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Summer cover crops impact weed biomass and C and N acquisition

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Abstract

Despite the potential to improve nutrient cycling, weed suppression, and system resilience, mixed-species cover crops remain underutilized in organic irrigated systems. This study evaluated the influence of cover crop diversity and associated weeds on biomass production (both cover crops and weeds), as well as carbon (C) and nitrogen (N) acquisition, and weed suppression. Three summer cover crop–carrot rotation cycles (2018–2019, 2019–2020, and 2021–2022) were established on a clay-textured soil in a 50-ha organic pivot-irrigated field in Alberta. Cover crops included a polyculture (POLY) and monoculture of mustard (MUST; white [*Sinapsis alba* L.] and brown [*Brassica juncea* (L.) Czern.]), buckwheat (BWHT, *Fagopyrum esculentum* Moench), faba bean (FABA; *Vicia faba* L.), and a no-cover control (CONT). Cover crop performance varied by species and year. POLY consistently produced the highest biomass (up to 2.79 Mg ha^{-1}) and, along with BWHT, achieved the greatest weed suppression (62%–72%), while FABA and MUST were least effective. FABA had the highest N concentration (27–32 g kg^{-1}) and lowest C:N ratios (13–16), whereas BWHT had the highest C:N ratios (21–36). C and N uptake were generally greater in POLY (up to 1.20 Mg C ha^{-1}; 74 kg N ha^{-1}) and lowest in FABA or MUST, with POLY and BWHT accounting for the largest share of total biomass nutrient uptake (53%–69%). Overall, these findings demonstrate that cover crop performance is highly context-dependent, with POLY and BWHT offering more consistent benefits in biomass production, weed suppression, and nutrient acquisition, and highlight the complementary role of weeds in nutrient cycling.

Abbreviations: AAFC, Agriculture and Agri-Food Canada; BWHT, monoculture of buckwheat; CONT, no-cover control; FABA, monoculture of faba bean; GDD, growing degree days; MUST, monoculture of mustard; POLY, polyculture.

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Plain Language Summary

Cover crops offer vital environmental benefits in organic farming, including enhanced soil health, nutrient retention, weed suppression, and, often resulting from these benefits, greater subsequent crop yield. Using mixed-species cover crops that combine legume and non-legume may improve sustainability by supplying organic nutrients to the soil and providing additional benefits like nutrient retention and weed suppression. This study assessed plant biomass production, nutrient uptake, and weed suppression by mixed-species versus single-species cover crops at an irrigated organic farm. Overall, mixed species was recommended for its superior biomass production and weed suppression while emphasizing the need for further investigation into the contribution of weed to nutrient cycling in organic systems as they contributed a large portion of nutrients.

1 | INTRODUCTION

Cover crops provide numerous agroecosystem benefits, including improved soil health, weed suppression, and pest management (Lavergne et al., 2021; Sharma et al., 2018; Souza et al., 2025). Traditionally, cover crops have been grown as monocultures or simple graminoid-legume mixtures (e.g., barley/pea [*Pisum sativa* L.]) (Smith et al., 2014). However, recent studies suggest that multi-species mixtures offer greater benefits and agroecosystem services (Finney et al., 2017; Florence & McGuire, 2020), with both ecological theory and empirical evidence supporting the use of species-rich polycultures (Elhakeem et al., 2021; Wendling et al., 2019). Adoption of complex mixtures is increasing among farmers (Franco et al., 2021; Hunter et al., 2019). According to the 2020 Prairie Cover Crop Survey, 30% of Canadian respondents still used monoculture, 45% had increased species diversity, and 11% grew mixes with 12 or more species (Morrison & Lawley, 2021). Similarly, 82% of cover crop growers in a US survey reported using species mixes (Conservation Technology Information Center, 2023).

Diverse cover crop mixes may be more resilient to environmental variability, as complementary traits like varied architecture and phenology may improve resource capture compared to monocultures (Finney et al., 2016; Florence et al., 2019; Wendling et al., 2019). For instance, Finney et al. (2017) reported that certain species combinations consistently delivered multiple ecosystem services such as biomass production, weed suppression, N retention, and increased profitability to subsequent cash crops. Among these services, weed suppression is one of the most significant benefits (Baraibar, Hunter, et al., 2018; Nichols et al., 2020; Osipitan et al., 2019). Cover crops can inhibit weed emergence and seed bank replenishment, and may exhibit allelopathic effects post-termination, which further reduce weed pressure in subsequent crops (Wauters et al., 2021). Increasing species diversity in cover crop mixes has been associated with enhanced weed suppression (McKenzie-Gopsill et al., 2022). However, Smith et al. (2020) found that in some cases, a highly suppressive monoculture outperformed species mixtures, suggesting that mixture performance can vary depending on species traits and objectives.

Weeds play a complex role in agroecosystems. While viewed as undesirable competitors that reduce crop yields, weeds can enhance species diversity and contribute to nutrient cycling, especially carbon (C) and nitrogen (N) dynamics. This creates a tension between the ecological benefits of weeds and the agronomic goal of suppressing weeds. Despite this potential role, the contribution of weeds in C and N cycling remains underexplored (Blaix et al., 2018; Chen et al., 2023). Some studies suggest that under certain conditions, weeds within cover crops may enhance ecosystem services (Baraibar et al., 2021). Strategic weed management could allow beneficial diversity without compromising productivity (Kordbacheh et al., 2023; Storkey & Neve, 2018). Esposito et al. (2023) proposed the concept of "neutral weed communities" that coexist with crops without negatively impacting crop yield. Although weeds compete for nutrients (Blackshaw et al., 2005), few studies have quantified weed contribution to C and N cycling when incorporated into the soil. Blackshaw et al. (2003) found that many weed species took up equal or greater amounts of soil N than wheat (*Triticum aestivum* L.) or canola (*Brassica napus* L.). In addition to influencing N release, weed residue quality (e.g., C:N ratio) can also affect residue persistence on the soil surface, which in turn can influence weed seedling emergence through physical or allelopathic effects (Chen et al., 2023; Lindsey et al., 2013), yet this remains an overlooked component of agroecosystem function.

Cover cropping is a common practice in organic vegetable production, and growers consider the seasonal niche, growing window, and integration within rotation strategies (Van Eerd

et al., 2023). These considerations are particularly important for summer cover crops in irrigated systems, as timely establishment and termination are critical to maximizing biomass production, weed suppression, and nutrient cycling without impacting subsequent cash crops. In Canada's cold climate, particularly the prairies, cover crops are generally categorized into two seasonal niches: summer-planted (full-season) or fall-planted (shoulder-season). Summer cover crops replace cash crops or fallow periods and are often used as a living mulch (Geddes & Gulden, 2021; Morrison & Lawley, 2021; Moyer et al., 2000), whereas fall-planted crops, such as barley (*Hordeum vulgare* L.) or fall rye (*Secale cereale* L.), often winterkill or re-grow in spring ahead of the next planting (Flood & Entz, 2019; Larney et al., 2015; Morrison & Lawley, 2021). Although fall or early cool-season cover crops are widely adopted, their biomass production depends on an extended fall growing window, which is often limited in short-season climates (Wauters et al., 2021). Summer-planted cover crops, particularly under irrigation, offer a more reliable approach to maximizing cover crop biomass and nutrient inputs within a constrained window (Candelaria-Morales et al., 2022). This is especially relevant in semiarid regions like southern Alberta, where dryland cover crop performance is frequently restricted by low precipitation.

