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Winter cover crop root biomass yield in corn and soybean systems

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Abstract

Cover crop (CC) roots are critical for soil ecosystem service delivery including soil stabilization, C and nutrient cycling, soil health improvement, and others. However, most CC studies only evaluate CC aboveground biomass yield, neglecting the belowground portion of the plant. The objectives of this study were to quantify the impacts of (a) CC planting (pre- and post-harvest) dates and (b) early (2–4 wk before main crop planting) and late (at main crop planting) CC termination with and without corn (*Zea mays* L.) residue removal on root biomass yield. We assessed the effects of CC planting or termination dates on root biomass yield for surface 10 cm of soil at four sites through sampling at CC termination and separating roots from soil with a hydropneumatic elutriation system. Pre-harvest CC planting had limited and variable impacts on root biomass yield compared with post-harvest planting. Corn residue removal had no impact on root biomass yield. However, CC termination date had effects at the Irrigated but not at the Rainfed site. At the Irrigated site, late-terminated CCs doubled root biomass yield in both years compared to early terminated and no CC. At this site, under late-terminated CCs, root biomass yield was 2.8 Mg ha^{-1} attributed to their higher aboveground biomass yield and later termination. At the Rainfed site, root biomass yield was 1.6 Mg ha^{-1}. Overall, late termination of CCs can increase root biomass yield; however, early planting into the cash crop did not consistently increase root biomass yield under the conditions of this study.

1 | INTRODUCTION

Plant roots are critical to the delivery of soil ecosystem services as they directly interact with the soil. Roots influence soil processes and properties more than aboveground biomass (Six et al., 2002; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004). Root contribution to soil C is often overlooked as many studies focus on the amount of retained aboveground biomass to preserve soil C (Rasse, Rumpel, & Dignac, 2005; Wilhelm, Johnson, Karlen, & Lightle, 2007). A review by Rasse et al. (2005) showed that root biomass contribution to soil C was, on average, 2.4 times that of aboveground biomass. As another example, 60–80% of new C in particulate organic matter can be from belowground biomass yield (Mazzilli, Kemanian, Ernst, Jackson, & Pineiro, 2015).

Abbreviations: CC, cover crop.

Further, the amount of C stabilized from belowground biomass yield may be 10–24%, but only 0.75% on average for the aboveground biomass depending on the crop (Mazzilli et al., 2015). In terms of aggregation, Six et al. (2002) found that root input to particulate organic matter within aggregates was 1.2–6.1 times that of aboveground biomass. Root-derived soil C contribution is the basis for many changes in soil health and ecosystem services (Blanco-Canqui et al., 2013). Indeed, increased soil C concentration increases wet-aggregate stability and water infiltration and reduces risk of soil compaction (Blanco-Canqui et al., 2013). Roots contribute to soil C more than aboveground biomass yield due to physical (enmeshment with soil particles, association with mycorrhizae, and root hairs), chemical (higher lignin and lignin/N ratios), and physical–chemical (specific root chemistry interacting with soil particles) processes (Rasse et al., 2005).

Roots, particularly fine, laterally spreading roots, stabilize slopes by enmeshing and holding the soil in place (Gyssels, Poesen, Bochet, & Li, 2005). Depending on their architecture, rooting depth, density, thickness, and angle of growth, roots can reduce the incidence of landslides and other erosion events (Stokes, Bengough, Fourcaud, & Sidle, 2009). Roots can also increase water infiltration and porosity by increasing macropore space and continuity (Gyssels et al., 2005). Roots such as those from fibrous-rooted species contribute to soil aggregation through enmeshment of soil particles and production of exudates (Gyssels et al., 2005). Cover crops with deep taproots such as brassicas improve pore space and infiltration (Blanco-Canqui et al., 2015), while CCs with fibrous roots such as cereal rye (*Secale cereale* L.) can enhance soil aggregation (Ruis, Blanco-Canqui, Jasa, Ferguson, & Slater, 2017).

Despite the critical importance of roots, and significant contribution to soil C (Mazzilli et al., 2015), most CC studies only consider aboveground biomass yield when assessing CC benefits. A review by Ruis et al. (2019) found that out of 389 studies on CC aboveground biomass yield, only six reported root biomass yield from grass CCs for corn, sorghum (*Sorghum bicolor* L.), and soybean [*Glycine max* (L.) Merr.] cropping systems in the United States (Ball-Coelho & Roy, 1997; Blesh & Drinkwater, 2014; Fae et al., 2009; Kuo, Sainju, & Jellum, 1996; Kuo, Sainju, & Jellum, 1997; Sainju, Singh, Whitehead, & Wang, 2006), four from legumes (Jani, Grossman, Smyth, & Hu, 2015; Kuo et al., 1996; Kuo et al., 1997; Puget & Drinkwater, 2001), and five from brassicas (Dean & Weil, 2009; Gieske et al., 2016; Gruver, Weil, Zasada, Sardanelli, & Momen, 2010; Kuo et al., 1997; Kuo et al., 1996). According to the few studies, root biomass yield (CC+main crop or CC only) ranges from 0.4 to 5.0 Mg ha^{-1} with an average of 1.89 ± 1.3 Mg ha^{-1} for an average soil depth of 0–32 cm, while CC aboveground biomass yield ranges from 0.28 to 6.95 Mg ha^{-1}, with an average of 3.6 ± 2.2 Mg ha^{-1} (Blanco-Canqui et al., 2020). This means aboveground biomass yield is higher than root biomass yield.

