SINful Consequences of Cover Cropping: Soil Inorganic Nitrogen (SIN) Provision and Retention from Warm-Season Cover Crops for Northern US Region Vegetable Production

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List of Abbreviations

C carbon

CCV Experimental rotation in which spring-planted cover crops preceded a vegetable crop

GDD growing degree day

N nitrogen

NH_4–N ammonium-N

NO_3^- nitrate

NO_3–N nitrate-N

PMN potentially mineralizable N

SIN soil inorganic N

SOM soil organic matter

VCC Experimental rotation in which a vegetable crop was followed by summer-planted cover crops

Review of the Literature

Introduction

Nitrogen (N) is the most vital nutrient to support plant growth and its management presents a grand challenge in contemporary agriculture: N must be supplied to crops to maintain yields, but N supplied in excess of or asynchronous with crop demand is prone to loss. The conventional agricultural paradigm is dependent on synthetic N inputs to replenish N depleted by intensive annual cropping regimes, despite the relatively high and unpredictable costs of this input. Though synthetic N has helped agricultural production keep pace with rapid population growth in the last century, it also threatens environmental quality (Erisman et al., 2008; Tilman et al., 2002). In just 70 years, the global application of synthetic N fertilizers increased tenfold, from ~10 Tg yr^{-1} in the 1950s to ~100 Tg yr^{-1} in 2008 (Cassman and Dobermann, 2022; Robertson and Vitousek, 2009), but only about 50% of applied synthetic N is taken up by crops (Cassman et al., 2002). Synthetic N that is not taken up by crops is vulnerable to losses via nitrate (NO_3^-) leaching, denitrification, and ammonia volatilization, all of which have negative consequences for humans and ecosystems. One widely recognized repercussion of NO_3^- leaching is coastal hypoxic, or "dead", zones, which affected over 10 million km^2 in 2020 (Dai et al., 2023), and continue to threaten marine life (Breitburg et al., 2018; Diaz and Rosenberg, 2008). Additionally, human communities that source their drinking water from groundwater can suffer negative health effects of leached NO_3^- contamination. Methemoglobinemia, or blue baby syndrome, in infants and various types of cancer in adults have been linked with increased NO_3^- ingestion (Brender, 2020). The challenges of surplus N, though too immense and complex to be significantly alleviated by one research project or individual, can be minimized at the farm scale by optimizing N management practices to meet localized production and conservation goals.

Vegetable systems are an important piece of the N management puzzle because they have intense N demands that can be particularly challenging to meet, yet are underrepresented in research. In 2017, vegetable production (including melons) accounted for 5% of total US agriculture sales and covered 1.78 million ha (4.4 million A) of US farmland (NASS, 2019). Compared with the large amount of land in vegetable production, there is a relatively small body of literature on best N management practices in vegetable production systems, which vary by region and therefore require specific guidance. Fertility recommendations for a single vegetable crop can vary by over 200 kg N ha^{-1} and reach as high as 300 kg N ha^{-1} (Congreves and Van Eerd, 2015), demonstrating a lack of clarity about proper N management that is often skewed toward high N applications. Fertilization levels above 200 kg N ha^{-1} can decrease vegetable N recovery by up to 40% relative to input (Greenwood et al., 1989), which could encourage N losses. Therefore, improved N management and the use of alternative N sources, such as cover crops, could improve environmental outcomes in vegetable production.

Cover Crops as an N Management Tool

Cover crops are an increasingly popular alternative source of N for vegetable production that can provide a multitude of other benefits (Schipanski et al., 2014). Interest in and use of cover crops appears to be growing in US agriculture broadly; in 2007, only 18% of US Corn Belt farmers had ever used a cover crop (Singer et al., 2007), but by 2017, 88% of a survey of 1500 farmers across the US reported having used a cover crop (SARE and CTIC, 2020). The foundation of knowledge of cover crop functions has been built primarily from studies of cover crops grown in winter fallows, where they have demonstrated the capacity to build soil organic matter (SOM) (Ding et al., 2006), mediate nutrient cycling (Blesh, 2018; Drinkwater et al., 1998), and suppress weeds and pests (Osipitan et al., 2019). When used as a fertility source, cover crops build stores of organic N, which are less prone to loss pathways than synthetic N fertilizers. Therefore, cover crops could alleviate challenges of N management by delivering N provision and retention benefits simultaneously.

The majority of cover crops used in US agronomic systems are over-wintering grasses, which are seeded in early fall and grow until the following spring, and provide mainly N retention benefits. Primary grass species include cereal rye (*Secale cereale*), winter wheat (*Triticum aestivum*), and oat (*Avena sativa*) (Singer, 2008), though broadleaf non-legumes such as Brassicas are also common. Grasses and other non-legume cover crops are proficient in N retention because they can scavenge N from deep within the soil profile and have demonstrated potential to decrease NO_3^- leaching by 70% in comparison to bare fallow conventional systems (Tonitto et al., 2006; Nouri et al., 2022; Thorup-Kristensen and Rasmussen, 2015). The timing of cover crop growth is also crucial to N retention. Vulnerabilities to NO_3^- leaching are typically greatest in the fall and early spring when there is no crop to assimilate soil inorganic N (SIN) from soil reserves. Fall fertilizer applications can amplify risks of leaching in these periods, making fall a crucial time for N retention benefits. When fall cover crop seeding coincides with fertilizer applications, cover crops can capture 60-80% of applied N that might otherwise be lost to leaching (Lacey and Armstrong, 2015). However, there are known tradeoffs between these N retention benefits and N provision (Finney et al., 2017b). Non-legume residues typically have C:N ratios above 30 which can promote N immobilization, the process by which SIN is taken up by microbes rather than remaining available for cash crops (Reberg-Horton et al., 2012; Parr et al., 2014). Therefore, where N provision is needed, non-legume cover crops may not be the best option.

Legume cover crops are proficient in N provision because they form symbioses with *Rhizobia* bacteria that can fix N_2 gas from the atmosphere. Fixed N is then stored in legume tissue, allowing a winter legume cover crop to accumulate up to 180 kg N ha^{-1} (Parr et al., 2011; Poffenbarger et al., 2015). When legume cover crops are terminated, their residues must undergo N mineralization, the process by which organic N is converted to SIN, to become available for cash crops. Legume residues typically support rapid N mineralization due to low C:N ratio residues (Thomsen et al., 2016; De Notaris et al., 2020), which makes them strong sources of N provision. Moreover, legume fertility inputs can recouple N cycles with those of carbon (C), which builds long-term nutrient storage and promotes multiple agroecosystem functions (Drinkwater et al., 1998; Drinkwater and Snapp, 2007).

Mixtures of legume and non-legume cover crops may be able to overcome tradeoffs between N provision and retention. Grass-legume mixtures have been shown to self-regulate in response to base fertility, expressing higher proportions of grass in high N environments and higher proportions of legume in low N environments (De Notaris et al., 2021; Blesh, 2018). However, in some studies, grasses have demonstrated an opportunistic tendency to dominate mixtures which can suppress N provision services from legumes (White et al., 2017; Brainard et al., 2011). Mixtures are also employed with more than two species, (Finney et al., 2017b; Kaye et al., 2019; De Notaris et al., 2021), which provides an opportunity to carefully choose species whose benefits are tailored to local goals. In this way, cover crop mixtures could expand the utility of cover crops beyond N management tools, which could make them more desirable options for growers.

Warm-season Cover Crops for Northern Region Vegetable Production

In this project, we collaborated with Minnesota vegetable producers to evaluate benefits and tradeoffs of warm-season cover crops. In MN, specialty crop producers are particularly interested in learning more about soil management (McCamant, 2014), but management tools like cover crops can be difficult to adopt because of cold climatic conditions characteristic of the state's northern latitude. The southern portion of MN is classified as USDA plant hardiness zone 4, which has a frost-free period ranging from 132-166 days, and the northern portion of MN is classified as zone 3, which has a frost-free period ranging from 115-137 days (Service, 2012). For comparison, zone 5, which begins just south of MN, has a frost-free period ranging from 166-197 days. The shortened growing season in MN increases the difficulty of integrating cover crops into existing rotations, as growing degree days (GDDs) are limited.

Cover crops are most commonly grown in winter fallows so that they do not interfere with the summer annual cash crop production, but many windows of cover crop growth have been explored (Snapp et al., 2005). Winter cover crops can be difficult to establish in the cold autumns of the northern US region and often need large portions of the spring and/or fall to produce substantial biomass. Producers who utilize spring or fall windows for vegetable growth may need an alternative growth window for cover crops. Warm-season cover crops could be integrated into fallow periods before or after cool-season vegetable production to avoid interference with spring or fall vegetables. However, there has been little exploration of these growth windows for cover crops in the northern US region, and it is not yet known if they could achieve similar functions to those of winter cover crops.

Warm-season cover crops offer an abundance of species options, but it is not yet clear what species are best suited for the northern region. A multitude of warm-season cover crop species have been studies in the southern and midwestern US regions (e.g. Blanco-Canqui et al., 2012; Creamer and Baldwin, 2000; Farney and Sassenrath, 2019). Legume species that have been explored as warm-season cover crops include hairy vetch [*Vicia villosa* Roth], sunn hemp (*Crotalaria juncea* L.), cowpea (*Vigna unguiculata* L.), sesbania (*Sesbania exaltata* L.), velvetbean (*Mucuna deeringiana* (Bort.) Merr.), and lablab (*Lablab purpureus* L.), which can return 30 to over 130 kg N ha^{-1} to the soil, or over 250 kg N ha^{-1} when used in mixture (Wauters et al., 2021; Holmes et al., 2019; Creamer and Baldwin, 2000; Candelaria-Morales et al., 2022). Non-legume species suitable for warm-season growth include sorghum-Sudangrass (*Sorghum bicolor* (L.) Moench × *S. bicolor var. Sudanese* Stapf.), buckwheat (*Fagopyrum esculentum* Moench), Japanese millet (*Echinochloa frumentacea* (Roxb.) Link), pearl millet (*Pennisetum glaucum* (L). R. Br.), and sunflower (*Helianthus annus* L.) (Brainard et al., 2011; Creamer and Baldwin, 2000; O'Connell et al., 2015).

