the rate of residue decomposition is less predictable, resulting in less certain N mineralization. This brings to question if changes are necessary in N management for no-till production in the cooler climates of the northern Great Plains and other parts of the United States (Alghamdi & Cihacek, 2021). Research in the region has not yet validated N availability of specific crop residues, which is essential to determine if producer fertilizer application needs are being met. There are a variety of crops grown in North Dakota, many of them are grown under conservation tillage or no-till conditions. To examine soil N mineralization potential, Stanford & Smith (1972) suggested long-term incubation studies under controlled environmental conditions.

The objectives of this research are (a) to measure N mineralization potential for individual crop residue common in North Dakota; (b) to evaluate N mineralization potential within the common soil series of the region; and (c) examine the effect of decomposition of different crop residues on soil pH using long-term incubation studies. This study is the first of a series of laboratory studies to evaluate N cycling from common crop residues under controlled and simulated North Dakota (and northern Great Plains) conditions. Findings from this study will establish plant available N baselines of these crop residues. With this study, we are evaluating N mineralization from common crop residues with methods representing a conventional system (conventional tillage with residue incorporation). This is to differentiate their mineralization characteristics from surface applied residues in conservation tillage systems (no-till).

2 | MATERIALS AND METHODS

2.1 | Experimental design

A laboratory study using a randomized complete block design with three replicates was set up using three soils and seven residue treatments, plus an untreated soil control for each soil. The three soils were from the Fargo (fine, smectitic, frigid Typic Epiaquert) (Soil Survey Staff, 2016), Forman (fine-loamy, mixed, superactive, frigid Calcic Argiudoll) (Soil Survey Staff, 1998a), and Heimdal (course-loamy, mixed, superactive, frigid Calcic Hapludoll) (Soil Survey Staff, 1998b)–Emrick (course-loamy, mixed, superactive, frigid Pachic Hapludoll) (Soil Survey Staff, 2014) soil series. Each soil series contained three replicates of seven residue treatments, plus one untreated control ($n = 24$ total samples for each soil). The seven residue treatments were corn (CN), soybean (SB), flax (FL), forage radish (R), winter pea (WP), spring wheat (SW), and winter wheat (WW). The C/N ratios for the crop residue treatments were: corn (73), soybean (53), flax (77), forage radish (8), winter pea (18), spring wheat (76), and winter wheat (101). Fresh residue was collected immediately in the fall following harvest and analyzed for C and N by high temperature combustion chemical composition using an Elementar Vario Max CNS analyzer during a previous study conducted by Aher, et al. (2016) in 2011 and 2012. Upon collection, residue was oven dried at 60 ˚C and ground in a Wiley mill to pass a <2-mm screen. In addition, those residues were analyzed for phosphorus, crude protein, and their lignin contents near infrared reflectance (NIR) (Table 1). The post-harvest residues were post-senescent while the winter pea and radish were green and growing at collection just prior to a killing frost but pea had not reached maturity at the time of collection. Pea and radish are often used in fall cover crop mixes to provide ground cover and to collect and store mineral N to prevent over winter N loss. These materials were collected from a bio-strip seeding in wheat stubble in the Aher et al. (2016) study.

The Fargo soil series samples were collected near the NDAWN weather station in Fargo, ND (46˚53′47″ N, 96˚48′42″ W). The Forman soil series samples were collected at the Conservation Cropping System Project (Aher et al., 2016) near Forman, ND (97˚38′38″ N, 46˚05′05″ W). The Heimdal–Emrick soil series samples were collected at the Carrington Research Extension Center near Carrington, ND (46˚53′34″ N, 102˚48′46″ W). Bulk soil samples were air-dried, crushed, and sieved through a 2-mm screen. Residue treatment samples ($n = 63$) were prepared containing 15 g of soil mixed with 15 g of quartz sand (20 mesh), to facilitate leaching and enhance aeration in the sample, and 0.5 g of residue. The purpose of having 0.5 g of residue is to mimic crop residue accumulation in conservation tillage. In this study, 0.5 g of crop residue is equivalent to 6.25 Mg ha^{-1} in a field setting calculated as follows (Equations 1 and 2).