Core Ideas

- Cover crop (CC) planting dates had minimal effects on root biomass yield.
- Planting dates of CCs had small or no effects compared with no CC.
- Early-terminated CCs did not differ in root biomass yield from no CC.
- Late-terminated CCs increased root biomass yield at one of two sites.
- Corn residue removal had no effect on CC root biomass yield.

Plant age can also influence root/aboveground biomass ratios (Amos & Walter, 2006). For example, Amos and Walter (2006) reviewed root/aboveground biomass ratios of corn and showed that this ratio decreased with plant age. The few previous CC root biomass studies did not investigate the impacts of different CC planting or termination dates on root attributes although some studies evaluated the amount of root biomass yield under plants of different ages (i.e., termination dates). For example, in Ohio, Fae et al. (2009) found that an annual ryegrass (*Lolium multiflorum* L.) CC planted in early September produced more root biomass in April than when planted in December. Similarly, in the Netherlands, den Hollander, Bastiaans, and Kropff (2007) reported that root biomass yield of three clover (*Trifolium* spp.) species was twice as high after 83 d of CC seeding than after 41 d of CC seeding, indicating that the longer the CC grows, the greater the accumulation of root biomass. A review of small grain belowground and aboveground partitioning showed that the amount of roots increased with plant age and growth stage through stem elongation (Sun et al., 2018). These comparisons suggest that extending CC growth for a few days or weeks could increase root biomass yield.

A better understanding of how CC management, such as planting and terminating at different times, impact root biomass yield is needed. Also, corn residue is also often baled or grazed (Schmer, Brown, Jin, Mitchell, & Redfearn, 2017). However, how such crop residue management practices impact CC belowground biomass yield is not well understood. The objectives of this study were to quantify the impacts of (a) CC planting (pre- and post-harvest-planted) dates and (b) early (2–4 wk before main crop planting) and late (at main crop planting) CC termination with and without corn residue removal on root biomass yield. We hypothesized that preharvest CC planting and late CC termination will increase root biomass yield.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

We used two ongoing winter cereal rye CC experiments managed under no-till continuous corn or corn–soybean at four sites in eastern Nebraska. Both experiments were under rainfed and irrigated conditions. The Irrigated sites were sprinkler irrigated, but CCs were not irrigated. Only the main crops were irrigated in June through August as needed. The first experiment (Experiment I) includes two planting dates: (a) preharvest or broadcast seeding into standing crops in September and (b) post-harvest or drill seeding after main crop harvest in October or November for rye and four additional CC treatments as described in detail by Barker et al. (2018) and Ruis et al. (2020). Note, that for this study we focused on rye, which yielded the most aboveground biomass. The second experiment (Experiment II) includes early (2–4 wk before corn planting) or late (at corn planting) CC termination under different corn residue removal rates, from which all treatments were sampled. The design and management of each experiment are described below. Additional information on Experiment II is provided by Ruis et al. (2017).

2.1.1 | Experiment I: Pre-and post-harvest-planted cover crops

We established Experiment I at two sites in fall 2015 and collected data in 2018 and 2019 (4 and 5 yr after experiment initiation). The first site was at the University of Nebraska-Lincoln's (UNL) Eastern Nebraska Research and Extension Center near Mead, NE (hereafter referred to as Rainfed site in Experiment I) and the second was at the UNL's South Central Agricultural Laboratory near Clay Center, NE (hereafter referred to as Irrigated site in Experiment I). Both sites were under no-till continuous corn and corn–soybean systems. The soil at the Rainfed site was Tomek (fine smectitic, mesic Pachic Argiudolls) and Filbert (fine, smectitic, mesic Vertic, Argialbolls) silt loams and at the Irrigated site was a Hastings silt loam (fine, smectitic, mesic udic Argiustolls) with slopes of <1%. Mean annual precipitation was 787 mm and temperature was 9.6 °C for the Rainfed site in Experiment I and 688 mm and 13 °C for the Irrigated site in Experiment I. Table 1 shows

TABLE 1 Monthly precipitation and mean temperatures at two experiments and four sites (Irrigated site at Clay Center included both experiments) under different cover crop management strategies in Nebraska during 2017–2019