Many of these cover crops are known to produce rapid, substantial biomass, particularly in the increased GDDs of the warm-season. Sorghum-Sudangrass alone can produce 14 Mg ha^{-1} over the course of the summer, or up to 9 Mg ha^{-1} within 90 days after planting in vegetable rotations in North Carolina (Finney et al., 2009; Creamer and Baldwin, 2000). Mixtures of multiple warm-season cover crop species can provide up to 9 Mg ha^{-1} aboveground biomass in upper Midwest vegetable rotations within 60 days after planting (Candelaria-Morales et al., 2022). Warm-season cover crop biomass has been shown to undergo N mineralization rapidly after termination (Kruse and Nair, 2016; Holmes et al., 2019), and can do so even with low quality tissues that would typically be associated with N immobilization (O'Connell et al., 2015), demonstrating potential for enhancements in biomass driven N benefits from warm-season cover crops.

Warm-season cover crops have potential to boost yields of cash crops, but management is not well enough understood to consistently attain this benefit. Yield effects are of concern to farmers interested in cover crops (Roesch-McNally et al., 2018), so a clear understanding of warm-season cover crop effects on yield could remove a major barrier from their adoption. Legume cover crops have demonstrated the ability to boost vegetable yields in both agronomic and vegetable systems (Blanco-Canqui et al., 2012; Wang et al., 2008), but species and termination methods governed when yield boosts occurred. Yield deficits are possible following non-legume cover crops due to N immobilization and are known to be prevalent following sorghum-Sudangrass cover crops because of allelopathy (Kruse and Nair, 2016; Weston et al., 1989). Warm-season cover crops require careful management to minimize negative effects on yields due to the nature of their rotations. Because warm-season cover crop rotations tend to have quick turnarounds between cash crops and cover crops, there can be increased competition for soil resources (e.g. moisture, N, P, and other nutrients) between crops. While some degree of negative yield effects could be tolerated in exchange for other benefits from warm-season cover crops, more information is needed about proper management so that negative effects are known and, ideally, minimized.

Nitrogen Provision and Retention Benefits from Warm-Season Cover Crops in Northern Region Vegetable Systems

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Abstract

Warm-season cover crops are promising tools to help meet high nitrogen (N) demands in vegetable cropping systems while preventing N losses, but species and management practices that achieve these goals in the northern US region are not yet clear. We explored six warm-season cover crop species and mixtures in two rotations at three field sites in Minnesota to evaluate biomass production, N provision and retention benefits, and impacts on vegetable yields. Biomass production in cover crop treatments ranged from 628-13,350 kg ha^{-1} and did not frequently exceed biomass produced in a weedy control. Cover crop biomass production was 41% lower in drought years than non-drought years among all cover crops except a mixture of cowpea (*Vigna unguiculata* (L.) Walp.) and sorghum-Sudangrass (*Sorghum bicolor* (L.) Moench

× *S. bicolor var. Sudanese* Stapf.), which produced 60% more biomass in drought years than non-drought years. Soil nitrate-N (NO_3–N) decreased beneath cover crops and increased after cover crop termination, demonstrating seasonal patterns that suggest improved synchrony of NO_3–N availability with vegetable demand. Crimson clover and pea/oat treatments often had the greatest soil NO_3–N availability during vegetable growth, indicating N provision, but demonstrated vegetable yield boosts only in a limited number of site-years relative to a weedy control. Vegetable yield deficits were frequent in all cover crop treatments relative to a weed-free control. Cover crops reduced NO_3^- leaching to buried resin lysimeters by up to 50% relative to a weed-free control, but these differences were not frequently significant. Evidence from this study suggests that warm-season cover crops could synchronize seasonal N patterns with vegetable demands in the northern region, but these patterns may not translate to boosts in vegetable yields.

Introduction

Vegetable cropping systems are characterized by intensive production practices that continuously extract soil nutrients, making nutrient replenishment a central challenge. To maximize vegetable yields, producers must supply sufficient quantities of nitrogen, but surplus N is prone to losses that contribute to pollution (Galloway et al., 2008; Robertson and Vitousek, 2009). Cover crops are versatile tools that can address N challenges while delivering other benefits such as reduced soil erosion, soil carbon (C) building, and beneficial insect conservation (Blanco-Canqui et al., 2015; Schipanski et al., 2014). Cover crops are commonly grown in winter fallows, but in the cold climate of the northern US region, winter cover crops often need an extended duration in spring and/or fall to accumulate GDDs sufficient to establish and reach maturity (Snapp et al., 2005). Therefore, northern region vegetable systems that utilize the spring or fall to produce cool-season vegetable crops may be better suited for warm-season cover crops. This paper explores N provision and retention benefits from warm-season cover crops grown before a fall vegetable crop or after a spring vegetable crop in northern region vegetable rotations.

Improvements in N management are necessary to meet high N demands of vegetable crops while minimizing negative consequences of surplus N. Fertility recommendations suggest that optimal N inputs for vegetable crop production are commonly upwards of 200 kg N ha^{-1} (Congreves and Van Eerd, 2015), which is conventionally supplied through synthetic fertilizer or manure. At the same time, soil inorganic N (SIN) levels after vegetable harvest can range from 20-225 kg N ha^{-1} (Neeteson et al., 1999; Neeteson and Carton, 2001), demonstrating low N recovery by vegetable crops (Goulding, 2000). In the fall, post-harvest SIN can be classified as residual N (Hirsh and Weil, 2019), as there is typically no subsequent crop to take up SIN. Residual N is at heightened risk of loss through NO_3^- leaching (Zhang et al., 2017) and may be more vulnerable to loss in the northern region where fall precipitation and then snow percolate through the soil profile, carrying residual NO_3^- to groundwater. It is crucial to minimize NO_3^- losses by leaching due to its contributions to water pollution, decreased water potability, and marine hypoxia (Erisman et al., 2008; Diaz and Rosenberg, 2008). Strategic improvements in N management, such as integrating cover crops in the spring or fall to utilize residual N, could improve environmental outcomes (Agostini et al., 2010), but more information is needed to inform such strategies.

Cover crops could improve N management by delivering complementary N provision and retention, but there are often tradeoffs between these services (Finney et al., 2017b). Legume cover crops are associated with N provision services because they engage in symbiotic relationships with *Rhizobia* bacteria that fix N gas (N_2) from the atmosphere. This symbiosis allows legumes to accumulate substantial N in their tissues, commonly between 80-200 kg N ha^{-1}, which contributes to the soil N supply (Luna et al., 2020; Parr et al., 2011), but may preclude them from efficient N retention (Tonitto et al., 2006). Meanwhile, grass cover crops like rye (*Secale cereale* L.) and oat (*Avena sativa* L.) are proficient in N retention because they can scavenge N from deep within the soil profile, reducing NO_3^- leaching and replenishing organic N near the soil surface, where it becomes available for mineralization (Thapa et al., 2018; Thomsen et al., 2016). Mixtures of legume and non-legume cover crops can achieve N provision and retention services simultaneously, and differential growth of each species can occur in response to endogenous soil N resources and environmental factors (Baraibar et al., 2020; De Notaris et al., 2021; White et al., 2017). For example, a mixture of durum wheat (*Triticum durum* Desf.) and winter pea (*Pisum sativum* L.) demonstrated a greater proportion of wheat biomass relative to pea, but lesser total yield, when N availability was high, and relatively equal proportions of wheat and pea biomass with greater total yield when N availability was low (Bedoussac and Justes, 2010). Grass dominance in mixtures can suppress N provision services from legume components (Blesh, 2018). Therefore, mixtures must be implemented with informed species selection and farm-specific strategies, which can reduce tradeoffs between N provision and retention considerably (Kaye et al., 2019). At present, suitable species selection and management strategies are all but unknown for northern region, warm-season cover crops in vegetable rotations.

Cover crops' impacts on N services are driven by biomass production (Ardenti et al., 2023;

Finney et al., 2016; Thapa et al., 2018), which makes it important to choose species that will produce ample biomass in the targeted growth window. To attain N retention services that exceed those of weedy fallows, it has been suggested that cover crops need to produce at least 2 Mg biomass ha^{-1} (Wortman, 2016). Northern region warm-season cover crops have demonstrated biomass potentials between 1.9–5.7 Mg ha^{-1} when grown in the short, 30–50 day window between spring and fall vegetables (Wauters et al., 2021). By comparison, warm-season cover crops in southern latitudes with warmer climates, still grown between two vegetable crops but for a longer duration, can produce 5–10 Mg biomass ha^{-1} with adequate moisture (Allar and Maltais-Landry, 2022; Rohwer, 2022). In both cases, cover crops consistently provided N retention services, but had varying effects on N provision and subsequent crop yield. Still, warm-season cover crop have demonstrated an ability to increase cash crop yields in agronomic systems (Blanco-Canqui et al., 2012), suggesting that there could be more mechanisms driving cover crop impacts on cash crop yields, like weed suppression or micronutrient competition (Teasdale and Mirsky, 2015; Pfeiffer et al., 2016).

Part of the disconnect between cover crop biomass production and subsequent N provision is caused by variation in N mineralization, a necessary process to convert organic N in cover crop tissue to SIN, which is more readily available for cash crop uptake. Cash crops utilize the most N from cover crops when N mineralization occurs in synchrony with crop demand (Ledgard, 2001), but the timing and extent of N mineralization is driven by multiple factors. Environmental factors and tillage events are widely known to mediate N mineralization (Finney et al., 2015; Thapa et al., 2021), often in ways that are difficult to predict. Cover crops may dampen these effects on N mineralization by recoupling N cycling with ecosystem functions (Drinkwater and Snapp, 2007). Cover crop tissue quality plays a key role in N mineralization dynamics by governing the balance between N mineralization and immobilization, a process that occurs when SIN is taken up by soil microbes and therefore unavailable for crops. Legume cover crops, due to their high quality tissue that favors N mineralization, have potential to create greater N availability than fallows (O'Connell et al., 2015) and increase synchrony between N mineralization and crop demand (Crews and Peoples, 2005).