Despite their potential, summer cover crops remain underutilized in organic systems, particularly in irrigated vegetable rotations, yet summer cover cropping offers promising opportunities to enhance weed suppression, nutrient cycling, and overall system resilience. This study aimed to examine how summer cover crop diversity and associated weeds interact to influence agroecosystem functioning. Specifically, this study (i) compared biomass production and weed suppression in monocultures versus polyculture cover crops, recognizing that weeds can reduce crop performance; (ii) quantified weed contributions to total aboveground biomass, acknowledging weeds potential role in ecosystem services such as nutrient cycling; and (iii) assessed C and N acquisition by both cover crops and weeds to evaluate their combined effects on soil nutrient dynamics. Agricultural producers considering the adoption of summer cover crops would benefit from this work, as it provides insights into how different cover crop strategies influence weed dynamics, nutrient acquisition, and overall system productivity.

Core Ideas

- Polyculture blend had increased biomass production and weed suppression.
- Biomass production and weed suppression are just two factors to consider with cover crops.
- Weeds also provisioned ecosystem services of carbon (C) and nitrogen (N) acquisition.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted on a 50-ha irrigation pivot circle (49° 49′ N, 112° 36′ W) located on an organic farm, 18 km northeast of the Agriculture and Agri-Food Canada (AAFC) Research and Development Centre in Lethbridge, AB. The soil was a clay-textured dark brown Chernozem (0- to 7.5-cm depth: 0.24 kg kg^{-1} sand, 0.27 kg kg^{-1} silt, and 0.49 kg kg^{-1} clay). Long-term (1981–2010) mean annual precipitation was 399 mm, with a mean air temperature of 6.4°C at the AAFC Lethbridge station. Detailed growing season weather conditions are presented in Table 1.

The farm fully transitioned to certified organic production in 2005 and, since that time, has followed a 5-year crop rotation of alfalfa (*Medicago sativa* L.)–alfalfa–alfalfa–winter wheat–dry bean (*Phaseolus vulgaris* L.). Each year, an area of the dry bean phase was replaced with a summer-planted polyculture cover crop, which was soil-incorporated in August and followed by planted carrots in the following May–June. For this study, three cover crop–carrot rotation cycles were established: 2018–2019, 2019–2020, and 2021–2022 (delayed 1 year due to the Covid-19 pandemic). Each cycle was located on a different area of the 50-ha irrigation pivot circle, that is, all the plots per year were contained within a designated subsection of the pivot. Irrigation was managed with a low-pressure pivot system and scheduled by the collaborating farmer to ensure non-limiting root-zone soil moisture.

2.2 | Cover crop treatments

Five cover crop treatments were established using a randomized complete block design with four replicates (28 plots year^{-1}, 5 m × 12 m [60 m^2] each) in 2018, 2019, and 2021 as follows: (i) polyculture (POLY): 15 species including five legumes, four grasses, two mustards, and one each of flax, borage, daisy, and buckwheat families, seeded at 117.6 kg ha^{-1}; (ii) mustard monoculture (MUST): white (*Sinapsis alba* L.) and brown [*Brassica juncea* (L.) Czern. mustard] seeded at 7 kg ha^{-1}; (iii) buckwheat monoculture (BWHT): seeded at 50 kg ha^{-1}; (iv) faba bean monoculture (FABA): seeded at 174 kg ha^{-1}; and (v) weedy control (CONT): no cover crop. Details of cover crop species and seeding rates are presented in Table 2.

Seeding was done with a Fabro cone drill (disc openers) with 20 cm row spacing (Fabro Ltd). Seeding dates ranged from June 5 to June 18 (Table 1), with cover crops growing

TABLE 1 Details of cover crop management, sampling, and weather conditions 2018–2021.

Year	2018–2019	2019	2021
Cover crop seeding	June 5	June 18	June 8
Biomass sampling	July 30–31	August 14	July 19
Biomass production period (day)	55–56	57	41
Soil incorporation (cover crop termination)	August 8[a]	August 20	July 20
Spring weed and winter wheat biomass sampling	May 14[b]	–	–
Weather conditions during biomass production[c]			
Maximum air temperature (˚C)	35.9	34.9	37.9
Minimum air temperature (˚C)	5.2	4.7	4.2
Mean air temperature (˚C)	18.0	18.0	20.4
Cumulative precipitation (mm)	74	70	17
Cumulative growing degree days (GDD), 5˚C base[d]	738	756	632

[a]All plots mowed August 1.
[b]2019.
[c]Measured at AAFC, Lethbridge.
[d]Daily values calculated as ([Maximum − minimum air temperature]/2) − 5; if negative then GDD = 0.

TABLE 2 Details of fifteen different species used in the cover crop treatments.

	Family	Species	Seeding rate (kg) ha^{-1}
1	Fabaceae (legume)	Faba bean (*Vicia faba* L.)	22.4
3		Forage pea (*Pisum sativum* L.)	22.4
4		Chickling vetch (*Lathyrus sativus* L.)	16.8
		Indian head lentil (*Lens culinaris* Medikus)	3.36
5		Subterranean clover (*Trifolium subterraneum* L.)	1.12
6	Poaceae (grass)	Oat (*Avena sativa* L.)	11.2
7		Sorghum sudangrass (*Sorghum bicolor* × *S. bicolor* var. *sudanense*)	11.2
8		Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.)]	0.56
9		German (foxtail) millet [*Setaria italica* (L.) P. Beauv.]	0.56
10	Brassicaceae (mustard)	Brown mustard [*Brassica juncea* (L.) Czern.]	0.56
11		Kale (*Brassica oleracea* L.)	0.56
12	Polygonaceae (buckwheat)	Buckwheat (*Fagopyrum esculentum* Moench)	22.4
13	Asteraceae (daisy)	Safflower (*Carthamus tinctorius* L.)	2.24
14	Borginaceae (borage)	Phacelia (*Phacelia tanacetifolia* Benth.)	1.12
15	Linaceae (flax)	Flax (*Linum usitatissimum* L.)	1.12
	Total		117.6

for 55–57 days in 2018 and 2019, and 41 days in 2021 due to on-farm logistical constraints.

2.3 | Cover crop and weed biomass sampling

Above-ground biomass was hand-harvested from 2 × 0.5 m^2 areas in two locations (from opposite ends of the plot) within each plot before cover crop termination. Cover crop and weed biomass were separated (except in CONT, which only had weed biomass). Weed biomass was further separated by species. In 2019, due to volunteer regrowth from the prior year's POLY crop, volunteer cover crops were separated in all treatments except POLY. Furthermore, cover crop and weed biomass samples were oven-dried at 60˚C for 5 days until constant weight before weighing for biomass yield.

2.4 | Post-sampling field operation

After biomass sampling (Table 1), all remaining biomass was incorporated into the surface soil to ∼10-cm depth using tandem disk harrows (Krause all-in-one, Kuhn North America, Inc.). In 2018, biomass was mowed and left on the soil surface for 7 days before incorporation.