$$\text{Surface area of leaching tube} = \pi r^2 = 8.04\ \text{cm}^2 \text{ or } 0.0008\ \text{m}^2 \tag{1}$$

$$\begin{aligned}\text{Residue rate} &= 0.5\ \text{g crop residue}/0.0008\ \text{m}^2 \\ &= 625\ \text{gm}^{-2} \text{ or } 6.25\ \text{Mg ha}^{-1}\end{aligned} \tag{2}$$

Controls ($n = 9$) contained 15 g of soil mixed with 15 g of sand only. Samples were then transferred to labeled glass leaching tubes kept in a controlled-environment constant temperature room at 22 ˚C with moisture at 80% saturation and were

TABLE 1 Initial residue characteristics for total nitrogen (TN), phosphorus (P), acid detergent fiber (ADF), dry matter (DM), neutral detergent fiber (NDF), acid detergent lignin (ADL), crude protein (CP), ash of residue (ASH), and C/N ratios for corn, flax, field pea, forage radish, soybean, spring wheat, and winter wheat as determined by near infrared refectance (NIR)

Residue type	Residue characteristics								C/N ratio
	TN	P	ADF	DM	NDF	ADL	CP	ASH	
	%								
Corn	0.93	0.09	29.1	92.9	55.6	6.07	5.78	6.13	73
Flax	0.83	0.04	46.3	97.6	na	5.76	na	13.3	77
Pea	1.52	0.26	na[a]	91.3	na	na	14.8	10.1	18
Radish	na	na	13.4	91.6	19.1	1.71	23.8	23.2	8
Soybean	0.27	0.23	na	90.2	na	na	8.84	7.62	53
Spring wheat	2.07	0.11	47.4	95.1	na	6.40	6.30	16.3	76
Winter wheat	1.95	0.17	49.2	97.2	na	5.68	5.88	14.8	101

[a]na = No standard available for comparison.

TABLE 2 Initial soil characteristics for nitrate (NO_3–N), phosphorus (P), potassium (K), pH, electrical conductivity (EC), and organic matter (OM) for Fargo, Forman, and Heimdal–Emrick soil series

Soil series	Soil characteristics								
	NO_3–N	P	K	pH	EC	OM	Sand	Silt	Clay
	kg ha^{-1}	μg g^{-1}		pH	ds m^{-1}	%			
Fargo	20	17	530	7.6	0.77	6.2	6.4	37.6	56
Forman	11	15	250	7.6	0.43	5.1	33.6	31.4	35
Heimdal–Emrick	91	17	410	5.8	0.34	4.4	37	39	24

incubated as described by Stanford & Smith (1972) using a humidifier to ensure consistent air moisture levels during the incubation study. The controlled temperature simulated soil temperatures that may be expected under field conditions with a crop residue cover in North Dakota (NDAWN, 2020). Before the mixed samples and controls were transferred to the leaching tubes, a small amount of glass wool was placed in the bottom of the leaching tubes to prevent soil sediment loss during leaching. After the mixed soil samples were transferred to the leaching tubes, glass wool was also placed at the top of the leaching tubes to prevent soil disturbance during leaching solution application. The soils were characterized for electrical conductivity (EC), organic matter (OM), plant available N, P, and K by the North Dakota State University Soil Testing Laboratory (Table 2) using standard NCERA-13 methods (Nathan & Gelderman, 2015). Although residue remains on the soil surface in no-till systems, in this research, we incorporated the residue into the soil in order to maximize N mineralization from these crop residues and to evaluate potential N contribution by these residues during a simulated growing season.