Our objective was to investigate a range of warm-season cover crops integrated in northern region vegetable rotations for biomass production, N provision and retention, and vegetable yield impacts. We examined warm-season cover crops in two rotations at three field sites in Minnesota for three years. We asked the following questions, specific to northern region vegetable production systems: (1) How much biomass do warm-season cover crops produce in the two selected rotations? (2) To what extent do warm-season cover crops affect N provision and retention services? And (3) To what extent do warm-season cover crops affect the yield of subsequent vegetable crops?

Materials & Methods

Field Site Descriptions

The field study was conducted at two sites in Minnesota, USA from 2020 to 2023: the Minnesota Agricultural Experiment Station in Ramsey County and Big River Farms in Washington County. A third site at White Earth Nation in Mahnomen County, MN, USA was added in 2021. Drought conditions were considerable throughout MN in 2021 and 2022, with 2021 being the worst drought in the state in ~30 years, characterized by a combination of low precipitation and above-average temperatures (Fig. 1).

The Ramsey County site (44°59'23.2"N 93°10'32.5"W) has an annual precipitation average of 828 mm and mean monthly temperatures that range from -10.5 °C in January to 22.6 °C in July. The frost-free period is typically 144 to 166 days long. The soil type is Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) with baseline soil organic matter 4.4 %, P 85 mg kg^{-1}, K 242 mg kg^{-1}, S 6.5 mg kg^{-1}, Ca 1636 mg kg^{-1}, Mg 346 mg kg^{-1}, and pH 6.4. The site is managed using organic practices and has a long-term history of manure application. No manure or other fertilizers had been applied in the two years preceding the experiment.

The Washington County site (45°10'07.7"N 92°48'54.9"W) has a mean annual precipitation of 942 mm and mean monthly high temperatures that range from -4.4 °C in January to 32.5 °C in July. The frost-free period is typically 139 to 159 days long. The soil type is Crystal Lake silt loam (fine-silty, mixed, superactive, frigid Oxyaquic Glossudalfs) with baseline SOM 2.4 %, P 66 mg kg^{-1}, K 153 mg kg^{-1}, S 5.8 mg kg^{-1}, Ca 1260 mg kg^{-1}, Mg 275 mg kg^{-1}, and pH 7.1. The site is USDA certified organic and had been previously managed for mixed vegetable production with minimal fertilizer inputs.

The Mahnomen County site (47°19'33.4"N 95°57'29.9"W) has a mean annual precipitation of 697 mm rainfall and mean monthly high temperatures that range from -7 °C in January to 28 °C in July. The frost free period is typically 114 to 135 days long. The soil is mapped as a

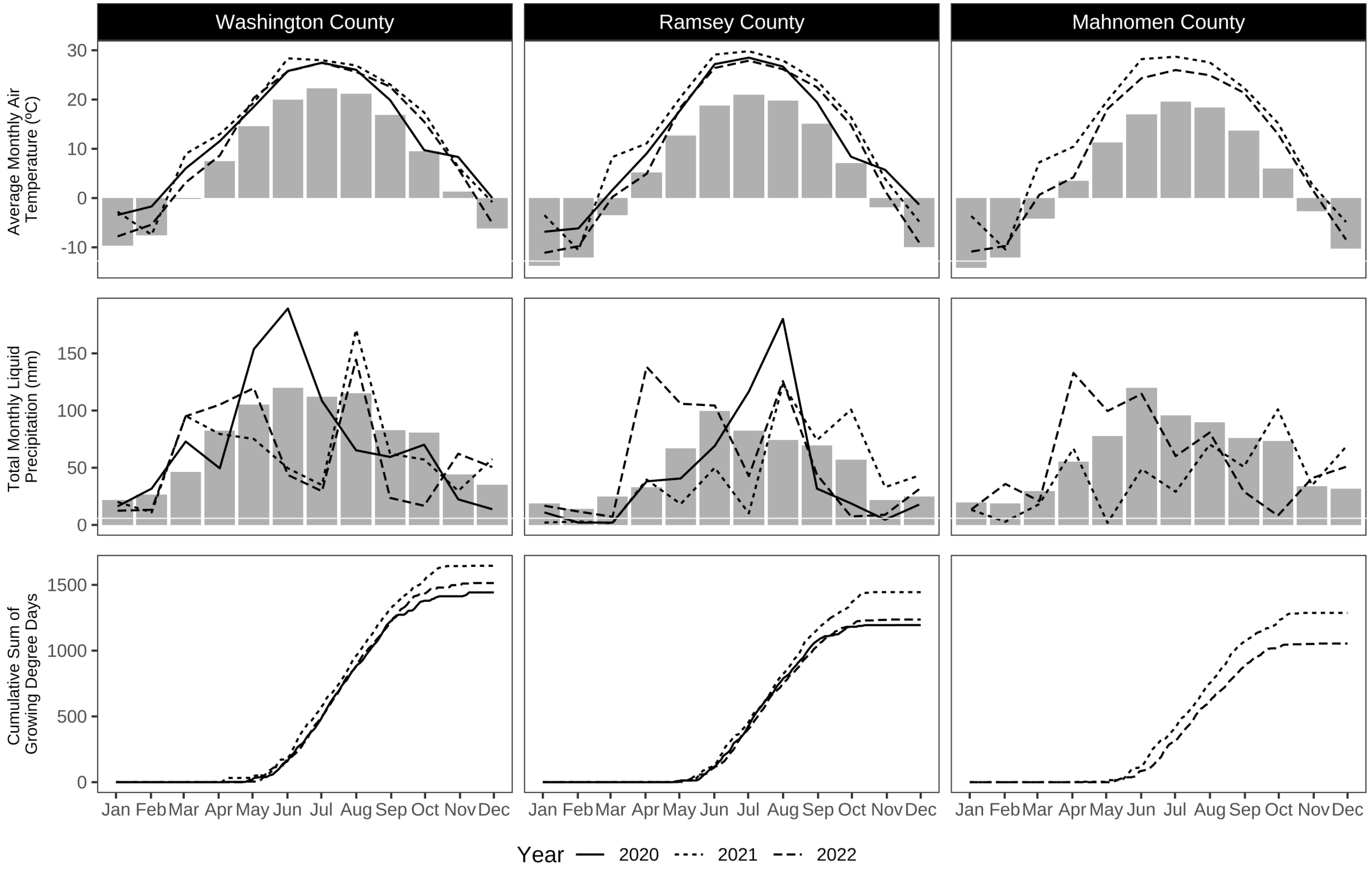

Figure 1. (Top) Average monthly air temperature (°C), (Middle) total monthly liquid precipitation (mm) for the three study years (lines) compared to 30 year average (bars) by site. (Bottom) Cumulative growing degree days (GDD; base temperature 10 °C) by year and site. Data were retrieved from the nearest NOAA or MN DNR climate data stations to each site.

Hamerly-Vallers complex. The Hamerly series is a calcerous loamy till (Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls). The Vallers series is a calcerous fine-loamy till (Fine-loamy, mixed, superactive, frigid Typic Calciaquolls). Baseline SOM was 1.6 %, P 1 ppm, K 189 ppm, Mg 399 ppm, Ca 2611 ppm, and pH 8.0. The site had a previous history of high-traffic application of fill material, resulting in composition and behavior distinct from what would be expected in the mapped soil type. Site managers' and our own observations indicated high gravel content and low productivity compared to neighboring fields. The three years prior to the experiment consisted of mixed row crop and vegetable production using organic practices. At the onset of the experiment, pelleted poultry manure was applied at a rate of 11.2 kg ha^{-1}.

Experimental Design and Field Operations

Two experiments were conducted at each site using the same cover crop treatments but in different rotations: one with spring-planted cover crops followed by a vegetable crop (hereafter CCV) and the other with summer-planted cover crops preceded by a vegetable crop (hereafter VCC). In two adjacent fields—one for each rotation—plots were established in a randomized complete block design with four replicates and left in place for all three years of the experiment. Each plot measured 8.3 m^2 in Washington County, 9.3 m^2 in Ramsey County, and 4.5 m^2 in Mahnomen County. Cover crop treatments included two legume-grass mixtures, one legume monoculture, three non-legume treatments, and two no cover crop controls (Table 1). Monoculture seeding rates were based on recommendations from Clark (2008) and seed suppliers and mixture seeding rates from Young-Mathews (2017) (Table 1). Cover crop seed was purchased from Albert Lea Seed (Albert Lea, MN). Cover crops in both rotations were broadcast seeded by hand and raked to increase uniformity and seed-soil contact. Cover crops were overhead irrigated as needed to provide 3 cm of moisture weekly until cover crops were well-established (~3-4 weeks after planting). Cover crops were spot weeded by hand in early development. In several instances, early weed pressure threatened the establishment of certain cover crop species; in those cases, all plots from the given treatment were wheel hoed and cover crops were reseeded. Weeds were removed from weed-free control plots weekly using a wheel hoe.

Table 1. Cover crop species and seeding rates in each experimental treatment.

Treatment	Legume Species (Common) Name	Seeding Rate (kg ha^{-1})	Non-Legume Species (Common) Name	Seeding Rate (kg ha^{-1})
Pea/oat	*Pisum sativum* L. (Field Pea)	105	*Arrhenatherum elatius* L. (Oat)	93
Cowpea/sorghum-Sudan	*Vigna unguiculata* (L.) Walp. (Cowpea)	105	*Sorghum bicolor* (L.) Moench × *S. bicolor var. Sudanese* Stapf. (Sudex)	33
Buckwheat			*Fagopyrum esculentum* Moench (Buckwheat)	90
Crimson clover	*Trifolium incarnatum* L. (Crimson Clover)	30		
Phacelia			*Phacelia tanacetifolia* Bendth. (Phacelia)	12
Sunflower/oat			*Helianthus annuus var. Peredovick* L. (Sunflower)	15
			Arrhenatherum elatius L. (Oat)[1]	93
Weedy control				
Weed-free control				

[1] Oat was added to sunflower/oat treatment in 2021.