Weed suppression by cover crop treatments was calculated using Blesh et al. (2019): $[(W_c - W_t)/W_c] \times 100$, where W_c is the mean weed biomass in CONT and W_t is the mean weed biomass in a cover crop treatment.

2.5 | Plant tissue analyses

Subsamples of oven-dried cover crop and weed biomass were coarsely ground (<2 mm), and a further subsample was finely ground (<0.15 mm) on a roller mill for the determination of total C and N through dry combustion using an automated CNS analyzer (CE Instruments). Due to an error in 2018, cover crop biomass yield data for that year are unreported.

Total C and N concentrations were determined for composite weed samples (pooled equal masses of individual weed species) in 2018 and individual weed species samples in 2019 and 2021. Carbon and N uptake were calculated by multiplying biomass yield by the respective C or N concentration for each biomass component, including cover crop, weeds, and volunteer cover crops. This calculation was assumed to represent C and N inputs or returns to the soil after incorporation.

2.6 | Statistical analyses

Data were analyzed using PROC MIXED in SAS (SAS Institute Inc., 2010) for variables (including cover crop biomass and C and N concentrations) that met assumptions of normality and homogeneity of variance, with cover crop treatments (POLY, MUST, BWHT, FABA, and CONT) as a fixed effect and replicates (blocks) as a random effect. When assumptions were violated, data (weed C and N concentrations and C:N ratio) were assessed for potential transformations and did not normalize residuals; thus, nonparametric tests were applied. Specifically, individual weed species were analyzed for C and N concentrations, and C:N ratio using the Kruskal–Wallis test, followed by post hoc pairwise comparisons with Dunn's test ($p < 0.05$). Furthermore, median weed C and N concentrations and C:N ratios (pooled by species) were compared using the Mann–Whitney rank-sum test. Parametric analyses used Tukey-adjusted pairwise comparisons when significant treatment effects were detected. Data from different years were analyzed separately to account for inter-annual variability.

3 | RESULTS AND DISCUSSION

3.1 | Cover crop biomass

The POLY had the highest biomass yield (2.79 Mg ha^{-1}) of the study in 2019 (Table 3), while FABA and MUST had the lowest biomass yields of the study in 2021 (0.60–0.64 Mg ha^{-1}), falling below the 1 Mg ha^{-1} threshold suggested for optimal ecological services by Van Eerd et al. (2023). However, it should be noted that the threshold was derived from studies across North America, conducted under different climatic conditions, soil types, and crop rotations, which may not be directly comparable to the semi-arid, irrigated context of southern Alberta. Nevertheless, this benchmark provides a useful point of reference for interpreting the relative performance of summer cover crops in our study.

On average, the POLY produced approximately twice as much biomass yield as MUST and FABA but did not differ from BWHT across 2019 and 2021 (Table 3). Biomass yields of MUST and FABA did not differ in either year. These results align with Lavergne et al. (2021), who reported that POLY mixes often outperformed monocultures in biomass yield in 16 out of 22 studies, which can be attributed to the increasing number of cover crop species. However, trade-offs with species-specific contributions to productivity and other ecosystem services should also be considered. For instance, fast-growing grasses such as BWHT can dominate mixtures and increase total biomass but simultaneously suppress legumes like FABA, thereby reducing N fixation and altering nutrient cycling outcomes. This highlights the importance of selecting species carefully, maintaining a balance of functional groups, and determining optimal seeding rates when designing mixtures to optimize both productivity and ecosystem services (Finney et al., 2016; Wortman et al., 2012).

Across all cover crop treatments, biomass yield was nearly twice as high in 2019 (2.03 Mg ha^{-1}) compared to 2021 (1.07 Mg ha^{-1}), which could be attributed primarily to the 16-day longer growing period (57 vs. 41 days) and higher cumulative growing degree days (GDD) (756 vs. 632; Table 2). Weisberger et al. (2023) and Nichols et al. (2020) deemed planting and termination dates key to cover crop biomass production, as they directly influence GDD. Also, since ecosystem services depend on the magnitude of biomass production (Finney et al., 2016), maximizing biomass can optimize these benefits (Wendling et al., 2017).

3.2 | Weed biomass

In 2018, the top five weed species by biomass yield (based on the number of plots with measurable biomass) were common lambsquarters (*Chenopodium album* L.), false cleavers (*Galium spurium* L.), redroot pigweed (*Amaranthus retroflexus* L.), field bindweed (*Convolvulus arvensis* L.), and stinkweed (*Thlaspi arvense* L.). Common lambsquarters had the highest weed biomass yield (3.04 Mg ha^{-1}) in FABA (Table 3). Cover crops suppressed four out of the top five weeds. The POLY, MUST, and BWHT effectively reduced common lambsquarters biomass yield by 61%–71%, compared to CONT, while FABA did not (Table 3). All cover crops, except FABA, reduced false cleaver biomass yield by 26%–42%. Redroot

TABLE 3 Effect of cover crop treatment on biomass yield, 2018, 2019, and 2021.

Year	Biomass component	POLY	MUST	BWHT	FABA	CONT	*p*-value
		Biomass yield (Mg ha^{-1})					
2018	Cover crop[a]	–	–	–	–	0.00[b]	–
	Top five weeds						
	Common lambsquarters (28)[c]	0.59b	0.70b	0.80b	3.04a	2.07a	<0.001
	False cleavers (28)	0.60c	0.59c	0.75bc	0.95ab	1.01a	0.002
	Redroot pigweed (25)	0.29bc	0.14c	0.38bc	0.55b	0.97a	0.002
	Bindweed (23)	0.33	0.31	0.35	0.31	0.38	0.98
	Stinkweed (17)	0.15b	0.26ab	0.22b	0.23b	0.45a	0.03
	Weeds (combined)	1.96b	1.99b	2.50b	5.07a	4.88a	<0.001
	Total (cover crop + weed)[a]	–	–	–	–	4.88	–
2019	Cover crop	2.79a	1.40c	2.38ab	1.55bc	0.00[b]	0.002
	Top five weeds						
	Common lambsquarters (28)	1.47	1.38	0.94	1.31	1.31	0.54
	False cleavers (26)	0.32	0.36	0.31	0.35	0.29	0.85
	Wild buckwheat (24)	0.28	0.39	0.26	0.34	0.29	0.64
	Redroot pigweed (18)	0.34a	0.41a	0.00b	0.47a	0.44a	0.06
	Spiny sowthistle (8)	0.06	0.18	0.05	0.10	0.18	0.46
	Weeds combined	2.47	2.71	1.56	2.57	2.51	0.18
	Volunteer cover crop (11)	–[d]	0.95	0.46	0.80	1.61	0.32
	Total (cover crop + weed + volunteer cover crop)	5.25a	5.06ab	4.40bc	4.91abc	4.13c	0.03
		Contribution to total biomass (%)					
	Cover crop	53a	28b	54a	32b	0[b]	0.005
	Weed	47	54	36	52	61	0.11
	Volunteer cover crop	–[d]	18	10	16	39	0.19
		Biomass yield (Mg ha^{-1})					
2021	Cover crop	1.53a	0.64b	1.50a	0.60b	0.0[b]	<0.001
	Top two weeds						
	Redroot pigweed (28)	0.64c	1.48ab	0.45c	1.17b	1.85a	<0.001
	Common lambsquarters (28)	0.32b	0.72a	0.27b	0.52ab	0.68a	0.003
	Weed	0.97c	2.21ab	0.71c	1.69b	2.53a	<0.001
	Total (cover crop + weed)	2.49	2.85	2.21	2.29	2.53	0.19
		Contribution to total biomass (%)					
	Cover crop	62a	26b	68a	27b	0[b]	<0.001
	Weed	38b	74a	32b	73a	100[b]	<0.001

Note: Within rows, values with different letters are significantly different ($p < 0.05$) from each other.