Month	Experiment I								Experiment II							
	Rainfed				Irrigated				Rainfed				Irrigated			
	Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature	
	mm		°C		mm		°C		mm		°C		mm		°C	
	2017–2018	2018–2019	2017–2018	2018–2019	2017–2018	2018–2019	2017–2018	2017–2018	2018–2019	2017–2018	2018–2019	2018–2019	2017–2018	2018–2019	2017–2018	2017–2018
September	128	195	19.5	19.4	62	137	19.8	19.6	95	194	20.7	19.9	62	137	19.8	19.6
October	111	62	12.2	9.2	113	115	12.4	9.6	158	81	12.7	10.1	113	115	12.4	9.6
November	5	20	3.4	−0.2	4	20	4.9	1.6	3	36	4.7	0.7	4	20	4.9	1.6
December	6	62	−2.5	−1.8	7	113	−1.3	−0.6	14	94	−2.6	−0.9	7	113	−1.3	−0.6
January	19	7	−7.4	−4.9	9	8	−4.6	−2.6	16	28	−4.7	−4.3	9	8	−4.6	−2.6
February	17	25	−6.0	−9.8	15	23	−4.5	−6.9	28	55	−4.8	−7.8	15	23	−4.5	−6.9
March	77	58	3.6	−0.3	28	68	4.3	0.9	82	58	4.6	1.2	28	68	4.3	0.9
April	7	31	5.7	10.7	27	11	5.7	11.2	17	27	6.4	12.1	27	11	5.7	11.2
May	77	174	19.8	14.1	75	242	19.7	14.2	46	191	20.4	15.4	75	242	19.7	14.2

the monthly precipitation and mean temperatures during the study years.

The experimental design at both sites for Experiment I was a factorial with pre- and post-harvest-planted CC treatments of no CC and cereal rye under continuous corn and corn–soybean. In Experiment I, the Rainfed site had three replications and Irrigated site four replications. Table 2 describes experiment location and layout, treatments, crop rotation, and management. We broadcast the pre-harvest-planted CCs into standing crops by hand in early to mid-September and drilled the post-harvest-planted CCs at 18 cm row spacing in mid-October to mid-November. For Experiment I, CCs were chemically terminated mid-April to early May, 1–4 wk before main crop planting depending on year and rotation (Table 2).

2.1.2 | Experiment II: Early and late-terminated cover crops

We established Experiment II at two sites in fall 2014 and collected data in 2018 and 2019 (5 and 6 yr after experiment establishment). The first site was at the UNL Rogers Memorial Farm near Lincoln, NE (hereafter referred to as Rainfed site in Experiment II) and second site was at the UNL South Central Agricultural Laboratory near Clay Center, NE (hereafter referred to as Irrigated site in Experiment II) under continuous no-till corn. The soil at the Rainfed site in Experiment II was an Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls) with about 3% slope and at the Irrigated site in Experiment II was a Hastings silt loam (fine, smectitic, mesic udic Argiustolls). Mean annual precipitation was 818 mm and mean annual temperature was 10 °C for the Rainfed site and 688 mm and 13 °C for the Irrigated site. Table 1 shows the monthly precipitation and mean temperatures during the study years.

The experimental design at both sites was a factorial with five corn residue removal rates (0, 25, 50, 75, and 100%) and three CC treatments (no CC, early terminated CC, and late-terminated CC) with four replicates (Table 2) for a total of 60 plots. We imposed the residue removal treatments each fall by shredding corn stalks at 10-cm height, manually removing residues from select rows, and redistributing remaining residue to achieve the 25, 50, 75, and 100% residue removal rates. For example, to achieve 50% residue removal, residue was removed from 6 of the 12 rows and remaining residue redistributed among all 12 rows. A winter rye CC was drilled at 15-cm row spacing at rates of 67 kg ha^{-1} at the Rainfed and 112 kg ha^{-1} at the Irrigated site after corn harvest. The early terminated CCs were chemically terminated early to mid-April about 2–4 wk prior to corn planting and the late-terminated CCs were chemically terminated in late April to mid-May at corn planting.

2.2 | Cover crop aboveground and root biomass sampling and processing

For Experiment I, we collected CC aboveground biomass yield from the pre-harvest- and post-harvest-planted rye and root biomass yield from no CC and rye in continuous corn and corn–soybean. We only evaluated the impact of the pre- and post-harvest planting of rye vs. no CC on root biomass yield as rye was the most successful treatment. For the corn–soybean rotation, the previous crop in 2018 was corn and previous crop in 2019 was soybean.

For Experiment II, we collected aboveground biomass yield from early and late-terminated CCs under all five residue removal rates, and root biomass yield from no CC and early and late-terminated CCs under all five residue removal rates. We measured aboveground CC biomass and root biomass at CC termination for both experiments in spring 2018 for all four sites and in 2019 for three sites. Cover crop aboveground and root biomass yield were not assessed at Rainfed site of Experiment I in 2019 due to flooding.