Vegetables were weeded by hand and with a wheel hoe weekly.

Prior to cover crop seeding and spring vegetable planting, fields were rototilled to 15 cm depth. This usually occurred in late April but workplace limitations due to COVID-19 delayed tillage to mid-May in 2020. Secondary tillage occurred 1-2 days before each new cover crop seeding and vegetable planting. Burial and excavation of resin lysimeters used to determine NO_3^- leaching proceeded between secondary tillage and cover crop seeding or vegetable planting, and is explained in greater detail below. Primary and secondary tillage events occurred again in the VCC field in June, between lettuce harvest and cover crop seeding. Cover crops in the CCV rotation were terminated in July by mowing and then incorporated by rototilling. Another rototill was performed 10-14 days after cover crop termination, then broccoli seedlings were transplanted into the field immediately thereafter. Cover crops in the VCC rotation were mowed after frost-induced senescence in October and incorporated by rototilling the following spring. Buckwheat often had to be terminated about 2 weeks earlier than other cover crops in the VCC rotation because of rapid seed set and senescence. A simplified example of field operations is shown in Figure 2.

Vegetable Production and Yield Measurements

In the VCC rotation, lettuce (*Lactuca sativa* L.) was transplanted each spring immediately following secondary tillage. One row of each of four varieties of lettuce (Johnny's Selected Seeds Salanova® Lettuce vars. 'Red Oak', 'Green Oak', 'Red Butter', and 'Green Butter') was transplanted in each plot with 61 cm spacing between rows and 25 cm spacing within rows. In the CCV rotation, broccoli (*Brassica oleracea* L. *var. Italica*, Johnny's Selected Seeds Belstar Organic (F1) Broccoli) was transplanted immediately following secondary tillage after cover crop termination in July. Broccoli was transplanted by hand into 1.8 m twin row beds with 76 cm between twins and in-row spacing of 46 cm. Lettuce and broccoli harvest took place when maturity was judged optimal for marketing: the majority of heads had attained marketable size, while bolting of the most advanced heads was minimal. At each site, the entire field was uniformly harvested at a single date. Lettuce yield was measured beginning in year two by weighing four randomly chosen, marketable heads from each plot. Broccoli yield was measured by weighing the four centermost plants in each plot. Head weights were collected when possible, but because broccoli heads did not reach maturity in four site-years (Ramsey and Washington Counties in 2020, Mahnomen County in 2021 and 2022), plant weights were used for yield analyses.

Biomass and Soil Measurements

To estimate N contributions from cover crop tissue, aboveground biomass was sampled prior to cover crop termination in both rotations. Two 0.1-m^2 quadrats were collected from each plot, sorted by species, and dried at 63 °C. After drying, biomass was ground and stored at room temperature until analysis. Ground tissue was analyzed for C and N content by combustion (Elementar Americas, Inc., New York City, NY, USA).

In the CCV rotation, soil was sampled at cover crop seeding, monthly throughout cover crop

Table 2. Soil sampling dates and ID codes by year and site. ID codes consist of the crop in place (CC = cover crop, V = vegetable) and a subscript indication of the timing of sampling (0 = At seeding/planting of the crop, 1 = first sampling after planting, where applicable; 2 = second sampling after planting; 3 = third sampling after planting; Final = At termination/harvest of the crop).

ID	Washington County			Ramsey County			Mahnomen County	
	Date (mm-dd) in 2020	Date (mm-dd) in 2021	Date (mm-dd) in 2022	Date (mm-dd) in 2020	Date (mm-dd) in 2021	Date (mm-dd) in 2022	Date (mm-dd) in 2021	Date (mm-dd) in 2022
CCV Rotation								
CC_0	05-12	05-04	05-05	05-11	05-03	05-04	05-18	06-03
CC_1	06-02	05-25	06-01	06-01	05-24	05-31	06-18[a]	06-28
CC_2	06-27[a]	06-22[a]	06-23	06-27[a]	06-21[a]	06-21		
CC_{Final}	07-13	07-16	07-06[a]	07-15	07-14	07-05[a]	07-21	07-13[1]
V_1	08-19	08-10	08-02	08-14	08-09	08-01	08-25[b]	08-17[b]
V_2	09-15[b]	09-10[b]	08-30[b]	09-17[b]	09-15[b]	08-31[b]		
V_{Final}	10-05	10-04	09-27	10-09	10-07	09-26	10-11	10-05
VCC Rotation								
V_0	05-12	05-04	05-05	05-11	05-03	05-06	05-18	06-03
V_1		05-25	06-01		05-24	05-31		06-28
V_{Final}		06-22[b]	06-17[b]	07-22	06-21[b]	06-16[b]	07-21	07-13[b]
CC_1	07-29	07-16	08-02	08-14	07-14	08-01	08-25[a]	08-17[2]
CC_2	08-19	08-10	08-30[a]	09-17[a]	08-09	08-31[a]		
CC_3	09-15[a]	09-10[a]			09-15[a]			
CC_F	10-05	10-04	09-27	10-09	09-30	09-19	10-11	09-21

[a] PMN during cover crop growth was measured with soils collected on these dates.

[b] PMN during vegetable growth was measured with soils collected on these dates.

growth, between mowing and incorporation at cover crop termination, and monthly throughout broccoli growth (dates in Table 2). In the VCC rotation, soil was sampled at lettuce planting, monthly throughout lettuce and cover crop growth, and between mowing and incorporation at cover crop termination (dates in Table 2). At each sampling, a push probe of 1.9 cm inner diameter was used to collect 10 cores of 15.2 cm depth from random locations within each plot. In Mahnomen County, soils were sampled to a depth of 10.2 cm because of rocky conditions deeper in the soil profile. Soils were then homogenized by mixing and separate subsamples were air dried at 35 °C and refrigerated at 3 °C. Refrigerated subsamples were used to calculate gravimetric water content (GWC). Air dried soils were used for NO_3–N quantification by extraction and colorimetric analysis as described below.

To measure KCl extractable soil NO_3–N content, air dried soils from each sampling were ground to 2 mm to homogenize, 8 g subsamples shaken in 40 mL of 1 M KCl for 1 hour at 180 rpm, then gravity filtered through Whatman 1 filter paper. Extracts were collected and frozen at -20 °C until analysis. To determine extractable NO_3–N concentrations, microplate colorimetric analyses based on the Greiss reaction (Doane and Horwáth, 2003) were performed on soil extracts using a SpectraMax 190 microplate reader (Molecular Devices, LLC, San Jose, CA, USA).

Potentially mineralizable N (PMN) was measured twice a year at each site and in each rotation. In the CCV rotation, PMN was measured during the final month of cover crop growth and one month prior to broccoli harvest (dates footnoted in Table 2). In the VCC rotation, PMN was measured at lettuce harvest and one month prior to fall cover crop senescence (dates footnoted in Table 2). PMN was quantified through 7 d, anaerobic incubations of soils according to Drinkwater et al. (1997). Ten grams of fresh soil were extracted as described above to determine baseline NO_3–N and ammonium-N (NH_4–N) content. Another 10 g of fresh soils were weighed into Falcon tubes with 10 mL DDI H_2O and capped using lids with a single, 0.4 mm diameter drill hole. Nitrogen gas (N_2) was injected into each tube to displace oxygen gas in the headspace and holes in each cap were immediately covered with stickers to prevent gas escape. Tubes were incubated at 37 °C for exactly 7 d, shaken for 1 hour in 30 mL of 1.33 M KCl, then filtered through Whatman 1 filter paper. Extracts were stored at -20 °C until analysis for NO_3–N as described above, as well as colorimetric analysis for NH_4–N as described in Sinsabaugh et al. (2000). PMN was calculated as the difference in NH_4–N before and after incubation. A lack of NO_3–N post-incubation verified the conditions of the incubation were anaerobic.

Potentially leachable NO_3–N (PLN) was measured using buried NO_3^- exchange resin lysimeters in both rotations at Ramsey County, where there was a high risk of loss due to high soluble N from a history of manure application. Lysimeters were constructed by loading 14.8 mL of NO_3^--specific, mixed bed resin particles (Purolite Ion Exchange Resins; Philadelphia, PA; type A520E) into an Organza mesh bag and sewed shut to a definitive area of 7.6 cm x 7.6 cm. Lysimeters were soaked in 10% KCl overnight to remove NO_3^- from resin particles, then rinsed thoroughly in DI water prior to burial. Three holes were drilled in each plot using a 6” auger. One lysimeter was buried completely flat in each hole to a depth of 30 cm. Plot whiskers were used to mark the locations of the lysimeters for ease of excavation.

In 2020, resin lysimeters were buried only from August to October, then beginning in the spring of 2021, they were buried as continuously as possible throughout the remainder of the experiment. Resin lysimeters were excavated about one week prior to each new planting of cover crops or vegetables and a new batch of lysimeters were buried one day before planting. Excavated lysimeters were immediately dried in a greenhouse to stabilize N species on the resin particles (Schnabel, 1983). Dried lysimeters were shaken in 300 mL of 3 M KCl for 1 hour and gravity filtered through Whatman #42 filter paper. Extracts were stored at -20 °C until analysis for NO_3–N as described above.