Abbreviations: CONT, no-cover control; BWHT, monoculture of buckwheat; FABA, monoculture of faba bean; MUST, monoculture of mustard; POLY, polyculture.

[a]Unreportable due to human error.

[b]Weedy control (no cover crop planted). Omitted from statistical analysis.

[c]Number of plots where weed biomass was enumerated in parentheses (of 28 total).

[d]Unable to assess due to inability to separate blend species seeded in 2019 from those volunteering from 2018.

pigweed biomass yield was reduced by 43%–86% across all cover crops. The POLY, BWHT, and FABA suppressed stinkweed (49%–67%), but MUST did not.

When combining the top five weeds, the POLY, MUST, and BWHT suppressed the combined weed biomass yield by 49%–60%, while FABA showed no effect (Table 3). These results align with previous studies that reported MUST often suppresses weeds by at least 50%, likely due to allelopathic compounds like glucosinolates rather than biomass suppression (Björkman et al., 2015; Gfeller, Glauser, et al., 2018; Jabran et al., 2015; Schreiner et al., 2011). In addition, Norsworthy et al. (2007) also reported that MUST

suppressed Palmer amaranth (*Amaranthus palmeri* S. Wats.), a close relative of redroot pigweed, due to glucosinolate activity.

In 2019, the most abundant weeds were common lambsquarters and false cleavers, with wild buckwheat (*Polygonum convolvulus* L.), redroot pigweed, and spiny sowthistle [*Sonchus asper* (L.) Hill] in fewer plots (Table 3). Wild buckwheat is an annual weed distantly related to buckwheat, commonly grown as a cover crop (Nordlee et al., 2011). The BWHT suppressed redroot pigweed biomass yield by 100%, but no cover crop reduced the combined weed biomass of the top five weeds (Table 3). Gfeller, Herrera et al. (2018) found that buckwheat can suppress redroot pigweed by 53%, likely through allelopathy, altering the metabolic profile of its root exudation in response to redroot pigweed, suggesting heterospecific recognition.

In 2021, weed diversity declined to only common lambsquarters and redroot pigweed across all plots (Table 3). The shortened growth period (41 vs. 55–57 days) may constrain successional emergence, benefiting rapid, early-emerging taxa such as *Amaranthus* and *Chenopodium* (Gallagher & Cardina, 1998; Myers et al., 2004). Even under irrigation, elevated evaporative demand may likely reduce near-surface soil moisture essential for germination of moisture-sensitive weeds (Chauvel et al., 2001; Forcella et al., 2000). Collectively, these conditions led to dominance by two highly plastic, stress-tolerant species capable of thriving under the extreme weather events increasingly characteristic of semi-arid prairie agroecosystems. Redroot pigweed (1.12 Mg ha^{-1}) had a higher biomass yield than common lambsquarters (0.50 Mg ha^{-1}) in 2021 (Table 3). Both POLY and BWHT suppressed redroot pigweed by 65%–76%, while FABA (37%) and MUST (20%) showed minimal effects. Additionally, POLY and BWHT suppressed common lambsquarters biomass by 53%–60%, while FABA and MUST were ineffective (Table 3). Combined weed biomass yield suppression was 33% by FABA and 62%–72% by POLY and BWHT, with no suppression from MUST (Table 3).

The low weed suppression observed is concerning, as species such as common lambsquarters and redroot pigweed can set seed in 42–56 days, coinciding with the growing period in this study (Wauters et al., 2021). Weed suppression can be influenced by cover crop biomass yield, which varies annually (Wittwer et al., 2017). Our results corroborate studies that have noted the challenges of predicting weed suppression due to factors such as seeding time and weed community composition (Baraibar, Hunter, et al., 2018; Björkman et al., 2015; Gfeller, Glauser, et al., 2018). Additionally, our findings largely concur with those of Baraibar, Mortensen et al. (2018), who reported that legume and brassica monocultures (such as FABA and MUST in this study) generally yield higher weed biomass compared to grass monocultures or mixes (like the POLY, which comprised five grass species).

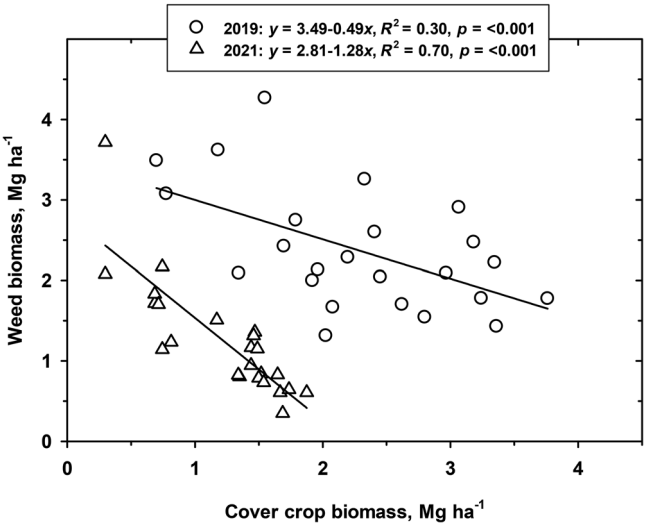


FIGURE 1 Relationships between cover crop biomass (POLY = polyculture, MUST = mustard monoculture, BWHT = buckwheat monoculture, and FABA = Faba bean monoculture) and weed biomass (n = 24), 2019, and 2021.

Cover crop biomass can also influence weed suppression through competition for light, water, space, and nutrients (Brennan & Smith, 2005; Finney et al., 2016; Wittwer et al., 2017), functional traits, seeding/termination timing, and management practices (Björkman et al., 2015; Dorn et al., 2015), together with noncompetitive mechanisms such as altered light quality (e.g., red:far-red ratio; Teasdale & Mohler, 1993), microclimate modifications (e.g., soil temperature and humidity; Teasdale & Mohler, 2000), and allelopathic effects (Weston & Duke, 2003; Singh et al., 2003), may further enhance suppression in cover crop systems. In this study, cover crop biomass explained 30% of the variation in weed biomass yield in 2019 but 70% in 2021 (Figure 1). The difference may be due to volunteer species, which may be interfering with the cover crop–weed biomass dynamic in 2019. Studies have shown that high spring cover crop biomass often correlates with better weed suppression, particularly as GDD increases (Baraibar, Mortensen, et al., 2018).

