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Carbon and nitrogen release from cover crop roots is poorly predicted by their chemical composition

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Abstract

Root-derived carbon (C) and nitrogen (N) release in relation to chemical composition has rarely been quantified in field studies. The objectives of this study were to evaluate C and N release from six summer cover crop roots and to correlate it with their chemical composition. Root decomposition and N release from velvet bean (*Mucuna aterrima*), pearl millet (*Pennisetum americanum*), dwarf pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria juncea*), showy rattlebox (*Crotalaria spectabilis*), and jack bean (*Canavalia ensiformis*) were evaluated over 2 years under no-till subtropical conditions. There was no difference in C release rates for either the labile or recalcitrant C compartments in the first (average: $k_1 = 0.0577$; $k_2 = 0.0017$) or the second year (average: $k_1 = 0.1657$; $k_2 = 0.0029$). Root C remaining after 140 days did not differ in the first year (average 46.4%), but it was higher in the second year for pearl millet (65.3%) compared to the other species (40.2%). N release was the most intense during the first 21 days and decreased drastically afterward. After 140 days, the N remaining in pearl millet and velvet bean roots was higher (77.7%) than in the other species (47.1%) in the first year, while in the second year, pearl millet contained more N (50%) compared to velvet bean (38%) and jack bean (28.1%). The C and N release rates were poorly correlated to the chemical composition of the summer cover crop roots. Our results reinforce the agronomic recommendation to sow main crops immediately after cover crop management to maximize N recovery from roots.

Plain Language Summary

Plant roots are a key component of the carbon cycle but remain understudied. Our study aimed to investigate the decomposition and nitrogen release mechanisms of cover crop roots. Notably, root decomposition and nitrogen release exhibited

Abbreviations: 100 – A, recalcitrant fraction; A, easily decomposed or labile fraction; C/N, carbon/nitrogen ratio; k_1, fraction decay rate of A; k_2, fraction decay rate of 100 – A.

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minimal correlation with plant tissue chemical composition, diverging from patterns commonly observed in laboratory-controlled experiments.

1 | INTRODUCTION

Cover crops are widely used in cropping systems due to their numerous benefits for agriculture (Abdalla et al., 2019; Adentunji et al., 2020; Moreno-Cadena et al., 2024). While summer cover crops are not as extensively adopted as winter crops, they are notable for their high biomass production and nitrogen (N) inputs to soil (Weiler et al., 2019), even over a short period. Quantifying cover crop residues decomposition and nutrient release is crucial for effectively planning their integration into cropping systems. Several studies have evaluated the decomposition and nutrient release from winter and summer cover crop shoots (Adentunji et al., 2020; Moreno-Cadena et al., 2024; Weiler et al., 2019). However, research focusing on the root systems of cover crops remains limited (Pisarčik et al., 2024), mainly because measuring in situ root biomass production and decomposition is difficult and onerous (Tahir et al., 2016).

Under subtropical no-till, Redin et al. (2018) estimated that root biomass production of summer cover crop species in the 0–20 cm soil layer ranges from 0.54 to 1.6 Mg ha^{-1}, corresponding to 0.25–0.72 Mg C ha^{-1} and 4.7-18.2 kg N ha^{-1}. In subtropical climates, winter cover crops have been reported to produce root biomass ranging from 1.2 to 3.6 Mg ha^{-1} and N inputs to the soil ranging from 19.8 to 71 kg N ha^{-1} (Jani et al., 2015; Sievers & Cook, 2018). In addition, Pinto et al. (2021) found that 10 winter legume species accumulated an average of 1 Mg ha^{-1} of root biomass, representing approximately 16% of the total plant biomass. Despite their lower biomass compared to shoots, roots play an important role in nutrient recycling and are an essential source of carbon (C) and N for deeper soil layers, particularly under no-till systems where residues remain on the soil surface. The decomposition of belowground residues under no tillage exhibits distinct characteristics compared to aboveground biomass, since there is greater contact with the soil and less edaphoclimatic variability. Austin et al. (2017) observed that, after 5 months of decomposition, root-derived C was three times more likely to remain in the soil than C derived from aboveground sources.

The chemical composition of crop residues generally serves as a key indicator of their decomposition dynamics, N release, and C sequestration (Berg et al., 2020). Silver and Miya (2001) suggested that, on a global scale, root chemical composition particularly the concentration of N, lignin, and the lignin:N ratio plays a dominant role in the decomposition process. In a controlled laboratory study involving roots of 20 species (cover and commercial crops), Redin et al. (2014) reported that C mineralization rates were negatively associated with hemicellulose content and positively correlated with N content. Conversely, Tahir et al. (2016) found that, when evaluated in situ, roots with distinct chemical characteristics do not differ in their decomposition.

The inclusion of cover crops in cropping systems brings benefits such as increased soil N availability and improved yields (Moreno-Cadena et al., 2024; Pott et al., 2021). Understanding the decomposition and N release from cover crop roots is critical for evaluating their benefits to production systems, as well as soil C accumulation and sequestration. However, summer cover crop roots are still poorly studied, and field studies in this area remain scarce. Therefore, this study aims to correlate the decomposition and N release from summer cover crop roots with their chemical composition over 2 years in a humid subtropical agroecosystem. We hypothesize that the C and N release from cover crop roots differs among species and is positively related to the labile fraction and N content in crop residues.