Soil textural analysis was performed using the hydrometer method (Bouyoucos, 1962). An initial leaching of the samples was done using 50 ml of 0.01 M $CaCl_2$ added to the glass tubes in 10-ml increments followed by 10 ml of nutrient solution. Methods followed those as described by Stanford & Smith (1972) to moisten the dry soil–residue mixture and remove ambient levels of NH_4^+–N and NO_3–N, and replace non-N nutrients at the beginning of the study. Subsequent leachings consisted of 30 ml of 0.01 M $CaCl_2$ and 10 ml (0.002 M $CaSO_4$■$2H_2O$, 0.002 M $MgSO_4$, 0.005 M $Ca(H_2PO_4)_2$, and 0.0025 M K_2SO_4) nutrient solution. The data from the initial leaching was not used in the evaluation of the mineralization data from this study because previous fertilization practices at some of the soil collection sites may have influenced the original mineral N content of the soil as well as removed free mineral N in the applied crop residues. Subsequently, biweekly leaching of the incubations (n = 10) were conducted at 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 wk. Following leaching, Plastic film (Pechiney Plastic Packaging) was used to cover leachate test tubes to prevent contamination and to preserve soil water content during this study. Air vents were created in the parafilm to allow for soil respiration. After collection, leachate was refrigerated (8–24 h) if necessary, until inorganic N (NO_3–N and NH_4–N) analysis could be determined using a Timberline TL 2900 NH_4/NO_3 analyzer (Timberline Instruments Inc.). However, since NO_3–N is the endpoint of N mineralization reactions and the conversion of NH_4–N to NO_3–N is rapid in soil, we have focused on the end result of the incubations as being NO_3–N. A second reason for focusing on the

NO_3–N analyses was that the observed NH_4–N values were relatively consistent from one incubation period to the next, and a soil NO_3–N test is generally used to predict fertilizer needs of crops.

Following the final incubation (20 wk, $n = 10$ total readings), soil pH for all incubated samples ($n = 72$) plus three pre-incubation control samples of each soil was determined to evaluate the decomposition effects of the crop residue on the soil. The 1:1 soil/water measurement was done with a Beckman Coulter Φ340 pH meter.

2.2 | Statistical analysis

A repeated measures ANOVA model was used to determine the effect of crop residue treatment, soil texture, incubation period, and their interactions on nitrate and ammonium mineralization with SAS Generalized linear mixed model (GLIMMIX) procedure. As the measurements of NO_3–N and NH_4–N mineralization were collected from the same experimental tube unit repeatedly over incubation period, certain covariance structure would be imposed on the error term of the model to address the correlation among the measurements. Akaike's Information Criteria (AIC) was used to determine the appropriate covariance structure and the smaller AIC value the better. Throughout this study, first order auto regressive [AR(1)] covariance structure was always producing a smaller AIC value. LS-mean of each level of crop residue treatment for each soil type was estimated and pair-wise multiple comparisons was performed with Tukey's Honest Significant Difference (HSD) test with an alpha level of .05. Similarly, LS-mean of each level of crop residue treatment within each incubation period for each soil type was estimated and Tukey's (HSD) test with an alpha level of .05 was used to find the LS-means that are significantly different from each other.

The one-way ANOVA model was also used to investigate the effect of crop residue treatment on soil pH for each soil texture. In this analysis, the comparisons between control and other levels of crop residue treatment were investigated, therefore, Dunnett's test was used as it was designed to control the familywise Type I error rate at or below.05 when multiple comparisons of treatment group with control are performed. All analyses were conducted by SAS version 9.4 (SAS Institute Inc., 2013).