Although cover crop biomass alone cannot always predict weed suppression, studies have shown that at least 5 Mg ha^{-1} of biomass is necessary for significant weed suppression (Nichols et al., 2020; Finney et al., 2016). This value should be interpreted cautiously, as it was derived under temperate, rain-fed conditions with moderate fertility and conventional tillage, where early-season weed pressure tends to be moderate. Other studies have reported lower thresholds; for instance, Gfeller, Herrera et al. (2018) showed that redroot pigweed growth suppression was negatively correlated

with cover crop biomass, but below a threshold of 3 Mg ha^{-1} of cover crop biomass yield. In practice, the effective biomass required for suppression may be substantially higher or lower depending on cover crop traits, management practices, soil moisture, nutrient status, and local climate, making biomass an important but context-dependent predictor rather. In our study, cover crop biomass was consistently below these reported thresholds, yet suppression varied across years and species. A substantial weed control was observed with lower biomass yield, such as 100% suppression of redroot pigweed with 2.38 Mg ha^{-1} of BWHT biomass yield in 2019 and 62%–72% suppression (based on redroot pigweed + common lambsquarters biomass) with 1.53–1.50 Mg ha^{-1} of POLY and BWHT biomass yield in 2021, indicating that short growing seasons, irrigation scheduling, and weed community composition modulated the strength of the biomass–weed suppression relationship.

3.3 | Total biomass

Total biomass yield, including cover crop, weed, and volunteer cover crop components, associated with cover crop treatments in 2019 and 2021, is presented in Table 3. In 2019, POLY produced the highest total biomass (5.25 Mg ha^{-1}) compared to BWHT (4.40 Mg ha^{-1}) and CONT (4.13 Mg ha^{-1}). Moreover, there were no differences in total biomass yield among POLY, MUST, and FABA (4.91–5.25 Mg ha^{-1}); MUST, BWHT, and FABA (4.40–5.06 Mg ha^{-1});or BWHT, FABA, and CONT (4.13–4.91 Mg ha^{-1}). In 2021, total biomass yield did not differ between cover crop treatments, with mean values ranging from 2.21 to 2.86 Mg ha^{-1} (Table 3), which was about 52% of the 2019 values due to a 16-day shorter growing period during 2021.

The biomass contributions from cover crops and weed/volunteer cover crops as a percentage of total biomass are shown in Table 3. In 2019, POLY and BWHT had higher cover crop contribution (53%–54%) of the total biomass than MUST and FABA (28%–32%). Similarly, in 2021, POLY and BWHT contributed 62%–68% of total biomass, while MUST and FABA contributed only 26%–27% (Table 3). In contrast, 68%–72% of total biomass production in MUST and FABA was derived from weed/volunteer cover crops in 2019, compared to 46%–47% in POLY (where the volunteer cover crop was not assessed) and BWHT (Table 3). In 2021, 73%–74% of total biomass in MUST and FABA was derived from weeds, while POLY and BWHT had only 32%–38%. Wauters et al. (2021) found that weed biomass as a fraction of total biomass (cover crop + weed) decreased linearly as total biomass increased to 2.17 Mg ha^{-1}, where weed biomass was about 25% of total biomass. No such relationship was observed in their study beyond this biomass threshold of 2.17 Mg ha^{-1}.

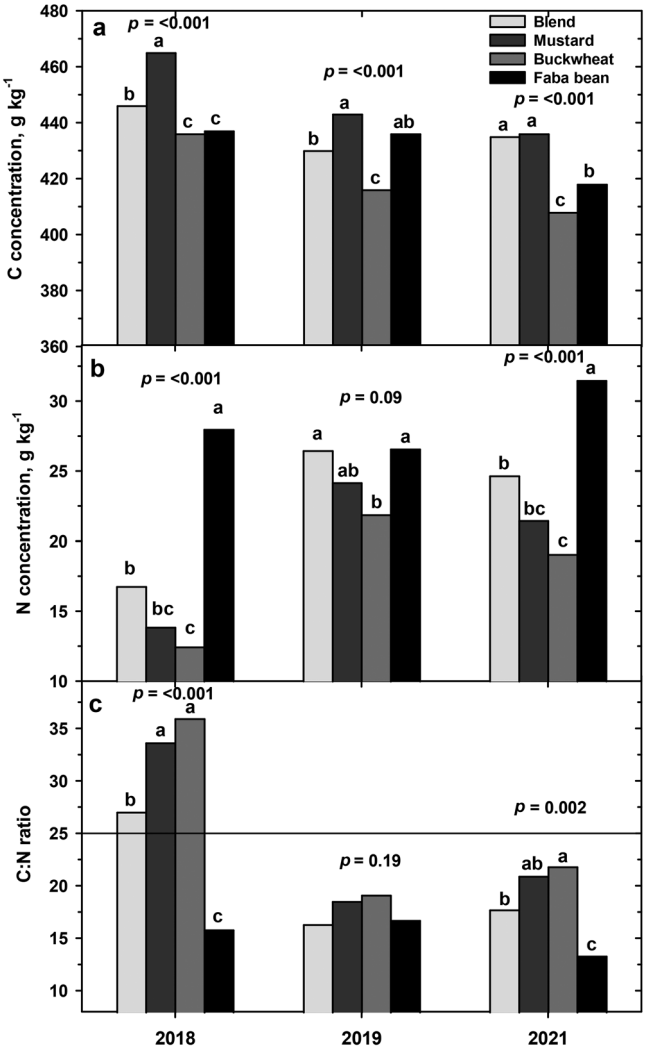


FIGURE 2 Cover crop (a) C concentration, (b) N concentration, and (c) C:N ratio 2018, 2019, and 2021. (POLY = polyculture, $n = 12$; MUST = mustard monoculture, BWHT = buckwheat monoculture; and FABA = Faba bean monoculture, $n = 4$). Within years, bars with different letters are significantly different from each other ($p < 0.05$).

3.4 | Cover crop C and N acquisition

The highest C concentration among cover crops was 465 g kg^{-1} for MUST in 2018, while the lowest was 408 g kg^{-1} for BWHT in 2021 (Figure 2a). Brennan et al. (2013) noted that C concentrations typically increase as cover crops mature. Comparing years, 2018, with the longest growing period (57 days), had the highest mean C concentration (446 g kg^{-1}), while 2021, with the shortest growing period (41 days), had the lowest (424 g kg^{-1}). MUST consistently showed higher C concentrations (by 7%) than BWHT across all 3 years (448 vs. 420 g kg^{-1}), and outperformed POLY in 2018 and 2019 (Figure 2a). BWHT had lower C concentration than all other cover crops in 2019 (416 vs. 430–443 g kg^{-1}) and 2021 (408 vs. 418–436 g kg^{-1}).

Cover crop N concentrations ranged from 12.5 g kg^{-1} in BWHT in 2018 to 31.5 g kg^{-1} in FABA in 2021 (Figure 2b). In 2018, N concentrations were substantially lower than in 2019 and 2021 for POLY (16.8 vs. 24.7–26.5 g kg^{-1}), MUST (13.9 vs. 21.5–24.2 g kg^{-1}), and BWHT (12.5 vs. 19.1–21.9 g kg^{-1}), but not for FABA (28.0 vs. 26.6–31.5 g kg^{-1}). As an N-fixing legume, FABA had the highest N concentration (28 g kg^{-1}) compared to all three other cover crops (12.5–16.8 g kg^{-1}) in 2018 and in 2021 (31.5 vs. 19.1–24.7 g kg^{-1}). In 2019, FABA's N concentration (26.6 g kg^{-1}) was higher than BWHT (21.9 g kg^{-1}), but not POLY or MUST. POLY, which contained five legume species (Table 1), consistently had a higher N concentration (22.7 g kg^{-1}) than BWHT (17.8 g kg^{-1}) in all years (Figure 2b).