Aboveground biomass was clipped at soil level from two 0.25 m^2 per plot, dried at 65 °C for 3 d, and weighed. Aboveground biomass was generally low and variable, but we hypothesized that it would still affect root biomass yield. Cores were collected using a truck-mounted Giddings hydraulic probe of 7.5 cm diam. to 20-cm depth and sliced into 0- to 10-cm and 10- to 20-cm intervals. Hand excavation of individual CC plants before coring showed the majority of roots were in the upper 10 cm. A study by Mazilli et al. (2015) also showed that the majority (82–95%) of corn and soybean roots are concentrated in the upper 10 cm of the soil. Thus, the total sample area was 132.5 cm^2 and total volume was 1324.7 cm^3 per 10-cm depth interval. Cores were collected from three locations in each plot after moving crop residues aside. Two samples were from within and one between the CC rows located on the shoulder of the corn rows. Our sampling protocols (i.e., area sampled, sampling depth, number of samples per plot, and sampling within and between CCs) were similar to those in previous studies (Fae et al., 2009; Gabriel & Quemada, 2011; Kuo et al., 1996). Soil cores were composited by plot and depth, sealed in plastic bags, and stored at 4 °C until processing about 1 mo later.

Roots from the 0- to 10-cm depth were separated using a hydropneumatic elutriation system (Gillison Variety Fabrication, Inc.) with 3.52 kg cm^{-2} of water pressure and 0.49 kg cm^{-2} of air pressure for 10 min (Smucker, McBurney, & Srivastava, 1982). Cover crop roots and main

TABLE 2 Location and management of the two experiments and four cover crop (CC) sites in Nebraska

Experiment	Location	Irrigation regime	Crop	Crop planting timing after CC termination	Plot size	CC Treatment	CC Seeding rate	CC Planting date	CC Termination date
				wk	m		kg ha^{-1}		
I (planting dates)	Mead, NE (41.15° N, 96.40° W)	Rainfed	Continuous corn Corn (2018)–soybean (2019)	2–3	4.5 × 9	Pre-harvest planted Post-harvest planted	75.6	Early September Mid-October to mid-November	Late April to early May
	Clay Center, NE (40.56° N, 98.13° W)	Irrigated	Continuous corn Corn (2018)–soybean (2019)	1–4	6 × 9	Pre-harvest planted Post-harvest planted	75.6	Mid-September Mid to late October	Mid-April to early May
II (termination dates)	Lincoln, NE (40.843° N, 96.465° W)	Rainfed	Continuous corn with five residue removal rates	2–3 <1	9 × 18	Early terminated Late terminated	67.0	Late October to early November	Early to mid-April Late April
	Clay Center, NE (40.56° N, 98.13° W)	Irrigated	Continuous corn with five residue removal rates	3–4 <1	7.5 × 18	Early terminated Late terminated	112.0	Late October to early November	Mid-April Early to mid-May

crop roots were not separated because our goal was to measure the contribution of CC roots to the total amount of roots. Any additional aboveground crop residues were removed, and roots dried at 60 °C for 24 h and weighed. We assessed root biomass by hand on a subset of samples for the 10- to 20-cm depth as the amount of roots was perceived to be too small to be accurately captured through the hydropneumatic elutriation method. Indeed, root biomass from the 10- to 20-cm depth was < 0.1 Mg ha^{-1} and was not evaluated further.

2.3 | Statistical analysis

Data on root biomass yield for the 0- to 10-cm depth and CC aboveground biomass yield were analyzed by year and site using PROC MIXED ANOVA in SAS v. 9.4 for a factorial design (SAS Institute, 2018). Fixed effects were planting date and treatment (CC vs. no CC) or residue removal rate and CC termination date. The random factor was replication. Treatment means separation was through LSD at the .05 probability level. Thus, the LSD comparisons from PROC MIXED for the Rainfed and Irrigated sites with pre-and post-harvest-planted CCs were used to compare the controls to (a) pre-harvest rye and (b) post-harvest rye which allowed for the investigation whether or not the pre-harvest or post-harvest planting had greater effects on root attributes than no CC.

3 | RESULTS

3.1 | Impacts of pre- and post-harvest planting rye on root biomass

As indicated earlier, pre- and post-harvest planted rye impacts on aboveground and root biomass yields were evaluated 4 and 5 yr after experiment establishment. Cover crop planting date effects on CC aboveground biomass differed by site and year. In Year 4, at the Rainfed site, pre-harvest-planted CC aboveground biomass yield was 16 times lower in continuous corn and 12.6 times higher in corn–soybean (following corn) compared to post-harvest-planted CCs (Table 3). At this site in Year 5, we did not assess root or aboveground biomass yield because multiple flooding events prevented sampling. At the Irrigated site, CC planting date did not affect aboveground CC biomass yield in either rotation or year (Table 3).

Similar to aboveground biomass yield, CC planting date impacts on root biomass yield varied by site and year. At the Rainfed site, CC planting date did not significantly affect root biomass yield in the 0- to 10-cm

TABLE 3 Influence of cover crop (CC) planting date of pre-harvest (about 1 mo prior to harvest) or post-harvest (Experiment I) on mean ± SD spring aboveground CC biomass yield in continuous corn and corn (2018)–soybean (2019) rotation at a Rainfed (Mead, $n = 6$ per rotation) and an Irrigated (Clay Center, $n = 8$ per rotation) site in Nebraska after 4 and 5 yr of CCs

Treatment	Aboveground biomass production							
	Rainfed				Irrigated			
	Continuous corn		Corn–soybean		Continuous corn		Corn–soybean	
	Year 4	Year 5	Year 4	Year 5	Year 4	Year 5	Year 4	Year 5
	Mg ha^{-1}							
Pre-harvest planted	0.21 ± 0.01a[a]	na	1.51 ± 0.67a	na	0.29 ± 0.02	0.12 ± 0.14	0.01 ± 0.10	0.08 ± 0.05
Post-harvest planted	0.01 ± 0.1b	na	0.12 ± 0.02b	na	0.40 ± 0.03	0.19 ± 0.07	0.03 ± 0.08	0.13 ± 0.06

Note. na denotes not available due to flooding events.
[a]Means with the same lowercase letter within a year, site, and crop rotation are not significantly different at $p < .05$.