2 | MATERIALS AND METHODS

2.1 | Research location

The study was conducted over 2 years in the Experimental Area at the Soil Department of the Federal University of Santa Maria, Santa Maria, RS (29° 41′ S, 53° 48′ W, approximately 90 m altitude). The region has a humid subtropical climate (Cfa2) according to the Köppen climate classification, with an average annual precipitation of 1769 mm and an average annual temperature of 19.3°C. The soil in the study area is classified as a Typic Hapludalf (Soil Survey Staff, 2014). Soil samples taken from the 0–10 cm layer before the experiment began revealed the following characteristics: 600 g kg^{-1} sand, 300 g kg^{-1} silt, 100 g kg^{-1} clay, pH 5.4, and 7.5 g kg^{-1} C.

2.2 | Experimental design and crop management

The experiment was conducted in a randomized block design with four replications. Prior to the experiment, the soil received a lime application of 3 Mg ha^{-1}, and the area was cropped with black oats as a cover crop. After the harvest, six summer cover crop species were grown in the area: velvet bean (*Mucuna aterrima*), pearl millet

(*Pennisetum americanum*), dwarf pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria juncea*), showy rattlebox (*Crotalaria spectabilis*), and jack bean (*Canavalia ensiformis*). The cover crops were manually sown and grown between January and April (summer/autumn) in rows spaced 0.45 m apart, without the addition of any fertilizer. Velvet and jack beans were sown in pits spaced 0.25 m between the plants. The other cover crop species were sown at densities of 12 kg ha^{-1} for pearl millet, 30 kg ha^{-1} for both sunn hemp and showy rattlebox, and 50 kg ha^{-1} dwarf pigeon pea, respectively. After the cover crops were terminated with a knife-roller, the area was sown with white oats (*Avena sativa* L.) in the first winter and black oats (*Avena strigosa* Schreb.) in the second winter. Both winter crops were sown at a seed density of 80 kg ha^{-1} and fertilized with 80 kg ha^{-1} of K_2O and P_2O_5. In the second year, cover crops were grown in the same experimental plots and managed in the same way.

2.3 | Cover crop roots characterization and litterbags

At the full flowering stage of the cover crop species, root biomass in the 0–0.2 m layer was sampled through excavation. First, the main roots were removed from the soil manually before washing the entire soil sample under running water over a 1-mm mesh sieve. All roots were dried in an oven at 40°C, and a subsample was further dried at 65°C to determine the dry mass. The Van Soest (1963) method was performed using subsamples of ground roots dried at 40°C to analyze soluble fraction, cellulose, hemicellulose, and lignin fractions. The total C and N content was determined from finely ground subsamples dried at 65°C using an elemental analyzer (FlashEA 1112, Thermo Electron Corporation). 0.5 g of ground roots was shaken in 60 mL of water for 30 min (Redin et al., 2014) before being filtered using Whatman #2 filter paper to determine the water-soluble C and N content according to the methods of Nelson and Sommers (1982) and Bremner and Mulvaney (1982), respectively. Roots were collected and chemically characterized using the same procedure for both years.

The cover crop roots used in the litter bags were those previously oven-dried at 40°C. The roots were added to the litter bags (with a 0.5 mm mesh) at a rate equivalent to 1 Mg ha^{-1} (4 g per litter bag) for both years following the procedure described by McCormack et al. (2015), using an order-based classification. The same amount of root material was used for all species and in both years to apply a uniform residue quantity and facilitate the quantification of the effect of root chemical composition on decomposition. The litter bags were buried in the soil at a depth of 0.1 m on the same day the cover crops were harvested and collected after 7, 14, 21, 35, 70, 105, and 140 days. On each date, the litter bags were collected and oven-dried at 65°C before being carefully cleaned using brushes to determine dry mass. The residues were then finely ground to determine the C and N contents using an elemental analyzer (FlashEA 1112, Thermo Electron Corporation). A subsample of the material was burned in a muffle furnace at 550°C to determine the ash content and correct for possible soil contamination.

Core Ideas

- Decomposition and N release from summer cover crop roots were evaluated over 2 years in a field experiment.
- Most of the N release from the roots occurred within the first 21 days of decomposition.
- C and N release rates were poorly related to the chemical composition of summer cover crop roots.

2.4 | Fitting and parameters of regression model

The remaining C and N data were adjusted using a double exponential decay model (Wieder & Lang, 1982) using the following equation:

$$\text{C or N} = Ae^{-k_1 t} + (100 - A)\, e^{-k_2 t}$$

where C and N are the amounts of C and N remaining in the crop residues (% of C and N added); A represents a relatively easily decomposed or labile fraction, and $(100 - A)$ represents a more recalcitrant fraction; each fraction decays exponentially at rates characterized by k_1 and k_2, respectively; and t is time (days).

Various parameters obtained from the model fitting were used to demonstrate how compartment sizes and decay rates affected the release of N from the crop residues. The angles θ_{k1} and θ_{k2} were derived from the tangents to the N release curves over time. These angles are directly related to the derivatives of the N release function, N(t), since the slope of a tangent line to a curve at a point is given by the derivative of the function at that point.