BWHT had the highest C:N ratio (36), reflecting its low N concentrations, while FABA in 2021 had the highest N concentration and the lowest C:N ratio (13.4). In 2018, C:N ratios were significantly higher for POLY (27.1 vs. 16.4–17.8), MUST (33.7 vs. 18.6–21.0), and BWHT (36.0 vs. 19.2–21.9) compared to 2019 and 2021, but not for FABA (15.9 vs. 13.4–16.8). The C:N ratio for MUST and BWHT was similar in 2018 (33.7–36.0) and 2021 (21.0–21.9). POLY had a lower C:N ratio than MUST and BWHT in 2018 but higher than FABA (15.9). In 2021, BWHT (21.9) had a higher C:N ratio than POLY (17.8), which was again higher than FABA (13.4). In 2019, there were no significant differences in C:N ratios across cover crop treatments.

The C:N ratio of cover crop residue is crucial for microbial decomposition, influencing nutrient mineralization and availability for subsequent crops. Residues with a C:N ratio <25 typically lead to net N mineralization, increasing soil N supply, while those >25 tend to result in N immobilization and slower degradation, reducing soil N supply (White et al., 2016). Among the cover crop treatments evaluated, only POLY, MUST, and BWHT in 2018 had C:N ratios >25 (27.1–36.0) (Figure 2c). These results align with Hunter et al. (2019), who reported that monoculture legume cover crops (e.g., FABA in this study) had lower C:N ratios (~12), while grass-dominated cover crop mixes had higher ratios (~30). However, POLY in our study, although not grass-dominated, contained five grasses and had a lower C:N ratio than MUST and BWHT in 2018 and BWHT in 2021.

Cover crop C uptake followed biomass production trends, with POLY having the highest C uptake (1.20 Mg ha^{-1}) in 2018 and FABA the lowest (0.25 Mg ha^{-1}) in 2021 (Table 4). In both 2019 and 2021, POLY had higher C uptake (0.66–1.20 Mg ha^{-1}) than both MUST and FABA (0.25–0.68 Mg ha^{-1}), with no significant difference between POLY and BWHT. Furthermore, cover crop N uptake was more variable than C uptake due to differences in N concentrations (Table 5). In 2019, POLY had the highest N uptake (74 kg ha^{-1}), while MUST in 2021 had the lowest (14 kg ha^{-1}). In 2019, POLY had higher N uptake than MUST and FABA (74 vs. 33–41 kg ha^{-1}), but not BWHT (53 kg ha^{-1}). In 2021, POLY had higher N uptake than all other cover crops (38 vs. 14–29 kg ha^{-1}). We assume that all C and N acquired by cover crop biomass were returned to the soil through tillage incorporation. However, we did not quantify the contributions from cover crop roots or rhizodeposition in this study.

3.5 | Weed C and N acquisition

This study examined weed C and N acquisition from two perspectives: (i) the effect of cover crops on weed C and N concentrations, influencing estimates of weed C and N uptake; and (ii) differences in C and N concentrations between weed species. In both 2019 and 2021, common lambsquarters in BWHT showed a trend toward higher N concentrations (38.3 g kg^{-1}) compared to common lambsquarters from MUST and FABA plots (31.1 g kg^{-1}), with p-values ranging from 0.08 to 0.09. This could suggest that common lambsquarters scavenged soil N, supported by the lower N concentration in BWHT biomass in 2019 and 2021 (Figure 2b). Regarding C:N ratios (data not shown), combined weeds from the CONT had a trend ($p = 0.10$) toward a higher C:N ratio (28.5) than those from POLY, BWHT, and FABA (22.1–23.2). This may be due to faster growth and greater maturity in the absence of competition. Additionally, common lambsquarters from MUST showed a trend ($p = 0.07$) toward a higher C:N ratio (12.5) compared to those from POLY, BWHT, and CONT (10.0–10.7).

To further investigate differences in C and N concentrations and C:N ratios between weed species (Figure 3), data were pooled from all cover crop treatments. Although 2018 data were combined for tissue analysis, the mean data are presented for comparison. The median C concentration in 2018 (418 g kg^{-1}) was similar to 2019 and 2021 (396–407 g kg^{-1}) (Figure 3a). However, the median N concentration was substantially lower in 2018 (18 g kg^{-1}) compared to 2019 and 2021 (3.0–3.1 g kg^{-1}) (Figure 3b), resulting in a higher C:N ratio in 2018 (23.7 vs. 13.1–14.3) (Figure 3c). This suggests that weed residue from 2018 would decompose more slowly than that from 2019 and 2021. Lindsey et al. (2013) found that N release from weed residue was negatively correlated with the C:N ratio, with residues <19 releasing 25%–45% of total N within 2 weeks and contributing N during the following growing season, whereas residues >19 led to immobilization. However, these findings were based on specific species (e.g., common lambsquarters, redroot pigweed, and giant foxtail) under controlled conditions, and the decomposition dynamics of weed residues can vary widely by species and environment. In our study, the elevated C:N ratio in 2018 suggests that weed residues likely contributed to short-term N immobilization, potentially reducing N availability for subsequent crops compared with 2019 and 2021, consistent with field observations

TABLE 4 Effect of cover crop treatment on biomass C uptake 2018, 2019, and 2021.

Year	Biomass component	POLY	MUST	BWHT	FABA	CONT	*p*-value
			C uptake (Mg ha^{-1})				
2018	Cover crop[a]	–	–	–	–	0.00[b]	–
	Top five weeds[c]	0.80b	0.83b	1.04b	2.12a	2.10a	<0.001
	Total (cover crop + weed)[a]	–	–	–	–	2.10	–
2019	Cover crop	1.20a	0.62b	0.99ab	0.68b	0.00[b]	0.004
	Top five weeds						
	Common lambsquarters (28)[d]	0.60	0.56	0.37	0.54	0.53	0.49
	False cleavers (26)	0.13	0.11	0.12	0.14	0.12	0.95
	Wild buckwheat (24)	0.12	0.17	0.11	0.14	0.12	0.58
	Redroot pigweed (18)	0.13a	0.16a	0.00b	0.19a	0.17a	0.06
	Spiny sowthistle (8)	0.02	0.07	0.02	0.04	0.08	0.42
	Weeds combined	1.01	1.07	0.63	1.05	1.02	0.21
	Volunteer cover crop (11)	–[e]	0.41	0.20	0.34	0.69	0.32
	Total (cover crop + weed + volunteer cover crop)	2.21a	2.11ab	1.82bc	2.07abc	1.71c	0.02
			Contribution to total C uptake (%)				
	Cover crop	54a	31b	55a	33b	0[b]	0.009
	Weed	46	50	35	51	60	0.15
	Volunteer cover crop	–[e]	19	10	16	40	0.18
			C uptake (Mg ha^{-1})				
2021	Cover crop	0.66a	0.28b	0.61a	0.25b	0.0[b]	<0.001
	Top two weeds						
	Redroot pigweed (28)	0.26c	0.60ab	0.18c	0.47b	0.74a	<0.001
	Common lambsquarters (28)	0.13b	0.29a	0.11b	0.21ab	0.26a	0.003
	Weed	0.39c	0.89ab	0.28c	0.68b	1.00a	<0.001
	Total (cover crop + weed)	1.05	1.17	0.90	0.93	1.00	0.16
			Contribution to total C uptake (%)				
	Cover crop	64a	27b	69a	28b	0[b]	<0.001
	Weed	36b	73a	31b	72a	100[b]	<0.001

Note: Within rows, values with different letters are significantly different ($p < 0.05$) from each other.