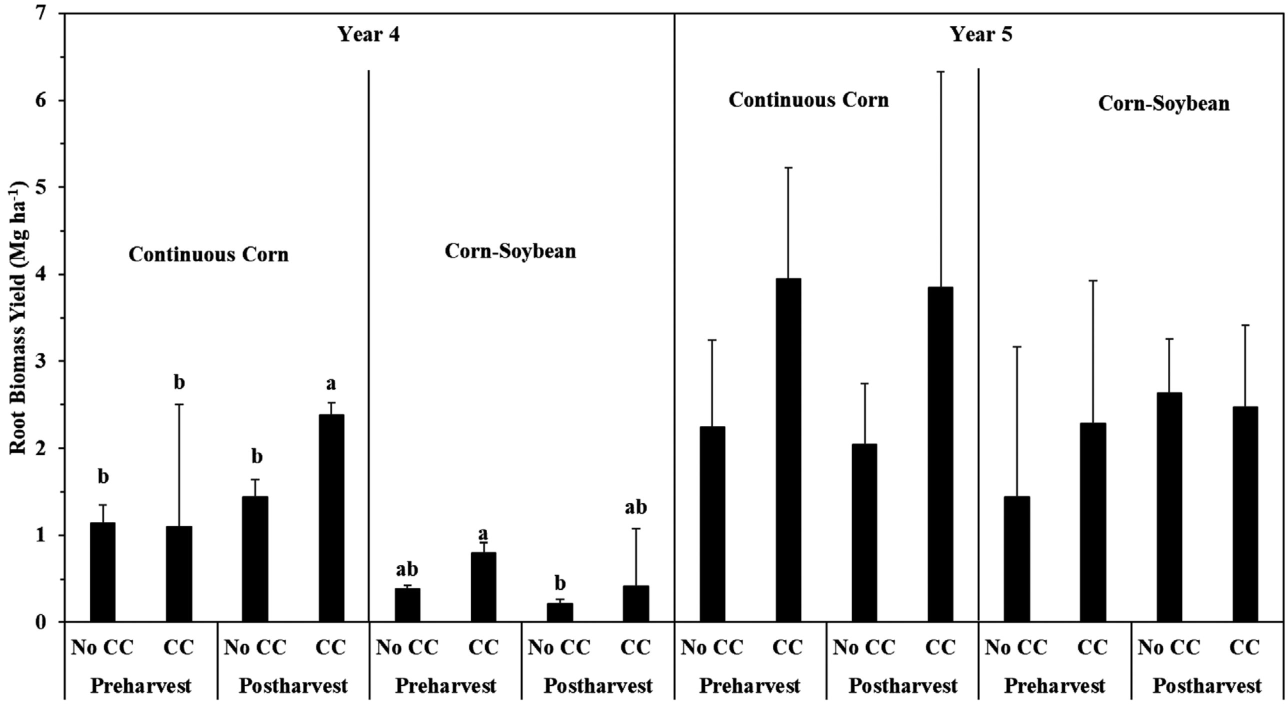

FIGURE 1 Pre- (about 1 mo prior to harvest) and post-harvest-planted cover crop (CC) impacts (Experiment I) on root biomass yield for the 0- to 10-cm depth under irrigated (Clay Center) continuous corn and corn (2018)–soybean (2019) after 4 and 5 yr of CCs in Nebraska. Bars with the same letter within a year and cropping system are not statistically different at $p < .05$. Error bars are standard deviation

TABLE 4 Influence of cover crop (CC) termination date of early (about 2-4 wk prior to planting) or late (at corn planting) (Experiment II) on spring mean ± SD CC biomass yield in continuous corn at a Rainfed (Lincoln, $n = 60$) and an Irrigated (Clay Center, $n = 60$) site in Nebraska after 5 and 6 yr of CCs

	Aboveground biomass production			
	Rainfed		Irrigated	
Treatment	Year 5	Year 6	Year 5	Year 6
	Mg ha^{-1}			
Early terminated CC	0.13 ± 0.24	0.10 ± 0.02b[a]	0.12 ± 0.03b	0.09 ± 0.02b
Late-terminated CC	0.16 ± 0.03	0.19 ± 0.08a	3.62 ± 1.72a	0.85 ± 0.17a

[a]Means with the same lowercase letter within a year and site are not significantly different at $p < .05$.

depth in either rotation. Root biomass yield in continuous corn averaged 2.46 Mg ha^{-1} under pre-harvest-planted and 1.31 Mg ha^{-1} under post-harvest-planted. In corn–soybean, root biomass yield averaged 1.53 Mg ha^{-1} under pre-harvest planted and 1.10 Mg ha^{-1} under post-harvest planted. In Year 4 at the Irrigated site in Experiment I, planting date and CC effects on root biomass yield differed by rotation. Post-harvest-planted CCs increased root biomass yield under continuous corn, but not under corn–soybean (Figure 1). At the same site in Year 5, CC planting date did not affect root biomass yield. Belowground biomass yield was not correlated with CC aboveground biomass yield, duration of the CC period, mean temperature during the CC period, or total precipitation during the CC period ($p > .05$).