2.5 | Statistical analyses

The data related to the remaining C and N in the roots were subjected to an analysis of variance (ANOVA), and the means were compared using Tukey's test ($p \leq 0.05$). The adjusted model parameters (roots vs. year and chemical composition

TABLE 1 Cumulative rainfall and mean air temperature between litter bag collections.

	Cumulative rainfall (mm)		Mean air temperature (°C)	
Days between litter bags collection	Year 1	Year 2	Year 1	Year 2
0–7	0.0	26.6	21.4	15.4
8–14	120.0	42.0	19.6	17.3
15–21	7.0	1.2	15.7	15.1
22–35	34.4	5.8	16.2	15.3
36–70	178.2	112.9	15.2	12.5
71–105	308.6	225.0	14.0	15.5
106–140	116.8	84.4	14.2	15.0
Total/mean	757.6	497.9	16.6	15.1

vs. year) were subjected to two-way ANOVA, while the means were compared by Tukey's test ($p \leq 0.05$). These analyses were performed using SISVAR software. Data were tested for normality with Shapiro–Wilk test and the correlation between the chemical composition of the roots and the C and N release rates was assessed using Pearson's correlation coefficients using SigmaPlot 11 software (Systat Software, Inc.).

3 | RESULTS

3.1 | Weather conditions of experimental years

The 2 years evaluated differed in terms of temperature and rainfall levels (Table 1). The first year was characterized by higher mean air temperatures and greater rainfall, but with no rainfall in the first 13 days. In fact, the total rainfall during the experiment in the first year exceeded that of the second year by >250 mm.

3.2 | Root-C and N release and rates

C and N release was characterized by an initial faster phase during the first 14–21 days followed by a slower phase that continued until the end of the experiment (Figure 1). This dynamic was accurately described using a double exponential model. In the first 14 days, the roots of velvet beans showed less remaining C than dwarf pigeon pea roots in the first year (88.3% vs. 93.1%), and when compared to millet and sunn hemp in the second year (67.7% vs. 92.1% and 87.2%, respectively) (Figure 1; Supporting Information). After 140 days in the first year, C remaining in the cover crop roots was around 46.4%, with no difference between the species. In contrast, in the second year, more C remained in millet roots (65.3%) than in the other species (average of 40.2%). The adjusted model parameters for C remaining in the root residues were not statistically different among the species in the first year (Table 2). However, in the second year, pearl millet roots had a lower labile and higher amount of recalcitrant C compartments compared to velvet bean roots. However, there was no difference between the species k_1 and k_2 decomposition rates in both years. The k_1 decomposition rate of dwarf pigeon pea, showy rattlebox, and jack bean roots was lower in the first year than in the second year; there was no effect of year on the k_2 decomposition rate (Table 2).

The N release dynamics were more intense compared to the C release dynamics, especially in the first 14 days (Figure 1). After 21 days in the first year, velvet bean and millet released only 23.2% of their N, while other species released an average of 46% of their N (Supporting Information). In the second year, velvet bean and millet released only 36% of N from roots, while showy rattlebox released 57.6% of its N in the first 21 days. After 21 days, the N released from the cover crop roots dramatically reduced. At the end of the first experimental year, velvet bean and millet released less N than other cover crop roots (77.7% vs. 47.1%). The labile N content of dwarf pigeon pea, sunn hemp, and jack bean was higher than velvet beans and pearl millet in the first year. However, showy rattlebox had a higher labile N content than velvet bean, pearl millet, and sunn hemp in the second year. The k_1 N release rate of showy rattlebox was higher than pearl millet, dwarf pigeon pea, and sunn hemp in the first year, while in the second year, dwarf pigeon pea showed the highest k_1 N release rate (Table 2). In the first year, there was no difference in the k_2 N release rates, while in the second year the k_2 rates of velvet and jack beans were higher than pearl millet, sunn hemp, and showy rattlebox.

3.3 | Roots chemical composition effects on C and N release

The chemical composition of the cover crop roots varied among the species (Table 3). Velvet bean roots showed the highest N content in addition to the lowest carbon/nitrogen ratio (C/N) and Lig:N ratio in both years. In the first year,