3 | RESULTS

Overall mean soil N mineralization for crop residue treatments varies with soil texture from 1.15 to 5.80 mg NO_3–N kg^{-1}. For all soil series, the control (bare, unamended soil) means showed net N mineralization varying from 0.66 to 2.95 mg NO_3–N kg^{-1}. When comparing the soil series and

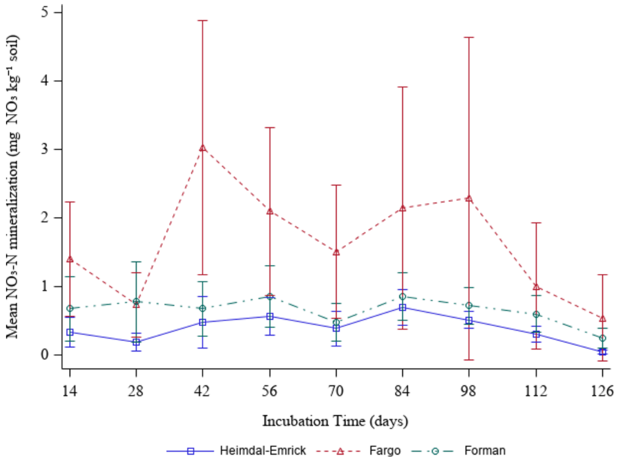

FIGURE 1 Nitrate-nitrogen mineralization means with a range of values for Heimdal–Emrick, Fargo, and Forman soil series over nine incubation periods, regardless of crop residue treatment

N mineralization over time, the Fargo soil series displays the highest overall mean NO_3–N mineralization among the three soils for the nine incubation periods [Fargo (1.63 mg NO_3–N kg^{-1}) > Forman (0.65 mg NO_3–N kg^{-1}) > Heimdal–Emrick (0.38 mg NO_3–N kg^{-1})] (Figure 1). The Fargo soil exhibited a high amount of N mineralization; likely due to high OM content and clay in this soil (Table 2). When higher OM is present, the potential for N mineralization to occur is also higher (Follett, 2008). Generally, in soils with high clay content, OM is protected from microbial decomposition and decomposition is slower due to adsorption and complexation by the clay. Therefore, the N mineralization potential in clay soils is typically greater than in sandy soils due to the higher levels of OM (Curtin & Wen, 1999; Delin & Linden, 2002; Hamarashid et al., 2010; Xu et al., 2016).

Net mineralization (Figure 2) occurs in the narrow C/N ratio crops earlier in the incubation series (i.e., growing season) as compared with later incubation series (i.e., end of the growing season). For example, forage radish mineralization rates peaks between Day 42 and Day 56, while the wider C/N (C/N > 25) ratio crops reach their peak mineralization between Day 98 and Day 112, but are still immobilizing N. Pea is the only other crop that exhibits mineralization over the control early in the incubation series. At Day 98, a spike in NO_3–N mineralization in spring wheat was observed for the Fargo soil series. A possible explanation for this is a natural microbial shift that occurs later in the growing season in the high OM environment of this soil.

Questions are often asked by farmers and crop advisors about the effects of decomposing crop residues on soil pH. The effects of specific crop residues on soil pH are shown in Table 3 where the soil–sand mixture was determined at the end of the study. Mean soil pH varied from 5.6 to 6.0 for the Heimdal–Emrick soil series, 6.7 to 6.9 for the Fargo soil