3.2 | Impacts of early and late-terminated rye on root biomass

The effects of early and late-terminated rye CC on aboveground and root biomass yield were studied 5 and 6 yr after experiment establishment. As indicated earlier, in this experiment, CC termination dates were studied under five levels of corn residue removal (0, 25, 50, 75, and 100%). At both sites, corn residue removal rate had no effect. Cover crop termination date did affect CC aboveground biomass yield, but this effect varied by site and year (Table 4). At the Rainfed site, CC termination date did not affect aboveground biomass yield in Year 5 but affected aboveground biomass yield in Year 6. In Year 6, late-terminated CCs produced 0.09 Mg ha^{-1} more biomass compared to early

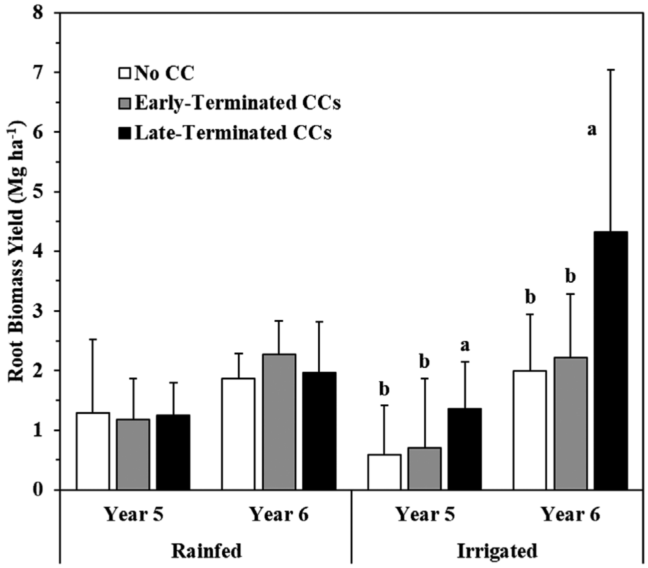

FIGURE 2 Cover crop (CC) termination date of early (2-4 wk prior to planting corn) or late (at corn planting) (Experiment II) on root biomass yield for the 0- to 10-cm depth in Rainfed and Irrigated no-till continuous corn sites in Nebraska after 5 and 6 yr of CCs. Bars with the same lowercase letter within site and year are not statistically different at $p < .05$. Error bars are standard deviation

terminated CC. At the Irrigated site, CC termination date affected CC aboveground biomass yield in both years. Late-terminated CCs produced 30 times more biomass in Year 5 and 9.4 times more in Year 6 compared with early terminated CCs.

Corn residue removal did not affect root biomass yield at any site. Thus, we averaged data on root biomass yield across the five residue removal rates. Cover crop termination date effects on root biomass yield varied by site. At the Rainfed site, CC termination date had no effect on root biomass yield. At this site, root biomass yield averaged across CC treatments was 1.2 Mg ha^{-1} in Year 5 and 2.0 Mg ha^{-1} in Year 6 for the 0- to 10-cm depth (Figure 2). At the Irrigated site, root biomass yield of early terminated CCs did not differ from no CC, but late-terminated CCs produced about two times more root biomass yield in both years (Figure 2).

Root biomass yield was not correlated with CC aboveground biomass yield at the Rainfed site in either year ($r = .084$ in 2018 and $r = .17$ in 2019, $p < .05$), but it was correlated at the Irrigated site in both years (Figure 3a–3b). Total root biomass yield was also correlated with the duration of the CC period ($r = .19$; $p = .016$; Figure 4), but not mean temperature during the CC period, or total precipitation during the CC period ($p > .05$). Thus, as CC aboveground biomass yield increased, root biomass yield also increased . Similarly, as the duration of the CC period increased, total root biomass yield increased by 0.043 Mg ha^{-1} d^{-1}.