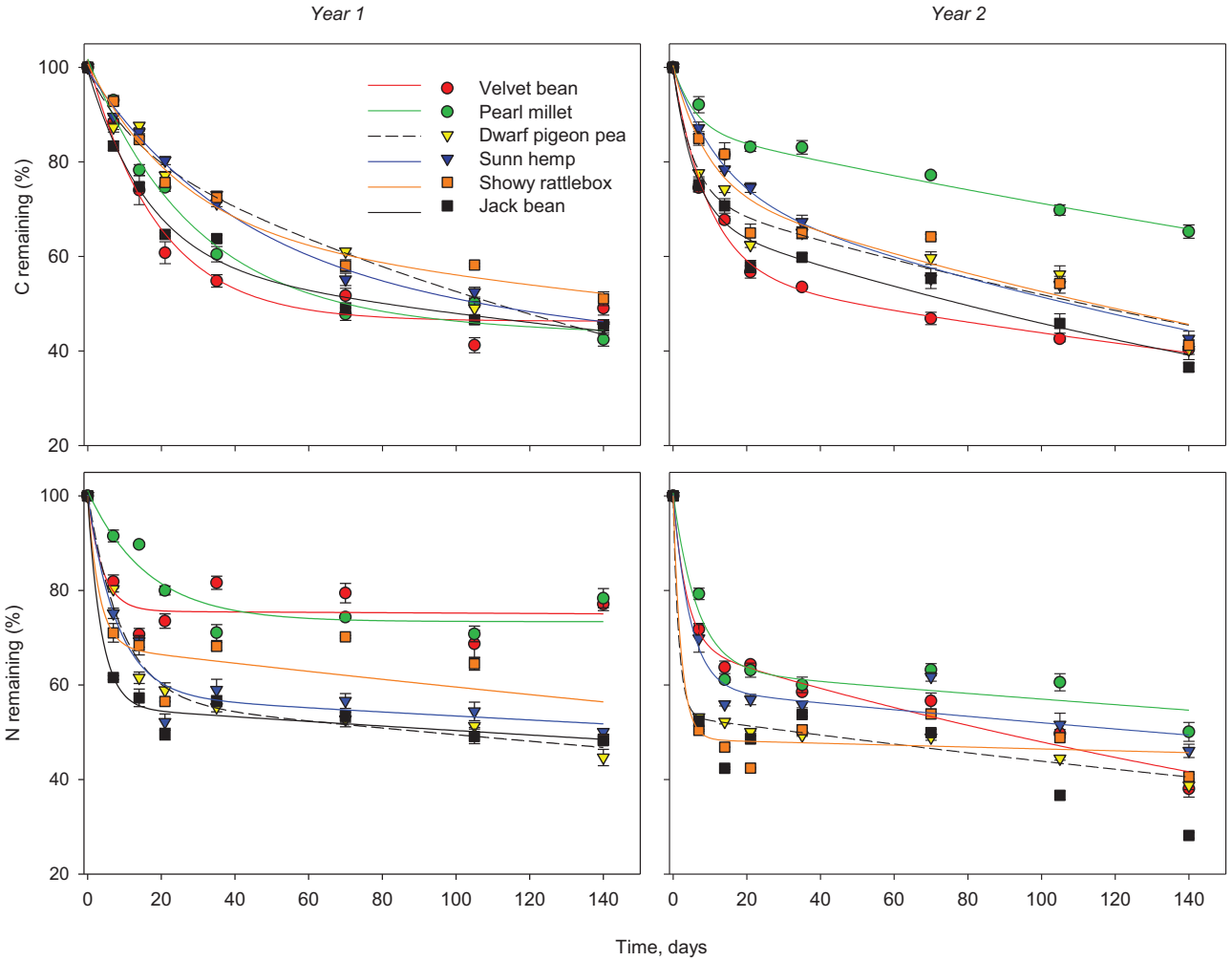


FIGURE 1 Percentage of carbon and nitrogen remaining for six summer cover crop roots measured over 140 days of decomposition in situ in two different years. Vertical bars indicate the standard error.

pearl millet roots showed the lowest soluble N and C contents but only the lowest soluble N and C content in the second year. Overall, the *k*N e *k*C rates were poorly correlated to root chemical composition (Figure 2). The k_1C was not significantly related to any chemical compounds in the roots of summer cover crops in either year. However, the k_1N was positively related to cellulose and the soluble C and N content in the first year, and positively related to soluble C, cellulose, and lignin content in the second year. The k_1N was positively related to lignin (0.46; $p < 0.01$) and negatively related to soluble fraction (−0.51; $p < 0.05$) in the second year. Significant correlations between k_2 and the roots chemical composition were observed only in the second year. The k_2C was positively related to the soluble C and cellulose content but negatively related to the Van Soest soluble fraction; the k_2N was positively related to the N content and the soluble fraction (Van Soest soluble fraction and C and soluble) but negatively related to hemicellulose, the C/N ratio, and the lignin/N ratio (Figure 2).

4 | DISCUSSION

The dynamics of C and N release followed the same pattern reported in several studies, where an initial, rapid release phase was followed by a slower phase (Jani et al., 2015; Sievers & Cook, 2018; Weiler et al., 2019). The decomposition of a labile fraction has been identified as responsible for the initial release of C and N from crop residues. Meanwhile, a more recalcitrant fraction, less accessible to microbial attack, tends to accumulate in the soil (Berg et al., 2020; Weiler et al., 2022). Although it is generally accepted that some components of crop residues degrade more easily (Berg et al., 2020; Redin et al., 2014), it is not always possible to establish significant relationships between these components and decomposition or nutrient release rates. Lignin is known to be one of the most difficult components of crop residues to degrade (Silver & Miya, 2001; Weiler et al., 2022). However, Sievers and Cook (2018), for example, observed a higher decomposition rate (*k*) for vetch roots compared to rye roots, despite the higher lignin content in vetch roots. In

TABLE 2 Model parameters fitted to the measured values of C and N remaining, half-life time and r^2 in each treatment.