Statistical Analysis

Data were analyzed using R version 4.2.2 (R Core Team, 2022). Data organization and summaries were conducted in the *tidyverse* (Wickham, 2023). Linear mixed effect models of cover crop treatment, site, year, and sampling date (where applicable) on each response variable (cover crop biomass production, soil NO_3–N, PMN, resin lysimeter NO_3–N concentration, and vegetable yield) were constructed using the *lme4* package with block as a random effect (Bates et al., 2023). Analysis of variance (ANOVA) was conducted on each model and post-hoc means comparisons were performed using the *multcomp* package with Sidak p-value corrections for multiple comparisons (Hothorn et al., 2023; Wright, 1992). ANOVA's assumptions of normality and homogeneity of variance of residuals were checked using Shapiro-Wilk and Levene's tests, respectively. When these assumptions were not met, log transformed data were used for analyses. Significant differences were considered at α=0.05. Analyses were conducted separately for each rotation because the experiment was not designed for rotational comparisons (i.e. the plots for each rotation were not randomized within each other). Figures were created using the *ggplot2* package and tables were created using the *knitr* and *kableExtra* packages (Wickham et al., 2023; Xie, 2023; Zhu, 2021).

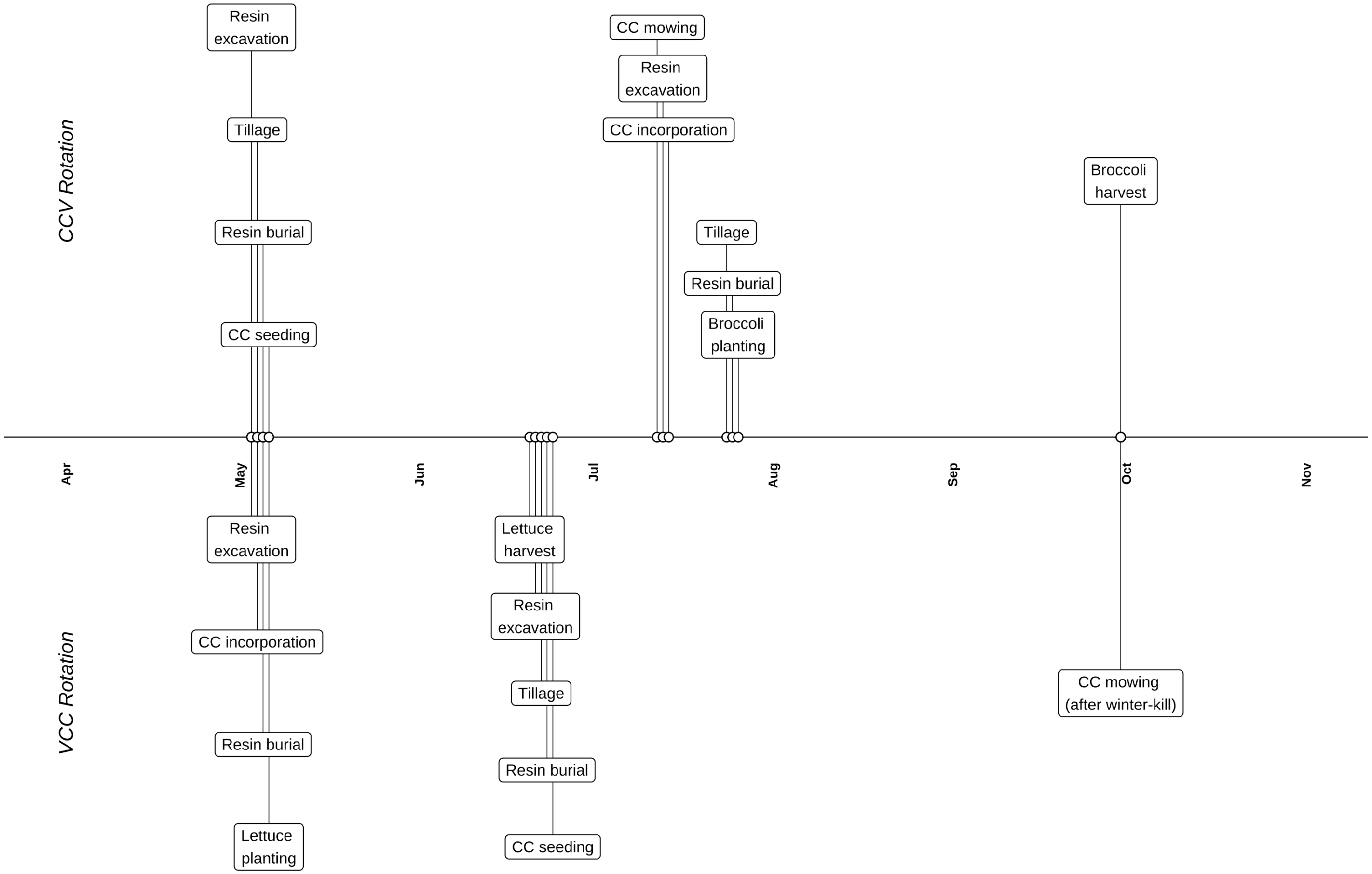

Figure 2. Example timeline for field activities. Resin burials and excavations were specific to the Ramsey County site, but all other activities occurred in this pattern at all sites. May resin excavations were performed only after resin burial in a prior year. CC = cover crop.

Results

CCV Rotation

Cover Crop Biomass Production

Biomass production was measured at cover crop termination and higher values indicated a greater potential of the cover crop to deliver N services. In the CCV rotation, total biomass (cover crops + weeds) ranged from 628-13,350 kg biomass ha^{-1} and averaged 3,160 kg ha^{-1} across cover crop treatments and site-years. Treatment, site, year, and all interactions between these parameters affected biomass production (Table 3). In Washington County, biomass production in cover crop plots was usually similar to the weedy control except in 2022, when biomass production in pea/oat and crimson clover plots exceeded the weedy control (Fig. 3). Similarly, in Ramsey County, biomass production in cover crop plots was similar to the weedy control except in 2022, when biomass production in pea/oat plots exceeded the weedy control. Biomass production in Mahnomen County did not differ between cover crop treatments and the weedy control in any year. Moreover, biomass production in Mahnomen County was 53% lower than in Ramsey and Washington Counties and cover crop biomass yield (excluding weeds) was less than the weedy control biomass in all treatments and years (Table S1).

Indicators of N Provision and Retention

PMN was measured as an indicator of the soil microbial community's capacity for long-term N provision, with larger PMN values indicating more mineralization and N provisioning by the cover crop treatment for the subsequent vegetable crop. The interaction of date, site, and year; the interaction of date and site; the interaction of date and year; cover crop treatment; site; year; and sampling date affected PMN in the CCV rotation (Table 3). PMN was lower in the weed-free control than all other treatments except the weedy control and phacelia ($F_{7,454}$=3.0, p=0.004; Fig. 4).

Monthly soil NO_3–N availability indicated cover crop effects on seasonal N dynamics, with greater NO_3–N availability during vegetable growth indicating N provision, and lesser NO_3–N availability during cover crop growth indicating N retention. Cover crop treatment, site, year, sampling date, and all interactions between these parameters affected NO_3–N availability in the CCV rotation (Table 3). Available soil NO_3–N was greater in the weed-free control than all other treatments across site-years when considering all sampling dates ($F_{7,1576}$=12.2, p<0.001), and sampling dates during cover crop growth only ($F_{7,841}$=18.9, p<0.001; Fig. 4). During vegetable growth, available soil NO_3–N was similar across all treatments ($F_{7,684}$=0.99, p=0.434; Fig. 4). From CC_0 to CC_{Final}, NO_3–N declined in all treatments except the weed-free control, where it increased (Fig. 5; sampling time codes in Table 2). Available soil NO_3–N in the weed-free control exceeded other treatments at CC_{Final} in all site-years. From CC_{Final} to V_1, NO_3–N consistently increased in all treatments except the weed-free control. In some site-years, NO_3–N in the weed-free control continued to increase from CC_{Final} to V_1 (e.g. 2020 in Ramsey County), while in other site-years, NO_3–N declined (e.g. 2021 at all sites; Fig. 5). The magnitude of NO_3–N increase from CC_{Final} to V_1 varied by site-year in cover crop and weedy control plots. For example, in Washington County, available soil NO_3–N increased from 1.4 to 2.9 mg kg^{-1} (twofold increase) from CC_{Final} to V_1 in 2021, then from 0.03 to 8.9 mg kg^{-1} (300-fold increase) in the same period in 2022. At V_2, NO_3–N in the weed-free control was frequently highest among treatments, though NO_3–N in crimson clover, pea/oat, and cowpea/sorghum-Sudan did not differ from the weed-free control in some site-years. By V_{Final}, which indicated residual NO_3–N vulnerable to loss, NO_3–N declined to near zero (range 0.3-2.8 mg kg^{-1}) in all years except 2020 (range 1.2-16.1 mg kg^{-1}), and did not differ between treatments on average ($F_{7,461}$=0.2, p=0.984; Fig. 4).

Treatment and burial period affected NO_3–N collected on resin lysimeters in the CCV rotation (Table 3; burial period appears as *Date* parameter). Total NO_3–N collected on resin lysimeters over the course of the experiment was greater in the weed-free control than phacelia and similar among all other treatments (Fig. 4). Lysimeter NO_3–N concentrations by treatment and burial period are available as a supplement (Table S4).

Broccoli Yield

Broccoli yield was measured as an indication of marketable response to cover crop treatments, especially through the proxy of their effects on N provision services. The interaction of site, treatment, and year; and treatment affected broccoli yield in the CCV rotation (Table 3). Across site-years, broccoli yield was greater in the weed-free control than all other treatments except crimson clover, and yield in crimson clover greater than that in sunflower/oat ($F_{7,237}$=6.0, p<0.001; Fig. 4). Within each site-year, broccoli yields in cover crop plots did not usually differ from those in the weedy control and yield deficits were common relative to the weed-free control (Fig. 6). In Washington County, broccoli yields in pea/oat plots exceeded those in weedy control plots in 2020 and 2021, and broccoli yields in crimson clover plots exceeded those in weedy control plots in 2021 and 2022. Phacelia and sunflower/oat plots demonstrated broccoli yield deficits relative to both the weedy control and the weed-free control in Ramsey County in 2022.