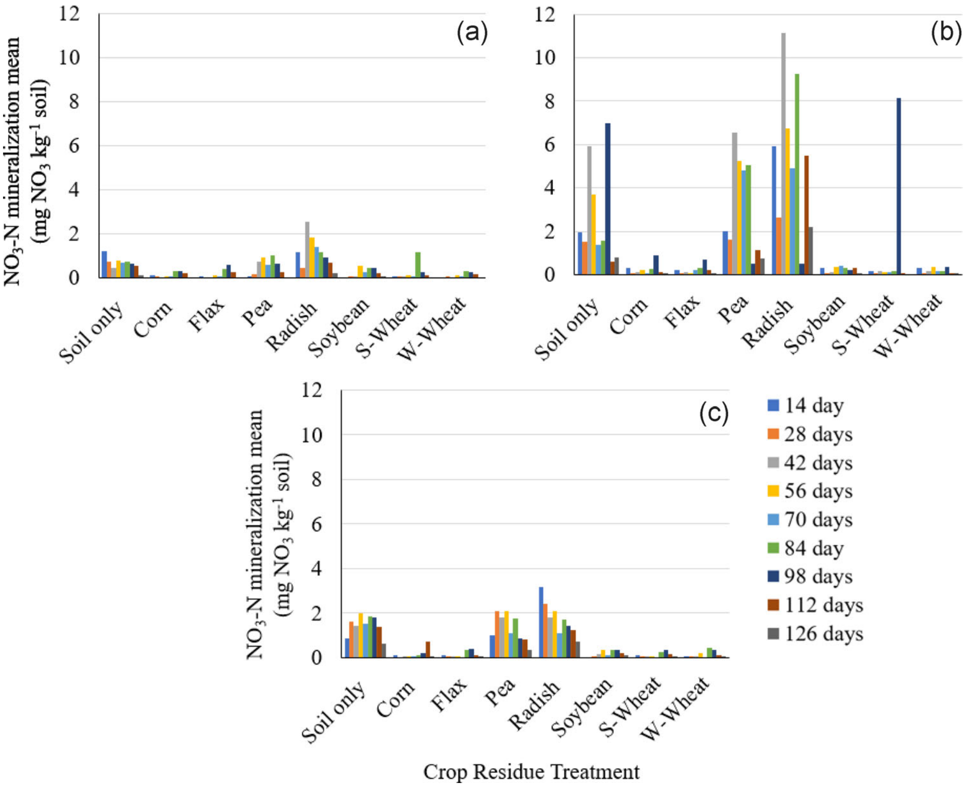

FIGURE 2 Mean NO_3–N mineralization patterns over time for soil control, corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residue treatment for the (a) Heimdal–Emrick, (b) Fargo, and (c) Forman soil series and their associated incubation days

TABLE 3 Mean soil pH with standard deviation by soil and crop residue type

Crop residue treatment	Soil pH Heimdal–Emrick	Fargo	Forman
Soil only	5.7b ± 0.27[a]	6.8a ± 0.10	6.2a ± 0.08
Corn	5.6b ± 0.04	6.7a ± 0.06	6.3a ± 0.08
Flax	5.6b ± 0.04	6.8a ± 0.07	6.3a ± 0.07
Pea	5.8b ± 0.04	6.8a ± 0.12	6.4a ± 0.02
Radish	6.0a ± 0.06	6.7a ± 0.10	6.6a ± 0.02
Soybean	5.8b ± 0.06	6.9a ± 0.02	6.4a ± 0.06
Spring wheat	5.8b ± 0.15	6.8a ± 0.09	6.4a ± 0.10
Winter wheat	5.6b ± 0.09	6.8a ± 0.10	6.4a ± 0.18

[a]Different letters within a column are significantly different at the .05 level using Dunette's multiple comparison test.

series, and 6.2 to 6.6 for the Forman soil series. Heimdal–Emrick is the only soil series that shows significant differences in the soil pH where the radish is the only crop residue treatment significantly different from the others. This was likely due to its lower buffering ability because of its coarser texture. The Fargo and Forman soils are fine textured and thus have a high CEC potential that buffers them against a significant pH change. Also, the addition of basic cations (Ca^{2+}, Mg^{2+}, K^+) in the nutrient solution after each leaching resulting in the pH being buffered from extreme changes. Under the conditions of this study, pH change due to residue decomposition is not a reliable indicator of changes that might occur in a field environment.

Figure 3 shows the net mineralization or immobilization relative to the soil N mineralization for each soil and incubation/leaching period. In the figure, the NO_3–N mineralization from each residue was compared with the bare, unamended soil represented by the zero line and is used as the baseline. Values above the zero line indicates N mineralization, while below the zero line suggests N immobilization. Mineralization and immobilization amounts varied based on soil type as shown in Figure 3.