	Remaining C					Remaining N				
Parameter/cover crop	**A (%)**	**k_1 (day^{-1})**	**100-A**	**k_2 (day^{-1})**	**r^2**	**A (%)**	**k_1 (day^{-1})**	**100-A**	**k_2 (day^{-1})**	**r^2**
	Year 1									
Velvet bean	54.30a	0.0642a	45.70a	0.0004a	0.93	23.07b*	0.2918abc	76.93a	0.0004a*	0.66
Pearl millet	51.83a*	0.0388a	48.17a*	0.0011a	0.97	26.49b*	0.0675d*	73.51a*	0.0002a	0.78
Dwarf pigeon pea	25.88a	0.0753a*	74.12a	0.0033a	0.98	43.23a	0.1175cd*	56.77b	0.0031a	0.96
Sunn hemp	40.09a	0.0446a	59.91a	0.0019a	0.99	42.54a	0.1432bcd	57.46b	0.0008a	0.91
Showy rattlebox	35.59a	0.0465a*	64.41a	0.0017a	0.98	32.63ab*	0.3302a*	67.37ab*	0.0015a	0.79
Jack bean	42.35a	0.0766a*	57.65a	0.0018a	0.98	44.60a	0.3052ab*	55.40b	0.0009a*	0.95
	Year 2									
Velvet bean	44.84a	0.1219a	55.16b	0.0022a	0.98	32.85d	0.2142c	67.15a	0.0032a	0.98
Pearl millet	22.56b	0.1457a	78.85a	0.0014a	0.91	36.43cd	0.1844c	63.57ab	0.0013bc	0.90
Dwarf pigeon pea	27.76ab	0.2055a	72.24ab	0.0034a	0.92	46.55ab	0.6840a	53.45ab	0.0020ab	0.99
Sunn hemp	31.06ab	0.0827a	68.94ab	0.0030a	0.95	42.13bc	0.1949c	57.87ab	0.0011bc	0.90
Showy rattlebox	25.43ab	0.1966a	74.57ab	0.0036a	0.93	51.51a	0.4811b	48.49b	0.0004d	0.95
Jack bean	31.69ab	0.2422a	68.31ab	0.0040a	0.95	46.29ab	0.5082b	53.71ab	0.0032a	0.94

Note: Means followed by the same letter are not statistically different within each year according to the Tukey's test ($p \leq 0.05$).
Abbreviations: 100 – A, recalcitrant fraction; A, easily decomposed or labile fraction; k_1, fraction decay rate of A; k_2, fraction decay rate of 100 – A.
*Indicates that differences between years are statistically significant according to the Tukey's test ($p \leq 0.05$).

TABLE 3 Chemical composition of cover crop roots.

Cover crop	**C (g kg^{-1})**	**N (g kg^{-1})**	**C SOL (g kg^{-1})**	**N SOL (g kg^{-1})**	**VS SOL (g kg^{-1})**	**CEL (g kg^{-1})**	**HEM (g kg^{-1})**	**LIG (g kg^{-1})**	**C/N (g kg^{-1})**	**LIG/N (g kg^{-1})**
	Year 1									
Velvet bean	439.9a	20.0a*	53.57a*	2.64a*	356.5a	350.3c	159.8b*	86.2c*	22.0c	4.3d
Pearl millet	430.8a	8.5d	6.09c	0.65c	355.3a*	257.4d*	91.9c*	97.3bc	50.9a*	11.5ab*
Dwarf pigeon pea	455.6a*	11.5bc	25.79b*	1.68b*	207.9b	418.5b*	232.4a*	105.6b*	39.6b	9.2bc*
Sunn hemp	454.0a*	11.4bc	32.90b	1.70b	187.8b*	422.1b*	260.5a*	91.8c*	40.1b	8.0c*
Showy rattlebox	445.5a*	9.0cd*	25.05b*	1.57b*	142.7c	451.6a*	249.8a*	120.0a*	49.8a*	13.4a*
Jack bean	444.7a*	13.0b*	25.42b*	2.48a*	210.0b*	435.3ab*	215.4a*	106.2b	34.4b*	8.2c*
	Year 2									
Velvet bean	447.6b	22.1a	33.15b	3.78a	379.8a	348.2c	91.2c	110.6bc	20.3c	5.0c
Pearl millet	449.7b	9.1d	12.45c	0.61c	395.8a	289.2d	208.5a	93.1d	49.4a	10.2b*
Dwarf pigeon pea	475.1a	11.3c	39.51b	2.05c	228.2c	436.2c	157.8ab	115.8b	42.3a	10.3b
Sunn hemp	472.4a	11.8c	32.84b	1.70c	220.2c	464.0b	199.9ab	102.4cd	40.3a	8.7b
Showy rattlebox	472.6a	11.7c	35.90b	1.69c	211.4c	473.8b	175.6ab	150.0a	40.6a	12.9a
Jack bean	464.4a	16.4b	55.88a	3.09b	288.5b	544.7a	143.5bc	108.1bc	28.3b	6.6c*

Note: Means followed by the same letter are not statistically different within each year according to the Tukey's test ($p \leq 0.05$).
Abbreviations: C, carbon; C SOL, soluble carbon; C/N, carbon/nitrogen ratio; CEL, cellulose; HEM, hemicellulose; LIG, lignin; LIG/N, lignin/nitrogen ratio; N, nitrogen; N SOL, nitrogen soluble; VS SOL, Van Soest soluble fraction.
*Indicates that differences between years are statistically significant according to the Tukey's test ($p \leq 0.05$).

addition, Solly et al. (2014) showed that fine root decomposition in grasslands was positively related to the lignin:N ratio, while the opposite relationship was found in forest ecosystems. These findings align with the apparent inconsistencies observed in our study (e.g., k_1N positively related to lignin but negatively related to the soluble fraction). Therefore, crop decomposition and nutrient release must be driven by a complex interaction of variables.