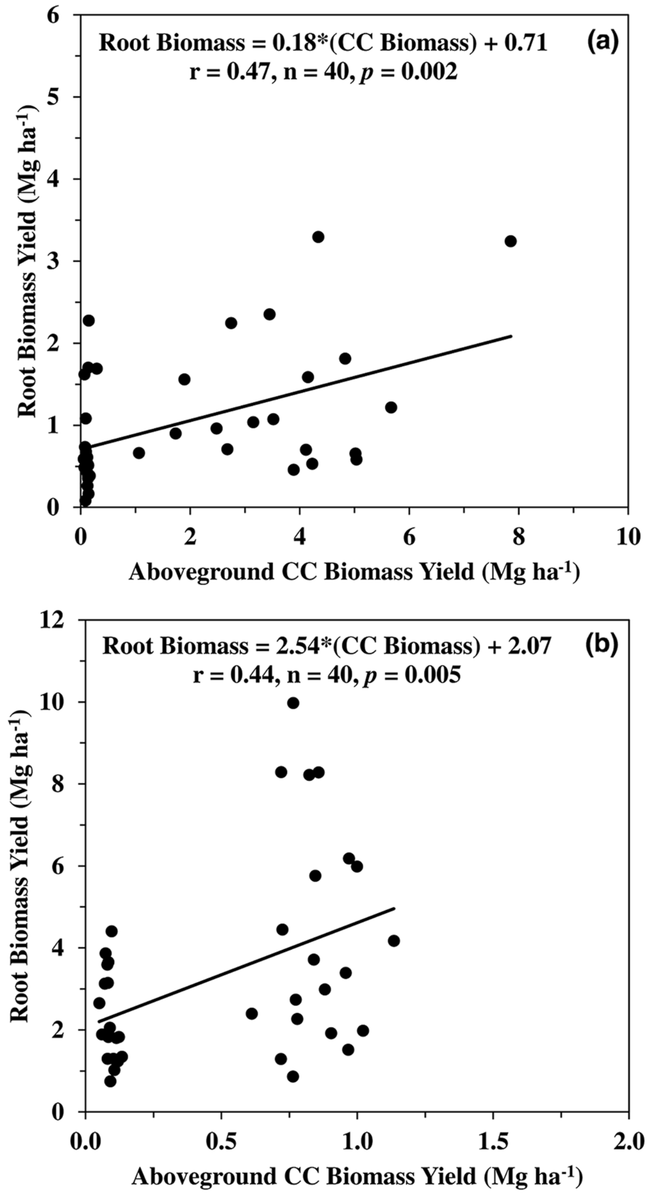

FIGURE 3 Relationship of total root biomass yield with cover crop (CC) aboveground biomass yield at the irrigated site in 2018 (a) and 2019 (b) for the early and late-terminated CC experiment

4 | DISCUSSION

4.1 | Impacts of pre- and post-harvest planting rye on root biomass

Pre-harvest planting of a cereal rye CC did not generally increase root biomass yield (CC+main crop roots) compared to post-harvest planting. The few effects of pre-harvest-planted CCs on root biomass yield at the Rainfed site in Experiment I coincide with the low aboveground biomass (<0.25 Mg ha^{-1}) yield in spring under both systems at this site (Table 3). The overall low CC biomass yield may have exerted small or no differences in root biomass

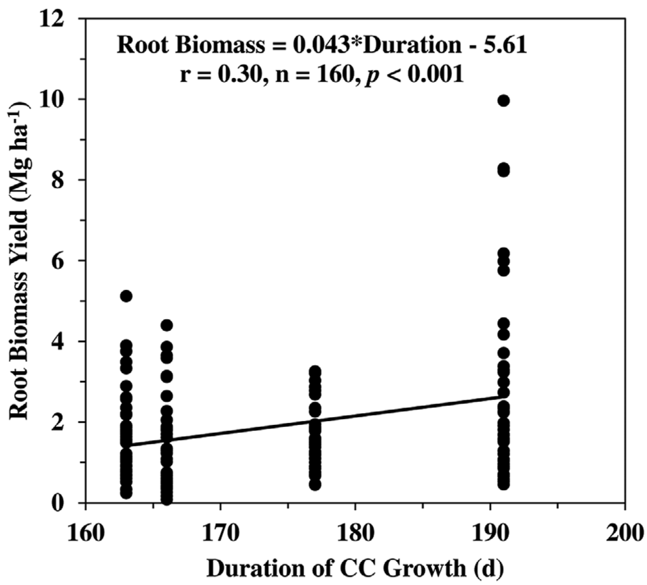

FIGURE 4 Relationship of total root biomass yield with duration of the CC growing period for the early and late-terminated CC experiment

yield making detection of changes more difficult. A study that evaluated corn root biomass yield at different growth stages showed that root biomass yield of corn was about 2 Mg ha^{-1} at physiological maturity (Amos & Walters, 2006), which indicates that much of what we measured in root biomass yield was from corn. Adopting additional CC management strategies such as planting CCs earlier than September or planting following corn silage or winter wheat may be potential options to increase root biomass yield (Ruis et al., 2019).

At the Irrigated site, the increase in root biomass yield with post-harvest compared to pre-harvest-planted CCs in continuous corn in Year 4 was not unexpected because post-harvest-planted CCs produced more aboveground biomass. The increased root biomass yield with post-harvest-planted CCs was likely due to differences in rainfall patterns. Pre-harvest-planted CCs were broadcast seeded in September when rainfall was 6.1 cm compared with 11.2 cm in October (Table 1). In Year 5, rainfall amounts were similar between September (13 mm) and October (11 mm). The lower rainfall in September of Year 4 and similar rainfall amounts between September and October in Year 5 likely led to the different responses in root biomass yield between years.