VCC Rotation

Cover Crop Biomass Production

In the VCC rotation, total biomass production (cover crops + weeds) in cover crop plots ranged from 930-7144 kg ha^{-1} and averaged 2849 kg ha^{-1} across cover crop treatments and site-years. Treatment, site, year, and all interactions between these parameters affected biomass production (Table 4). Cowpea/sorghum-Sudan produced more biomass than any other treatment when averaged across site-years ($F_{6,204}$=23.9, p<0.001). The weedy control was next highest, with biomass production greater than pea/oat, phacelia, and crimson clover, and similar to buckwheat and sunflower/oat. Crimson clover was the lowest biomass producer and produced less biomass than all treatments except pea/oat and phacelia. When site-years were considered separately, cowpea/sorghum-Sudan produced more biomass than the weedy control in 2021 and 2022 in Washington and Ramsey Counties (Table S2), and was the only treatment to produce more biomass in 2021 and 2022 than 2020 ($F_{2,18}$=0.05, p=0.014). In other treatments, biomass production in each site-year was usually equal to the biomass of the weedy control, except in pea/oat plots in Ramsey County in 2022, in which biomass production was less than the weedy control. Biomass production by species, treatment, and site-year is available as a supplement (Table S2).

INDICATORS OF N PROVISION AND RETENTION

The interaction of date, site, and year; the interaction of date and year; the interaction of site and year; treatment; site; year; and sampling date affected PMN in the VCC rotation (Table 4). PMN was lower in the weed-free control than all other treatments ($F_{7,397}$=8.9, p<0.001; Fig. 8).

Treatment, site, year, sampling date, and all interactions between these parameters affected NO_3–N availability in the VCC rotation (Table 4). Available soil NO_3–N was greater in the weed-free control than any other treatment across site-years when considering all sampling dates ($F_{7,1291}$=11.6, p<0.001), and sampling dates during cover crop growth only ($F_{7,779}$=12.2, p<0.001; Fig. 8). Soil NO_3–N during spring lettuce growth was not measured monthly until year 2, after cover crop treatments had been established, and was greater in crimson clover plots than cowpea/sorghum-Sudan and sunflower/oat plots; additionally, soil NO_3–N was greater in pea/oat, phacelia, and weed-free control plots than cowpea/sorghum-Sudan ($F_{7,397}$=5.0, p<0.001; Fig. 8). From V_0 to V_{Final}, NO_3–N tended to increase, and crimson clover, pea/oat, and weed-free control plots frequently had more NO_3–N than other treatments (Fig. 9; sampling time codes in Table 2). In all treatments except the weed-free control, NO_3–N typically reached a yearly peak at CC_1, then decreased until approaching zero through CC_{Final}. In the weed-free control, NO_3–N was frequently higher than other treatments from CC_1 to CC_{Final}. In 2020 at Ramsey County, NO_3–N in the weed-free control increased to over 50 mg kg^{-1} at CC_2, over two times higher than any other NO_3–N measurement across the experiment, and remained high through CC_{Final}, which indicated residual fall NO_3–N vulnerable to loss. On average, residual fall NO_3–N did not differ between treatments, though it was between 68 and 89% lower in cover crop treatments than the weed-free control ($F_{7,237}$=0.4, p=0.914; Fig. 8).

Buried resin lysimeters collected NO_3–N at the Ramsey County site to quantify N losses through NO_3^- leaching. Burial period and year affected lysimeter NO_3–N concentrations in the VCC rotation (Table 4; burial period appears as *Date* parameter). Consequently, treatment differences in lysimeter NO_3–N concentrations were not detected (Fig. 8). Lysimeter NO_3–N concentrations by burial period are available as a supplement (Table S5).

Lettuce Yield

Lettuce yield was measured as an indication of marketable response to the cover crop treatments, especially through the proxy of their effects on N provision services. The interaction of treatment and site, the interaction of treatment and year, and site affected vegetable yield in the VCC rotation (Table 4). Across site-years, lettuce yield was greater in the weed-free control than in cowpea/sorghum-Sudan and sunflower/oat, while lettuce yield in remaining treatments did not differ from any treatment ($F_{7,141}$=3.5, p=0.002). Treatment differences by site indicated greater lettuce yields in weed-free control plots than in cowpea/sorghum-Sudan plots at Ramsey County, with no treatment differences detected at other sites (Fig. 10A). Treatment differences by year indicated greater lettuce yield in weed-free control plots than cowpea/sorghum-Sudan and sunflower/oat in 2022, but no treatment differences in 2021 (Fig. 10B).

Table 3. ANOVA statistics for each measured response variable in the CCV rotation. Variables were modeled on the interactive effects of cover crop treatment (Trt), site, year, and sampling date (Date). Block was included as a random effect in each model. F values are presented with subscript numerator and denominator degrees of freedom. P values are followed by asterisks to indicate significance: * at α=0.05, ** at α=0.01, and *** at α=0.001. PMN = potentially mineralizable N.

	Cover Crop Biomass		PMN		Soil NO_3–N		Resin Lysimeter NO_3–N		Vegetable Yield	
Parameter	$F_{Ndf,Ddf}$	P	$F_{Ndf,Ddf}$	P	$F_{Ndf,Ddf}$	P	$F_{Ndf,Ddf}$	P	$F_{Ndf,Ddf}$	P
Date†			$24.6_{1,344}$	<0.001***	$774.7_{6,1211}$	<0.001***	$217.4_{1,92}$	<0.001***		
Site	$53.4_{2,10}$	<0.001***	$34.9_{2,9}$	<0.001***	$191.8_{2,10}$	<0.001***			$144.3_{2,9}$	<0.001***
Trt	$3.0_{6,135}$	0.009**	$4.5_{7,344}$	<0.001***	$57.7_{7,1211}$	<0.001***	$4.7_{7,92}$	<0.001***	$17.8_{7,183}$	<0.001***
Year	$293.5_{2,135}$	<0.001***	$18.7_{2,344}$	<0.001***	$425.3_{2,1211}$	<0.001***	$82.9_{2,92}$	<0.001***	$205.9_{2,183}$	<0.001***
Date†:Site			$6.9_{2,344}$	0.001**	$128.4_{10,1211}$	<0.001***				
Date†:Trt			$1.7_{7,344}$	0.106	$17.3_{42,1211}$	<0.001***	$1.2_{7,92}$	0.287		
Date†:Year			$18.3_{2,344}$	<0.001***	$179.6_{12,1211}$	<0.001***				
Site:Trt	$3.2_{12,134}$	<0.001***	$1.5_{14,343}$	0.110	$13.7_{14,1211}$	<0.001***			$8.1_{14,183}$	<0.001***
Site:Year	$61.6_{3,134}$	<0.001***	$33.5_{3,343}$	<0.001***	$65.5_{3,1211}$	<0.001***			$32.1_{3,183}$	<0.001***
Trt:Year	$3.3_{12,134}$	<0.001***	$0.7_{14,344}$	0.750	$4.0_{14,1211}$	<0.001***	$0.7_{14,92}$	0.779	$3.6_{14,183}$	<0.001***
Date†:Site:Trt			$0.7_{14,343}$	0.740	$6.7_{70,1211}$	<0.001***				
Date†:Site:Year			$9.0_{2,344}$	<0.001***	$34.5_{15,1211}$	<0.001***				
Date†:Trt:Year			$0.7_{14,344}$	0.728	$2.6_{84,1211}$	<0.001***				
Site:Trt:Year	$1.9_{16,134}$	0.023*	$1.1_{21,343}$	0.366	$5.0_{21,1211}$	<0.001***			$3.1_{21,183}$	<0.001***
Date†:Site:Trt:Year			$0.6_{14,343}$	0.838	$2.5_{105,1211}$	<0.001***				

† Date parameter captures slightly different, temporal-based variables for each response variable. For soil NO_3–N, Date is a numeric variable of the date of each sample collection. For PMN and resin lysimeter NO_3–N, Date is a nominal, binary indicator for each of the two sampling or lysimeter excavation time points per year.