Although C and N release rates were poorly related to overall chemical composition, some clear species-specific differences were observed. N content is recognized as one of the main drivers of crop residue decomposition and nutrient

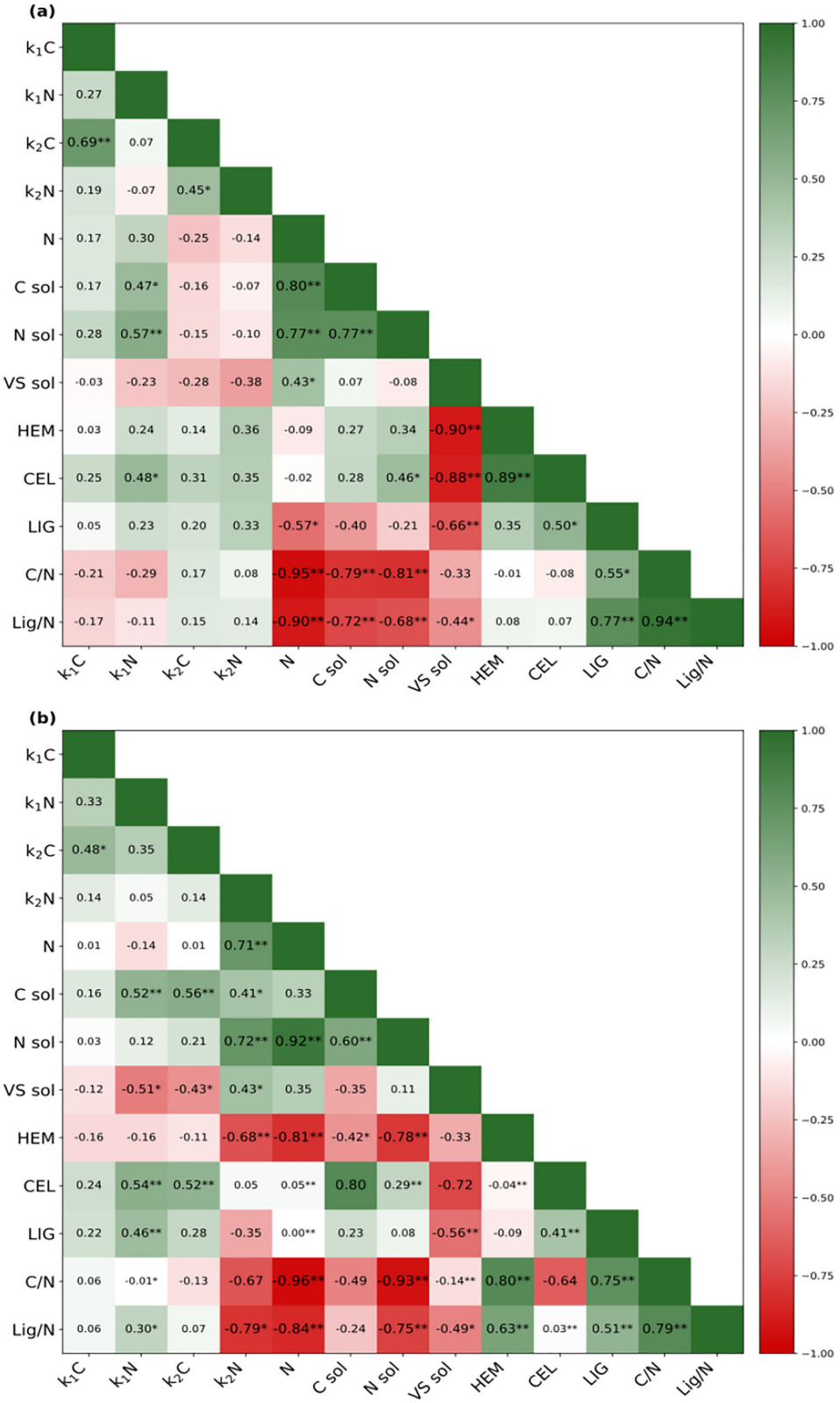


FIGURE 2 Pearson's correlation matrix between constant decomposition, N release rates (*k*C and *k*N), and the chemical composition of six summer cover crop roots for year 1 (a) and year 2 (b). C sol, water soluble carbon; C/N, carbon/nitrogen ratio; CEL, cellulose; HEM, hemicellulose; k_1C and k_2C, rates for C release; k_1N and k_2N, rates for N release; LIG, lignin; Lig/N, lignin/nitrogen ratio; N, nitrogen; N sol, water soluble nitrogen; VS sol, van Soest soluble fraction. *$p < 0.05$; **$p < 0.01$.

release (Chaves et al., 2021; Seneviratne, 2000), which may explain the higher remaining N in pearl millet roots observed in 2 years of our study. However, N content alone may not be a reliable predictor of crop residue decomposition. Although velvet bean contained the highest N concentration among the evaluated species, the amount of N retained in its residues during the first year was comparable to that of pearl millet. Among the species evaluated in our study, velvet bean roots were probably the residues with the highest polyphenol content (Redin et al., 2014). Polyphenols may reduce microbial access to N, thereby limiting both decomposition and N release from crop residues (Putasso et al., 2011; Seneviratne, 2000).