4 | DISCUSSION

Inorganic N availability from residue varies based on the crop residue and its C/N ratio. The forage radish's (C/N = 8) mean N mineralization across the incubation periods is significantly higher when compared with each of the other crop residue treatments in nearly all soil series (Figure 1). Forage radish is the only treatment that shows overall net mineralization in all soil series over the soil control. Pea (C/N = 18) shows a significantly lower N mineralization from the forage radish except for the Forman soil. Corn (C/N = 73), flax (C/N = 77),

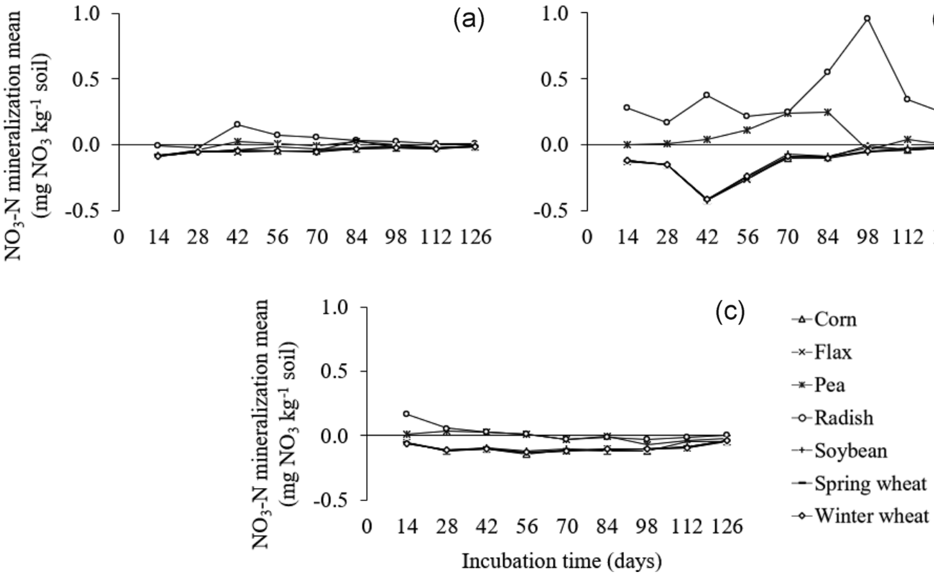

FIGURE 3 Mineralization/immobilization of NO_3–N for the (a) Heimdal–Emrick, (b) Fargo, and (c) Forman soil series over nine incubation periods for corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments. The horizontal *x* axis line represents soil mineralization and the residue N mineralization is shown relative to soil mineralization

soybean (C/N = 53), spring wheat (C/N = 76), and winter wheat (C/N = 101) collected from the Aher et al. (2016) show a net immobilization and are often similar regardless of soil series, and significantly different from the forage radish and pea treatments. The differences between forage radish and pea as compared with corn, flax, soybean, spring wheat, and winter wheat is due to the narrow C/N ratio in forage radish and pea (C/N < 25). These residues are green and growing at the end of the growing season when used in a cover crop role while the other residues are senescent.

Over 18 wk of lab incubation, there were noticeable differences in the cumulative mineralization due to soil texture and OM content for the three soil series (Figure 2 and Table 4). The highest cumulative mineralization for the Fargo soil series was due to its texture, soil pH, water holding capacity, and OM content (6.2%). It is evident that for the control treatments (soil only) the N mineralization ranking (Fargo > Forman > Heimdahl–Emrick) was related to soil organic matter (SOM) (6.2% > 5.1% > 4.4%). For all of the soils, the high C/N residues reduced N mineralized below that of the control. For the Fargo and Forman soils, both radish and pea consistently showed net mineralization when compared with the control. However, for the Heimdal–Emrick soil, radish was the only residue that shows cumulative mineralization greater than the untreated control.