Abbreviations: CONT, no-cover control; BWHT, monoculture of buckwheat; FABA, monoculture of faba bean; MUST, monoculture of mustard; POLY, polyculture.

[a]Unreportable due to human error.

[b]Weedy control (no cover crop planted). Omitted from statistical analysis.

[c]Derived using C concentrations of mixed samples of common lambsquarters, false cleavers, redroot pigweed, bindweed, and stinkweed from each plot.

[d]Number of plots enumerated in parentheses (of 28 total).

[e]Unable to assess due to inability to separate blend species seeded in 2019 from those volunteering from 2018.

that residues with C:N ratios >20 often induce immobilization (Vigil & Kissel, 1991; Kaye & Hart, 1997).

In 2019, wild buckwheat had a higher median C concentration (423 g kg^{-1}) than false cleavers, redroot pigweed, and spiny sowthistle (393–406 g kg^{-1}), while redroot pigweed (393 g kg^{-1}) had a lower C concentration than common lambsquarters and false cleavers (both 406 g kg^{-1}) (Figure 3a). Median N concentration was higher in redroot pigweed (35 g kg^{-1}) than in common lambsquarters, false cleavers, and wild buckwheat (28–32 g kg^{-1}) (Figure 3b). The median C:N ratio was highest in wild buckwheat (15.1) compared to redroot pigweed and spiny sowthistle (11.1–12.4). In 2021, redroot pigweed had a higher median C concentration (397 vs. 392 g kg^{-1}), lower N concentration (22 vs. 37 g kg^{-1}), and higher C:N ratio (17.9 vs. 10.7) than common lambsquarters (Figure 3c), showing opposite trends to those in 2019 for these two weeds.

In 2018, cover crop type affected C (Table 4) and N (Table 5) uptake by weeds, reflecting weed biomass trends (Table 3). FABA and CONT did not differ, and both had higher C (2.10–2.12 vs. 0.80–1.04 Mg ha^{-1}) and N (75–94 vs. 34–47 kg ha^{-1}) uptake than POLY, MUST, and BWHT (Tables 4 and 5), whereas, in 2019, as with biomass, cover crop type had no effect on C or N uptake by common

TABLE 5 Effect of cover crop treatment on biomass N uptake 2018, 2019, and 2021.

Year	Biomass component	POLY	MUST	BWHT	FABA	CONT	*p*-value
		N uptake (kg ha^{-1})					
2018	Cover crop[a]	–	–	–	–	0.00[b]	–
	Top five weeds[c]	35b	34b	47b	94a	75a	<0.001
	Total (cover crop + weed)[a]	–	–	–	–	75	–
2019	Cover crop	74a	33b	53ab	41b	0.00[b]	0.002
	Top five weeds						
	Common lambsquarters (28)[d]	44	42	35	36	42	0.79
	False cleavers (26)	9	8	8	10	9	0.86
	Wild buckwheat (24)	8	11	7	9	8	0.81
	Redroot pigweed (18)	12a	15a	0b	16a	16a	0.04
	Spiny sowthistle (8)	2	6	2	4	6	0.45
	Weeds combined	75	81	52	75	82	0.29
	Volunteer cover crop (11)	–[e]	25	12	21	43	0.32
	Total (cover crop + weed + volunteer cover crop)	149	139	117	137	125	0.18
		Contribution to total N uptake (%)					
	Cover crop	50	26	45	31	0[b]	0.009
	Weed	50	57	44	56	68	0.12
	Volunteer cover crop	–[e]	17	11	13	32	0.28
		N uptake (kg ha^{-1})					
2021	Cover crop	38a	14c	29b	19c	0[b]	<0.001
	Top two weeds						
	Redroot pigweed (28)	15c	30ab	11c	24b	41a	<0.001
	Common lambsquarters (28)	12b	22a	10b	17ab	25a	0.002
	Weed	27c	52b	21c	42b	66a	<0.001
	Total (cover crop + weed)	65a	66a	50b	61ab	66a	0.04
		Contribution to total N uptake (%)					
	Cover crop	58a	23b	57a	31b	0[b]	<0.001
	Weed	42b	77a	43b	69a	100[b]	<0.001

Note: Within rows, values with different letters are significantly different ($p < 0.05$) from each other.

Abbreviations: CONT, no-cover control; BWHT, monoculture of buckwheat; FABA, monoculture of faba bean; MUST, monoculture of mustard; POLY, polyculture.

[a]Unreportable due to human error.

[b]Weedy control (no cover crop planted). Omitted from statistical analysis.

[c]Derived using N concentrations of mixed samples of lambsquarters, false cleavers, redroot pigweed, bindweed and stinkweed from each plot.

[d]Number of plots enumerated in parentheses (of 28 total).

[e]Unable to assess due to inability to separate blend species seeded in 2019 from those volunteering from 2018.

lambsquarters, false cleavers, wild buckwheat, or spiny sowthistle (Table 4).

In 2021, because cover crop treatments did not affect C and N concentrations or C:N ratios for redroot pigweed and common lambsquarters, C (Table 4) and N uptake (Table 5) mirrored biomass trends (Table 3). Due to the lack of a cover crop in the CONT treatment, C uptake for redroot pigweed was higher in CONT (0.74 Mg ha^{-1}) than in POLY and BWHT (0.18–0.26 Mg ha^{-1}), and C uptake for common lambsquarters was also higher in CONT (0.26 Mg ha^{-1}) compared to POLY and BWHT (0.11–0.13 Mg ha^{-1}) (Table 4). Similarly, N uptake in the CONT treatment was higher than in POLY and BWHT for redroot pigweed (41 vs. 11–15 kg ha^{-1}) and common lambsquarters (25 vs. 10–12 kg ha^{-1}) (Table 5). For the combined weeds, C uptake in CONT (1.00 Mg ha^{-1}) was higher than FABA (0.68 Mg ha^{-1}), which was in turn higher than POLY and BWHT (0.28–0.39 Mg ha^{-1}). For N uptake of combined weeds, CONT (66 kg ha^{-1}) had greater uptake than MUST and FABA (42–52 kg ha^{-1}), which were higher than POLY and BWHT (21–27 kg ha^{-1}).