Some studies have suggested that exponential models offer a more realistic representation of crop residue decomposition, both mathematically and in reflecting true biological behavior (Harmon et al., 2009; Wieder & Lang, 1982). The rates of C and N release may indicate how much C and N can be released into the soil. However, even if two species exhibit a similar decomposition rate (k), this does not always result in the same amount of specific nutrients being released into the soil. The amount of nutrients released is determined by a combination of the release rate and the size of the nutrient pool. Using nitrogen (N) release from velvet and jack beans in the first year as an example (Figure 3), we observed that, despite similar release rates between the species (0.2918 vs. 0.3052), the amount of N released into the soil by jack bean roots during the first 35 days was higher compared to velvet bean roots. In this case, the N released from the roots is primarily influenced by the size of the nutrient pool (23.07 *vs.* 44.60%). The point at which the equation becomes asymptotic defines the size of the nutrient pool. In other words, species with a larger pool tend to release N more quickly (phase I). After that stage, N release from crop residues is determined by k_2 rate (phase II). Conversely, when comparing species with similar nutrient pool sizes (i.e., sunn hemp: 42.54 and jack bean: 44.60), the intensity of N release during the first phase is determined by the constant k_1 (resulting in a longer phase I). In the simplest terms, the nutrient pool is "how much" nutrient will be released, while the k rates determine "when" it will be released. This may help explain the weak correlation observed between decomposition rates (kC), N release (kN), and root chemical composition.

The contact between crop residues and the soil is also an important factor and might explain the low correlations observed between root chemical composition, decomposition, and N release rates in our study. Several studies have indicated that crop residues incorporated into the soil decompose faster than those left on the surface (Jahanzad et al., 2016; Lacey et al., 2020). In addition, water availability enhances the access of microorganisms to the nutrients within the roots (particularly C and N), which is essential for decomposition (Aita et al., 2012). When crop residues are buried in the soil, the chemical composition of the crop residues seems to play a less critical role in driving the decomposition process. Here, the placement of crop residues becomes more influential for their decomposition because soil moisture is less variable and there is greater access to N for microbial