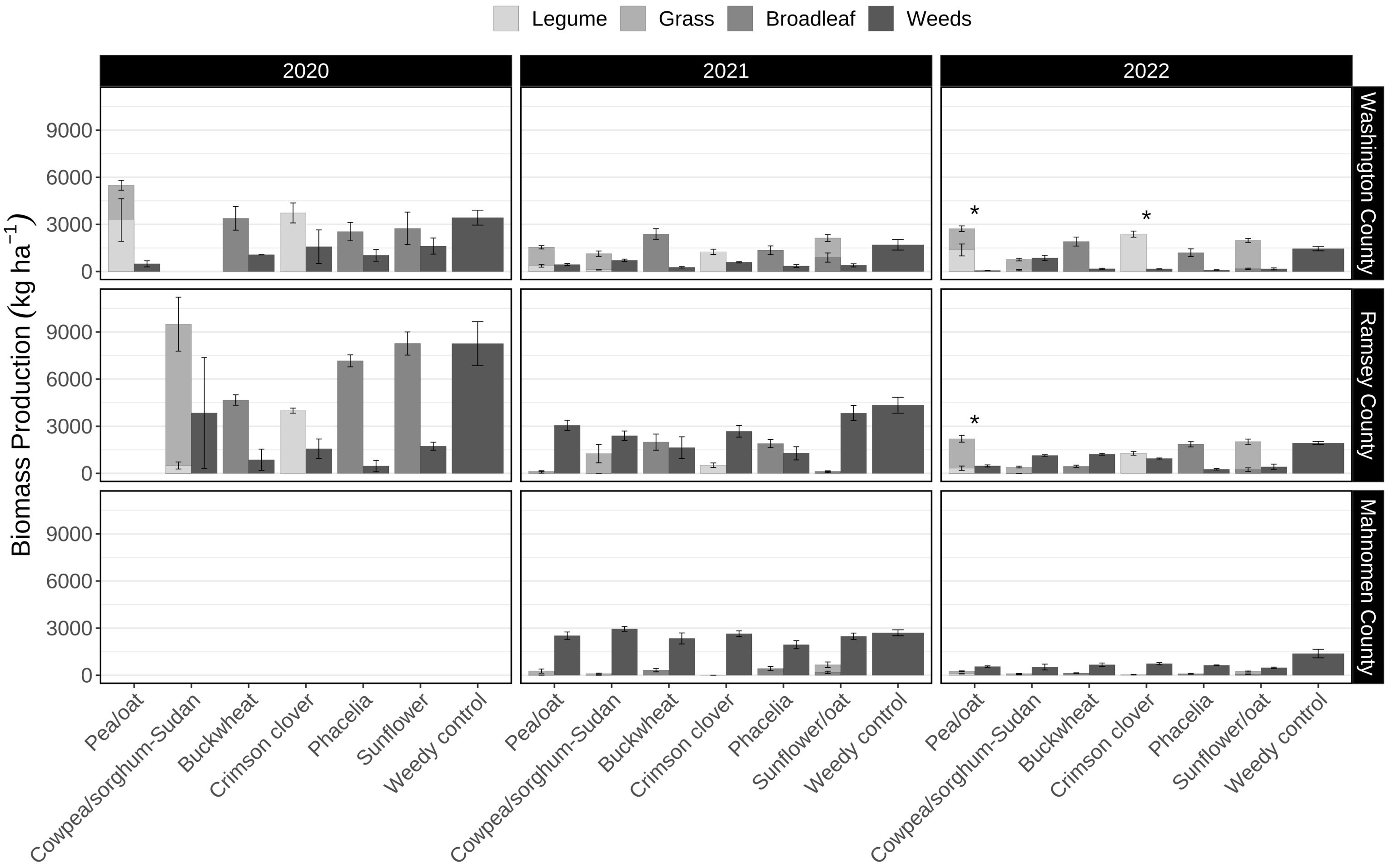

Figure 3. Mean ± standard error of biomass production during the cover crop phase of the CCV rotation by site-year, treatment, and species or weeds. For each treatment, cover crop species are stacked to the left of weeds from the same plots. Asterisks above a cover crop treatment indicate significant difference in total biomass production of that treatment from the weedy control in the same site-year. Open circles above cover crop biomass bars indicate significant difference in biomass production of cover crops only (excluding weeds) from the weedy control in the same site-year. Differences were considered at α=0.05.

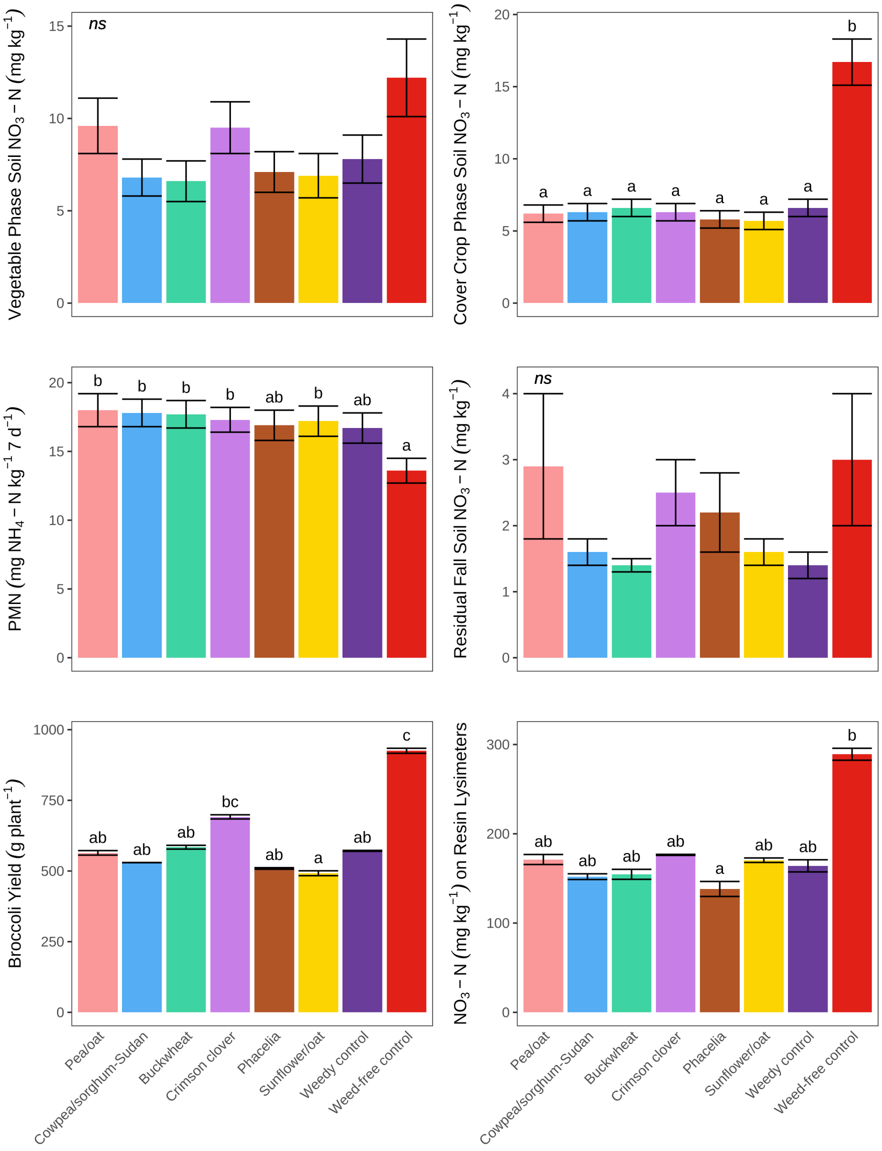

Figure 4. Indicators of N provision and retention by treatment in the CCV rotation, averaged across site-years. Indicators in the left-hand column are associated with N provision, while those in the right-hand column are associated with N retention. Within each indicator, similar letters above bars indicate no significant difference between treatments. “Ns” indicates that the effect of treatment was not significant for an indicator. Error bars represent standard error. Resin lysimeter NO_3–N represents the mean of total NO_3–N collected on resin lysimeters over the entire experiment.

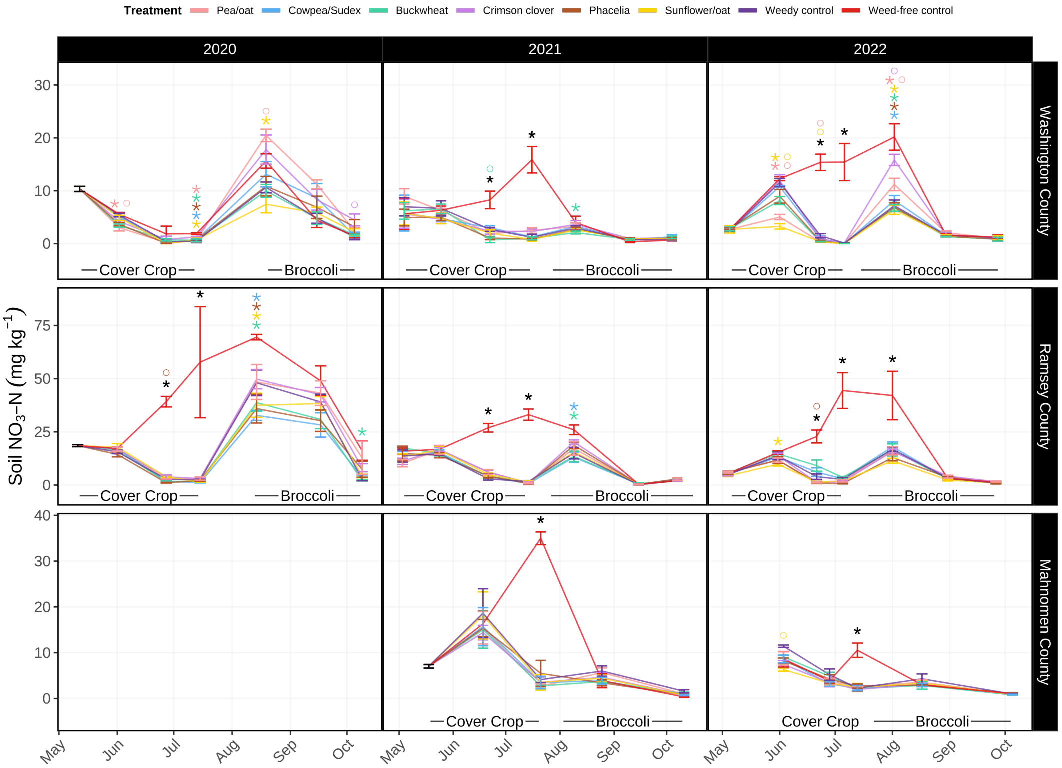

Figure 5. Mean ± standard error of soil NO_3—N in the CCV rotation at monthly intervals by treatment and site. Black data points are displayed at or before implementation of cover crop treatments and represent the grand mean. On dates where treatment had a significant effect on soil NO_3—N, symbols indicate which cover crop treatments differed from each of the two controls. Asterisks of the same color as a treatment indicate significant difference between that treatment and the weed-free control. Open circles of the same color as a treatment indicate significant difference between that treatment and the weedy control. Black asterisks indicate significant difference between all cover crop treatments and the weed-free control. Differences were considered at α=0.05. At the bottom of each panel, line segments indicate time periods in which cover crops or broccoli were growing.