Forage radish was the only treatment that showed an overall net mineralization of NO_3–N in all soil series over the bare soil. Corn, flax, soybean, spring wheat, and winter wheat showed a net N immobilization in all three soils. Pea (legume) NO_3–N mineralization was slightly higher or near the mineralization rate of the untreated soil controls. The radish (mixed aboveground roots and foliage) and pea were green plant materials harvested just prior to fall freeze-up which explains the narrow C/N ratio and N mineralization trends observed among the three soil series. Radish and pea materials allowed them to be used as another type of control besides the soil itself for the study as it was understood that they would mineralize under these conditions. These two species were often used as bio-strip plantings or as part of a multi-species cover mixture seeded after harvest of short-season crops (in this case spring wheat) to protect the soil and promote soil health. Each soil had a distinctively different N mineralization based on its texture and SOM content where the Fargo soil series displayed the highest SOM value. The effect of soil texture on the N mineralization was evident throughout the study where clayey soils protected OM from microbial decomposition in the Fargo soil series.

An observation of immobilization of NO_3–N by nonleguminous post-harvest crop residues is consistently observed in our studies and is supported by other studies (Alghamdi & Cihacek, 2021). Kaur et al. (2018) observed similar results in other North Dakota soils in short-term incubations. Mineralization of the low C/N crop species (radish and pea) was also shown to occur in the earlier incubation periods as compared with other crop residue treatments. Other studies, including those with similar soils and northern region of the United States, have concluded that despite cover crops providing NO_3–N benefits, the benefits may not be an adequate substitution to fertilizer application and that N mineralization from crop residue alone may not be enough to award credit for the following crop season (Gieske et al., 2016; Hill et al., 2016;

TABLE 4 Mean and cumulative NO_3–N mineralization for nine incubation periods and overall mean for corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for Heimdal–Emrick, Fargo, and Forman soil series in North Dakota