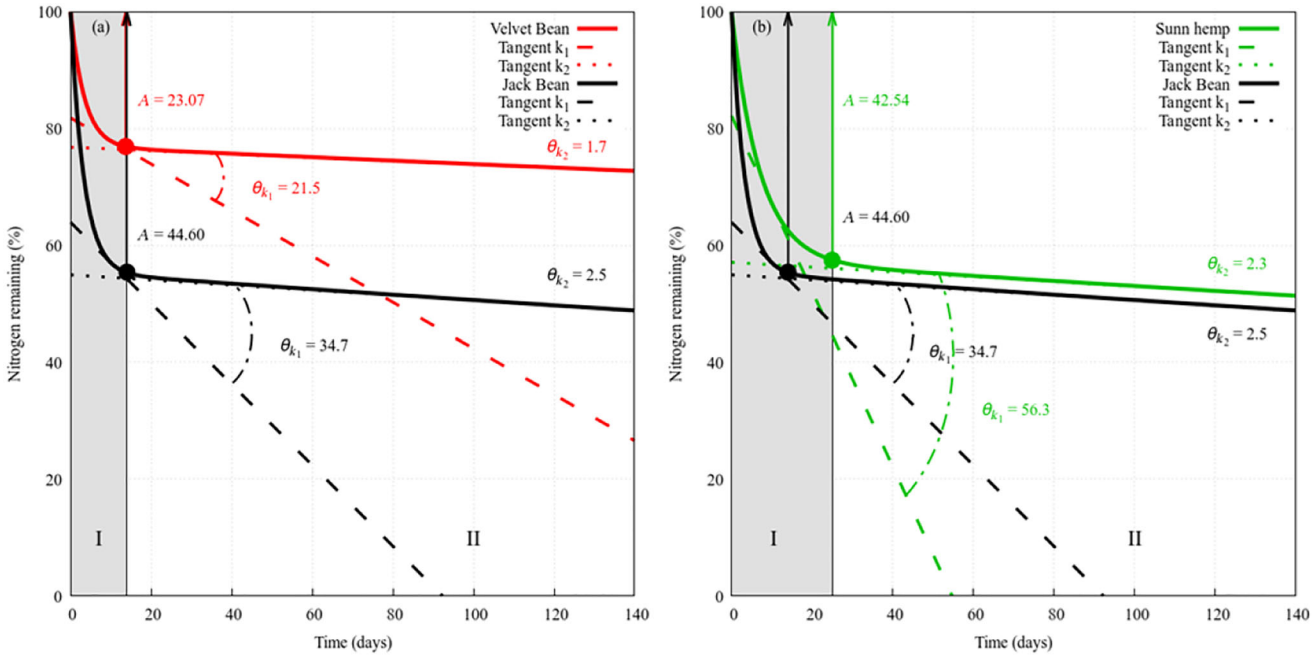


FIGURE 3 Nitrogen release curves over time and their respective tangents and decay rates for the exponential terms k_1 and k_2. The angles (θ_{k1} and θ_{k2}) were obtained by calculating the slope of the tangents on the graph. Data from velvet bean and jack bean of year 1 (a) and sunn hemp and jack bean of year 1 (b).

biomass throughout the decomposition process (Chaves et al., 2021; Tahir et al., 2016). In the first year of the study, the soil had low moisture due to a drought period before cover crops management, and no rainfall occurred during the first 13 days after litter bags were placed in the field. This may have restricted access to N and root decomposition, which would explain the slightly lower decomposition rates in the first year.

Root traits are other important factors to consider when evaluating C and N release. Jani et al. (2015) observed a higher rate of decomposition and so N release with the fine roots of vetch and red clover compared to thicker roots. Zhang and Wang (2015) demonstrated that the decomposition of fine roots was best predicted by lignin content, whereas coarse root decomposition was more dependent on climatic conditions. Based on the study by Redin et al. (2018), we can consider it likely that the pearl millet in our study had a higher proportion of fine roots compared to the other species. According to their findings, approximately 73% of pearl millet roots fall within the 1–2 mm diameter range, whereas about 33% of sunn hemp, jack bean, and velvet bean and only 13% of showy rattlebox and pigeon pea roots are of this size. However, despite this distribution, pearl millet did not exhibit the highest decomposition rates in our study, suggesting that root decomposition dynamics can result from an interaction between root morphological traits and chemical quality. Thicker roots decompose more slowly due to lower quality material and limited access for microbial populations (Silver & Miya, 2001). Typically, the chemical composition of crop residues is determined using finely ground samples. However, this method may not accurately represent how accessible these components are to microbial populations in intact samples. Therefore, it is sometimes difficult to establish clear relationships between the chemical composition and decomposition rates. In addition, the anatomical structure of the roots introduces an additional level of complexity to decomposition. Cutin and suberin are considered recalcitrant components that form barriers that limit enzymatic access and generally slow root decomposition (Rase et al., 2005). These physical and biochemical constraints are not adequately captured by conventional chemical analyses, which may help explain the weak correlations observed between root chemical composition and decomposition rates in our study.

An aspect still poorly studied in no-till systems is the relationship between root decomposition and the addition of biomass and nutrients from aboveground plant residues. In the case of legumes, it is possible that the decomposition of crop residues on the soil surface increases soil N availability, potentially speeding up root decomposition. Herrera et al. (2017) observed that wheat root decomposition was faster when N was supplied in a crop rotation system. In our study, the N contribution from aboveground biomass of summer cover crops ranged from 88.4 to 219.9 kg N ha^{-1} (Weiler et al., 2018). In the case of pearl millet, the relatively low N input from aboveground residues may have resulted in lower soil N availability during decomposition. This could have limited microbial activity and contributed to the lower root decomposition rates observed despite the higher proportion of fine roots.

5 | CONCLUSIONS

The C and N releases from the roots of summer cover crops were evaluated under subtropical field conditions and were related to their chemical composition. The C and N release from roots is intense in the first days and decreases over time. Almost 50% of root N from jack bean, showy rattlebox, sunn hemp, and dwarf pigeon pea is released within the first 21 days, representing about 88% of the total N released from roots. This rapid release highlights the importance of sowing close to cover crop termination to improve N uptake by the subsequent crop. After 21 days, a small amount of N was released from the roots, indicating a minor contribution to the N demand of the subsequent crop beyond this period. The amount of the nutrient released from roots is determined by a combination of the release rate and the size of the nutrient pool. The labile fraction is a critical determinant in short-term N availability, as the decay rates k_1 and k_2 influence the temporal behavior of N release. These findings highlight the importance of considering both root decomposability and the size of labile nutrient pools when predicting short-term nutrient dynamics. However, the C and N release rates were poorly correlated to the chemical composition of summer cover crop roots. This suggests that biochemical composition alone is insufficient to explain the variability in C and N release patterns from summer cover crop roots under field conditions.

AUTHOR CONTRIBUTIONS

Douglas Adams Weiler: Conceptualization; data curation; formal analysis; investigation; writing—original draft; writing—review and editing. **Celso Aita**: Conceptualization; formal analysis; writing—review and editing. **Raquel Schmatz**: Data curation; investigation. **Guilherme Dietrich**: Data curation; investigation. **Bruno Chaves**: Data curation; investigation. **Janquieli Schirmann**: Formal analysis; writing—review and editing. **Guilherme Jurkevicz Delben**: Formal analysis. **Sandro José Giacomini**: Conceptualization; formal analysis; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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