No previous study compared the influence of CC planting date on root biomass yield. Thus, we compared our results with studies assessing root biomass yield at different times. In Ohio, annual ryegrass CC had root biomass yield of 1.3 Mg ha^{-1} in December and 2.0 Mg ha^{-1} in April (Fae et al., 2009). In the Netherlands, three clover species was twofold higher after 83 d of CC seeding compared with 41 d after CC seeding, indicating longer CC growth equates to greater accumulation of root biomass (den Hollander et al., 2007). Our root biomass yields under pre- vs. post-harvest-planted CCs generally did not change in spite of the additional 1–2 mo of growth under pre-harvest planting. This could be due to the overall low CC biomass being overwhelmed by the previous year's main crop roots. Further, our correlation analysis suggests that lengthening the CC period in the fall, by planting into the main crops may not enhance belowground biomass yields. Since minimal changes were observed in belowground biomass yields, we would expect few changes in soil properties due to CCs as described in a companion study by Ruis et al. (2020).

4.2 | Impacts of early- and late-terminated rye on root biomass

The lack of residue removal rate effects on CC root biomass yield can be attributed to corn residue removal rate generally not impacting CC aboveground biomass yield (Ruis et al., 2017). However, it is important to note that high rates of crop residue removal can negatively impact soil properties (Ruis et al., 2017). The rye CCs terminated in early to mid-May increased root biomass yield compared to CCs terminated in mid-April. The delayed termination led to an additional 0.2–0.7 Mg ha^{-1} of root biomass yield per week beyond early termination. This suggests that prolonging the CC growing season, even by just a short time can increase root biomass yield. Late-terminated CCs were expected to have higher root biomass yield compared to early terminated CCs due to the higher aboveground biomass yield owing to the longer growing time (2–4 wk). At the Rainfed site of this experiment, the additional 2 wk of growth (late termination in late April) did not result in higher root biomass yield while at the Irrigated site, late-terminated CCs (late termination in early to mid-May) grew more due to the 3–4 wk longer growth period, increasing both aboveground and root biomass yield. The positive and significant relationship between CC period and belowground biomass yield in Figure 4 further supports that growing CCs longer can improve biomass yields.

A review of literature shows that no study has evaluated root biomass yield under different CC termination dates. However, because longer durations of CC growth are known to increase CC biomass production (Table 4; Ruis et al., 2017) they would also be expected to increase root biomass. Aboveground and root biomass yield of fibrous-rooted CC species is positively correlated across studies in the literature, regardless of root separation from main crops ($r = .27$; $n = 50$; $p = .056$) (Ball-Coelho & Roy, 1997;

Kuo et al., 1997; Griffin, Kiebman, & Jemison, 2000; Blesh & Drinkwater, 2014; den Hollander et al., 2007; Fae et al., 2009; Gabriel & Quemada, 2011; Jani et al., 2015; Kankanen & Eriksson, 2007; Puget & Drinkwater, 2001), suggesting that as aboveground biomass yield increases, root biomass yield increases.

If the rate of increase in belowground biomass yield was 0.043 Mg ha^{-1} d^{-1}, and crop roots contain about 38% C (Ma et al., 2018), 0.016 Mg C ha^{-1} d^{-1} of CC growth. Thus, if increasing root C content is the goal of planting the CC, then longer CC growing periods, particularly in spring, may be needed to attain sufficient CC biomass yield. In the case of our study, the delayed termination at the Irrigated site increased root yield by 0.2–0.7 Mg ha^{-1} per week depending on the year, equating to 0.08–0.27 Mg ha^{-1} increase in C. It is important to note that allowing the CC to grow for longer periods can negatively impact main crop yields in some years due to reductions in soil water content (Ferguson, Nienaber, Eigenberg, & Woodbury, 2005; Nielsen et al., 2016; Ruis et al., 2017). In some years, yields can decline, but when main crop yields are already high, the reduction in yield can be of less concern (Ruis et al., 2017).

5 | CONCLUSIONS

In general, this study evaluating the impact of (a) CC planting dates and (b) CC termination dates with and without corn residue removal on root biomass yield showed that the longer the CC growing season, the more CCs may increase root biomass. Results suggest that corn residue removal did not impact root biomass yield although excessive rates of residue removal can negatively impact soil properties. Pre-harvest planting of CC did not generally enhance belowground biomass yield, nor was fall planting time correlated with the CC growing period, indicating that planting earlier in the fall may not improve root attributes compared to traditional planting after main crop harvest. However, terminating the CC later in the spring, such as a corn planting, can improve CC root contribution to belowground biomass yield by 0.043 Mg ha^{-1} d^{-1}, which equates to about 0.016 Mg ha^{-1} d^{-1} of C potentially added to the soil. The balance among maximizing CC growth, soil health, and crop yields needs consideration in future research. Overall, late termination of CCs can increase root biomass yield; however, early planting by overseeding into the cash crop did not consistently increase root biomass yield under the conditions of this study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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