3.6 | Total biomass C and N uptake

In 2019, POLY (2.21 Mg ha^{-1} C) had greater C uptake by total biomass (cover crop + weed) compared to BWHT and

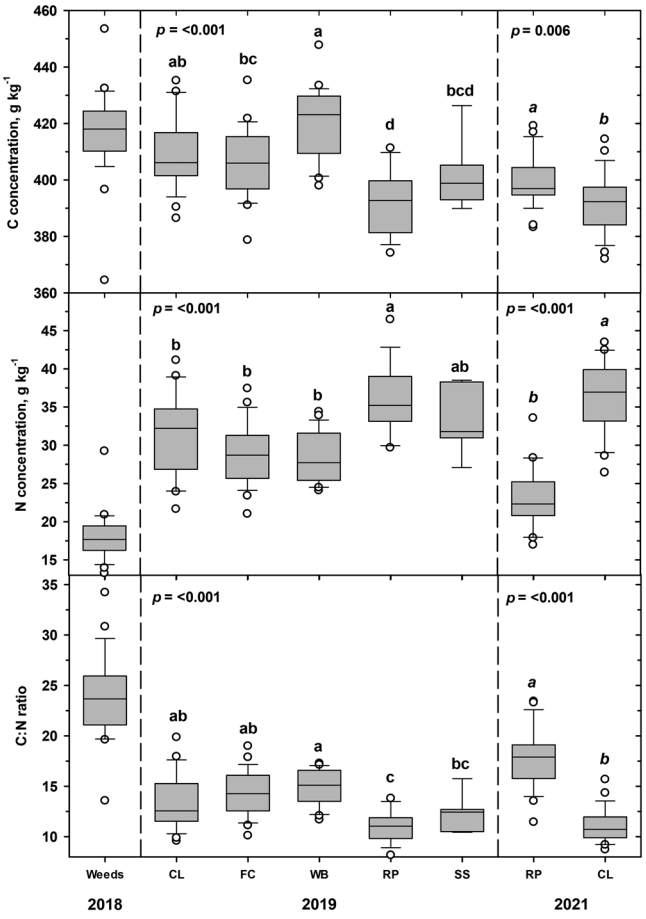


FIGURE 3 Box plots of weed biomass (a) C concentration, (b) N concentration, and (c) C:N ratio on cover crop treatments ($n = 28$) in 2018, 2019, and 2021. Within boxes, a horizontal line marks the median concentration. The lower boundary of the box indicates the 25th percentile, and the upper boundary the 75th percentile. Whiskers (error bars) indicate 10th and 90th percentiles. Circle symbols indicate outliers falling outside the 10th and 90th percentiles. *p* values are presented for Kruskal–Wallis tests between weeds in 2019, and Mann–Whitney rank sum tests in 2021. Within years, weed box plots with different letters have significantly different median concentrations ($p < 0.05$). CL, common lambsquarters; FC, false cleavers; WB, wild buckwheat; RP, redroot pigweed; SS, spiny sowthistle.

CONT (1.71–1.82 Mg ha^{-1} C) but did not differ from MUST (2.11 Mg ha^{-1} C) or FABA (2.07 Mg ha^{-1} C) (Table 5). In 2021, similar to the trends in total biomass, cover crop type did not affect C uptake by total biomass (Table 4). For N uptake by total biomass in 2019, cover crop type had no effect, with all treatments showing a range of 117–149 kg ha^{-1} N (Table 5), whereas in 2021, POLY, MUST, and CONT had higher N uptake (65–66 kg ha^{-1}) than BWHT (50 kg ha^{-1}), but not FABA (61 kg ha^{-1}). These results contrast with findings from Holmes et al. (2019), who reported that cover crop monocultures and mixes provided 28%–33% more biomass tissue N than fallow weeds in an Illinois study. The difference in results can be attributed to differences in climate, cover crop species, and management, as Illinois' warmer, longer season conditions favored greater biomass and N accumulation, whereas southern Alberta's semi-arid, short-season environment may have constrained production, highlighting the context-dependent nature of cover crop C and N contributions.

Carbon and N uptake by cover crop and weed/volunteer cover crop biomass components was expressed as a percentage of total biomass C and N uptake (Table 4). The CONT derived 100% of C and N uptake from weeds. In 2019, a greater proportion of total C uptake was attributed to the cover crop in POLY and BWHT (54%–55%), compared to MUST and FABA (31%–33%) (Table 4). In 2021, the cover crop accounted for a higher percentage of total C uptake in POLY and BWHT (64%–69%) than in MUST and FABA (27%–28%). In contrast, in 2019, 67%–69% of total C uptake came from weeds and volunteer cover crops in MUST and FABA, compared to 45%–46% from the weed component only in POLY (where volunteer cover crops could not be separated from seeded cover crops) and BWHT. In 2021, 72%–73% of total C uptake was derived from weeds in MUST and FABA, compared to only 31%–36% in BWHT and POLY.

For N uptake by total biomass (Table 5), allocation trends followed a similar pattern to C uptake. In 2019, 45%–50% of total N uptake in POLY and BWHT was attributed to the cover crops, compared to only 26%–31% in MUST and FABA. In POLY, there was an even split in N uptake, with 50% derived from cover crops and 50% from weeds. In 2021, the portion of total N uptake attributed to the cover crop was 58% for POLY, which was higher than MUST and FABA (23%–31%), but similar to BWHT (57%).

4 | CONCLUSIONS

This study emphasizes the significance of cover crops in enhancing biomass production, suppressing weeds, and regulating C and N dynamics in agroecosystems, with varying effects depending on the cover crop type, growth period, and year. Cover crops with higher biomass production, such as POLY, tended to accumulate more C, while leguminous crops like FABA exhibited higher N concentrations due to their nitrogen-fixing capabilities. Additionally, cover crops with higher C:N ratios, such as BWHT and MUST, are likely to decompose more slowly, potentially limiting nutrient mineralization and availability for subsequent crops, consistent with established relationships between residue C:N and decomposition rate. Weed biomass, particularly in the CONT treatment, significantly contributed to C and N uptake, with notable differences in the nutrient profiles of different weed species observed across the years. Despite this, weeds with higher N concentrations and lower C:N ratios compared to cover crops played an important role in overall nutrient

cycling. This raises the question: *why grow a cover crop when similar benefits are provided by letting weeds as a "cover crop" grow*? While weeds can provide similar benefits, caution is necessary to prevent the replenishment of weed seeds in the soil seedbank, emphasizing the importance of integrated weed management and careful cover crop selection to optimize both carbon sequestration and N dynamics. Future research should explore the longer term impacts on soil health (including microbial communities and soil structure), interactions between cover crops, weeds, and subsequent cash crop yield under diverse climatic conditions, and the economic implications of the different cover crop systems to guide sustainable farming decisions.

AUTHOR CONTRIBUTIONS

Francis J. Larney: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Haley A. Catton**: Conceptualization; data curation; formal analysis; methodology; project administration; writing—original draft; writing—review and editing. **Charles M. Geddes**: Investigation; methodology; writing—original draft; writing—review and editing. **Newton Z. Lupwayi**: Formal analysis; funding acquisition; investigation; methodology; writing—original draft; writing—review and editing. **Thomas A. Forge**: Formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Henry W. Chau**: Supervision; writing—original draft; writing—review and editing. **Bobbi L. Helgason**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; writing—original draft; writing—review and editing. **Ekene Mark-Anthony Iheshiulo**: Formal analysis; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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