Soil series	Crop residue treatment	Nitrogen mineralization per leaching incubation period (days) 1st (14 d)	2nd (28 d)	3rd (42 d)	4th (56 d)	5th (70 d)	6th (84 d)	7th (98 d)	8th (112 d)	9th (126 d)	Cumulative	Overall mean[a]
		mg NO_3 kg^{-1}										
Heimdal–Emrick	soil only	1.23a	0.74a	0.44b	0.78b	0.69ab	0.73a	0.64ab	0.56a	0.11b	5.91b	0.66b ± 0.35
	corn	0.09b	0.03b	0.00b	0.06b	0.02b	0.33a	0.30b	0.21a	0.00c	1.04d	0.12d ± 0.14
	flax	0.03b	0.00b	0.00b	0.12b	0.08b	0.38a	0.57ab	0.28a	0.00c	1.46d	0.16 cd ± 0.22
	pea	0.01b	0.18b	0.73b	0.93ab	0.57ab	1.04a	0.66ab	0.24a	0.00c	4.35bc	0.48bc ± 0.42
	radish	1.17a	0.45ab	2.54a	1.83a	1.42a	1.16a	0.93a	0.69a	0.21a	10.4a	1.15a ± 0.88
	soybean	0.00b	0.02b	0.05b	0.55b	0.24ab	0.44a	0.46ab	0.19a	0.00c	1.95c	0.22c ± 0.24
	spring wheat	0.07b	0.01b	0.03b	0.10b	0.04b	1.15a	0.25b	0.11a	0.00c	1.75c	0.19c ± 0.53
	winter wheat	0.00b	0.00b	0.00b	0.11b	0.00b	0.29a	0.26b	0.14a	0.00c	0.80d	0.09d ± 0.12
Fargo	soil only	1.94b	1.51ab	5.93a	3.70ab	1.39ab	1.55a	6.98a	0.61b	0.79b	24.4b	2.95b ± 3.37
	corn	0.31b	0.02b	0.12b	0.23b	0.05b	0.27a	0.87a	0.12b	0.02b	2.01c	0.25c ± 0.46
	flax	0.22b	0.00b	0.11b	0.02b	0.19b	0.33a	0.69a	0.21b	0.01b	1.80c	0.22c ± 0.35
	pea	1.99b	1.61ab	6.52a	5.24a	4.81a	5.05a	0.49a	1.15b	0.75b	27.6ab	3.36ab ± 2.68
	radish	5.89a	2.62a	11.1a	6.72a	4.88a	9.25a	0.52a	5.47a	2.21a	48.7a	5.81a ± 4.49
	soybean	0.32b	0.01b	0.10b	0.38b	0.43b	0.30a	0.23a	0.30b	0.08b	2.15c	0.26c ± 0.19
	spring wheat	0.18b	0.02b	0.15b	0.10b	0.10b	0.16a	8.12a	0.03b	0.00b	8.85bc	1.11bc ± 4.59
	winter wheat	0.32b	0.03b	0.14b	0.35b	0.16b	0.19a	0.34a	0.09b	0.03b	1.63c	0.20c ± 0.19
Forman	soil only	0.85b	1.62a	1.43ab	1.96a	1.49a	1.85a	1.82a	1.40a	12.69a	12.7a	1.55a ± 0.56
	corn	0.11b	0.00a	0.02b	0.01b	0.02b	0.12b	0.18c	0.73ab	1.21b	1.21b	0.15b ± 0.25
	flax	0.10b	0.02a	0.06b	0.07b	0.00b	0.36b	0.40c	0.09b	1.15b	1.15b	0.14b ± 0.16
	pea	0.10b	2.06a	1.82a	2.08a	1.09a	1.74a	0.86bc	0.83ab	11.7a	11.7a	1.43a ± 1.03
	radish	3.19a	2.39a	1.81a	2.08a	1.05a	1.70a	1.43ab	1.26ab	18.5a	18.5a	1.87a ± 1.16
	soybean	0.00b	0.04a	0.15b	0.35b	0.10b	0.32b	0.33c	0.22ab	1.61b	1.61b	0.19b ± 0.18
	spring wheat	0.08b	0.01a	0.06b	0.06b	0.00b	0.24b	0.36c	0.13ab	0.94b	0.94b	0.12b ± 0.13
	winter wheat	0.03b	0.03a	0.04b	0.18b	0.00b	0.42b	0.32c	0.11b	1.12b	1.12b	0.14b ± 0.21

Note. Different letters within a column in each soil series are significantly different at the .05 level using Tukey's HSD test.

[a]Nitrogen mineralization mean over all incubation periods for each crop residue within individual soil series.

Lacey & Armstrong, 2015; Li et al., 2015; O'Reilly et al., 2012; Ruark et al., 2018; Vyn et al., 2000).

5 | CONCLUSIONS

The question still remains about the source of the N to provide a N credit in fields with >6 yr of no-till management in North Dakota. Given the extremes in temperature throughout the region and the wide variation in moisture conditions across the state from East to West, further studies should aim to integrate climate conditions (i.e., wetting and drying, freezing and thawing) and the potential impact of soil moisture on mineralization and immobilization trends. In this study, crop residue was incorporated into the soil to speed up mineralization. Our subsequent studies will include surface applications of crop residue to more closely simulate the field conditions of the no-till system. Based on these results and the observations of Aher et al. (2016), additional N fertilizer may be needed in fields where the crop residue accumulation may encourage N immobilization trends which in our case, may have been magnified by soil incorporation. However, additions of NO_3–N as fertilizer may aid in C mineralization of the residue and suppress mineralization of C in SOM, narrowing the C/N ratio to improve residue decomposition and N mineralization (Mahal et al., 2019).

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AUTHOR CONTRIBUTIONS

Rashad S. Alghamdi: Conceptualization; Data curation; Formal analysis; Methodology; Writing – original draft; Writing – review & editing. Larry Cihacek: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing – review & editing. Aaron Lee M. Daigh: Validation; Writing – review & editing. Shafiqur Rahman: Validation; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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