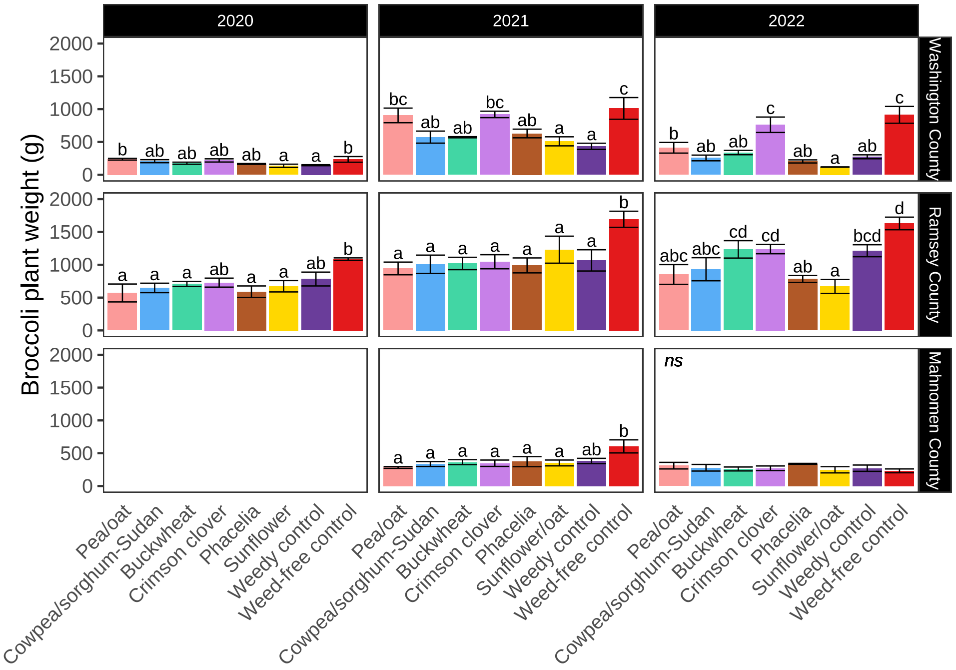

Figure 6. Yield of broccoli (g plant^{-1}) following spring-planted cover crops in the CCV rotation by treatment and site-year. Error bars indicate standard error of the mean. Similar letters above bars within the same site-year indicate no difference in broccoli yield between treatments (α=0.05). “Ns” indicates no significant effect of treatment on broccoli yield according to ANOVA.

Table 4. ANOVA statistics for each measured response variable in the VCC rotation. Variables were modeled on the interactive effects of cover crop treatment (Trt), site, year, and sampling date (Date). Block was included as a random effect in each model. F values are presented with subscript numerator and denominator degrees of freedom. P values are followed by asterisks to indicate significance: * at α=0.05, ** at α=0.01, and *** at α=0.001. PMN = potentially mineralizable N.

	Cover Crop Biomass		PMN		Soil NO_3–N		Resin Lysimeter NO_3–N		Vegetable Yield	
Parameter	$F_{\mathrm{Ndf,Ddf}}$	P	$F_{\mathrm{Ndf,Ddf}}$	P	$F_{\mathrm{Ndf,Ddf}}$	P	$F_{\mathrm{Ndf,Ddf}}$	P	$F_{\mathrm{Ndf,Ddf}}$	P
Date†			$5.8_{1,304}$	0.017*	$350.9_{6,974}$	<0.001***	$151.7_{1,90}$	<0.001***		
Site	$72.9_{2,10}$	<0.001***	$81.5_{2,12}$	<0.001***	$79.6_{2,12}$	<0.001***			$69.3_{2,14}$	<0.001***
Trt	$12.0_{6,156}$	<0.001***	$9.5_{7,304}$	<0.001***	$76.2_{7,974}$	<0.001***	$1.0_{7,90}$	0.445	$3.7_{7,113}$	0.001**
Year	$4.0_{2,156}$	0.020*	$14.5_{2,304}$	<0.001***	$269.6_{2,974}$	<0.001***	$15.7_{2,90}$	<0.001***	$0.6_{1,113}$	0.424
Date†:Site			$1.8_{2,304}$	0.167	$93.8_{10,974}$	<0.001***				
Date†:Trt			$0.6_{7,304}$	0.743	$9.1_{42,974}$	<0.001***	$1.1_{7,90}$	0.395		
Date†:Year			$5.4_{1,304}$	0.021*	$199.7_{8,974}$	<0.001***				
Site:Trt	$10.9_{12,156}$	<0.001***	$1.5_{14,304}$	0.115	$10.1_{14,974}$	<0.001***			$2.2_{14,113}$	0.011*
Site:Year	$7.7_{3,156}$	<0.001***	$20.1_{3,304}$	<0.001***	$13.1_{3,974}$	<0.001***			$47.5_{1,113}$	<0.001***
Trt:Year	$7.6_{12,156}$	<0.001***	$1.2_{14,304}$	0.279	$5.4_{14,974}$	<0.001***	$0.7_{14,90}$	0.733	$2.3_{7,113}$	0.030*
Date†:Site:Trt			$0.3_{14,304}$	0.993	$2.5_{70,974}$	<0.001***				
Date†:Site:Year			$4.3_{1,304}$	0.039*	$52.1_{9,974}$	<0.001***				
Date†:Trt:Year			$0.5_{7,304}$	0.846	$4.1_{56,974}$	<0.001***				
Site:Trt:Year	$2.8_{18,156}$	<0.001***	$1.4_{21,304}$	0.131	$3.1_{21,974}$	<0.001***			$1.0_{7,113}$	0.411
Date†:Site:Trt:Year			$0.7_{7,304}$	0.686	$2.0_{63,974}$	<0.001***				

† Date parameter captures slightly different, temporal-based variables for each response variable. For soil NO_3–N, Date is a numeric variable of the date of each sample collection. For PMN and resin lysimeter NO_3–N, Date is a nominal, binary indicator for each of the two sampling or lysimeter excavation time points per year.

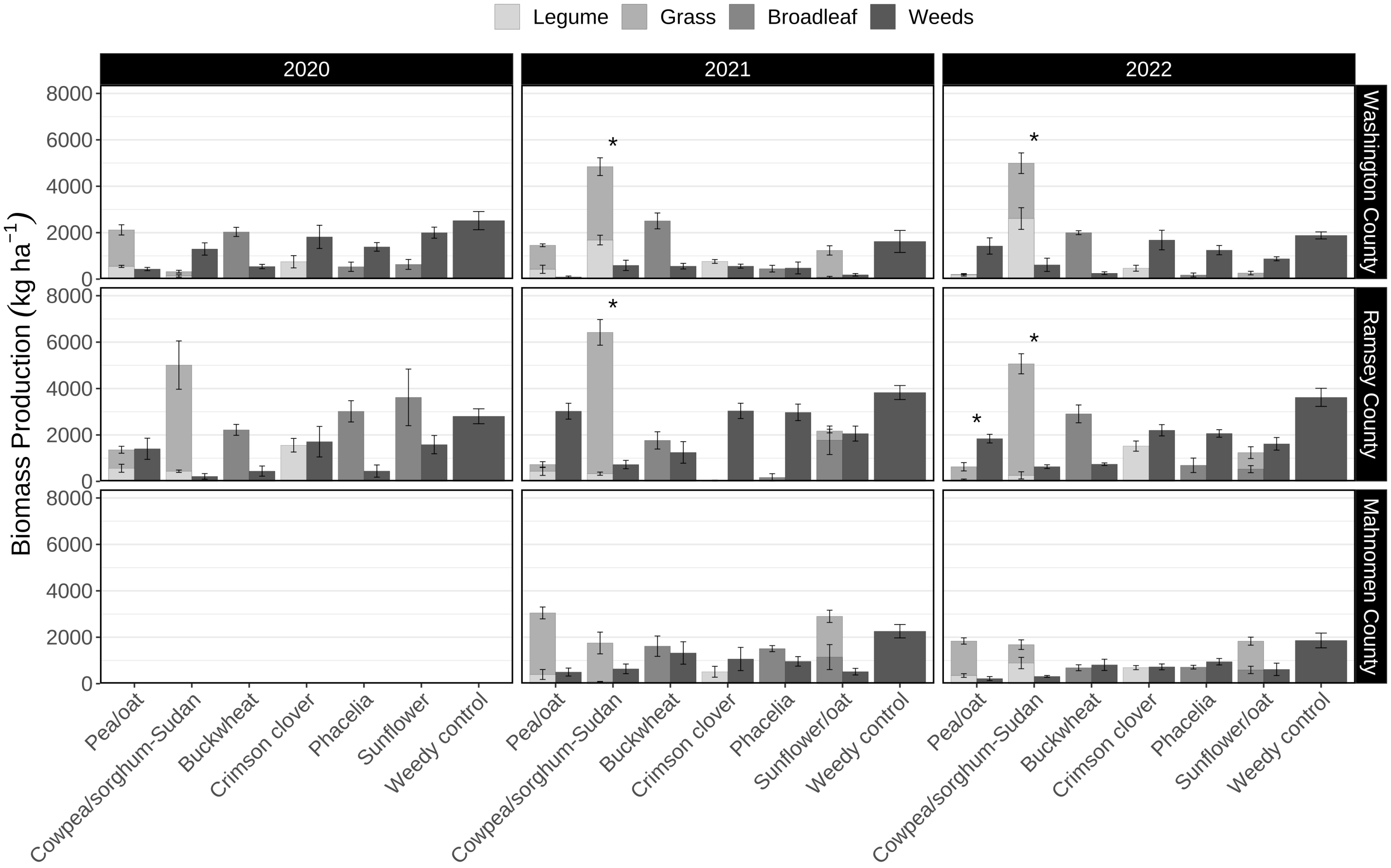

Figure 7. Mean ± standard error of biomass production during the cover crop phase of the VCC rotation by site-year, treatment, and species or weeds. For each treatment, cover crop species are stacked to the left of weeds from the same plots. Asterisks above a cover crop treatment indicate significant difference in total biomass production of that treatment from the weedy control in the same site-year. Open circles above cover crop biomass bars indicate significant difference in biomass production of cover crops only (excluding weeds) from the weedy control in the same site-year. Differences were considered at α=0.05.

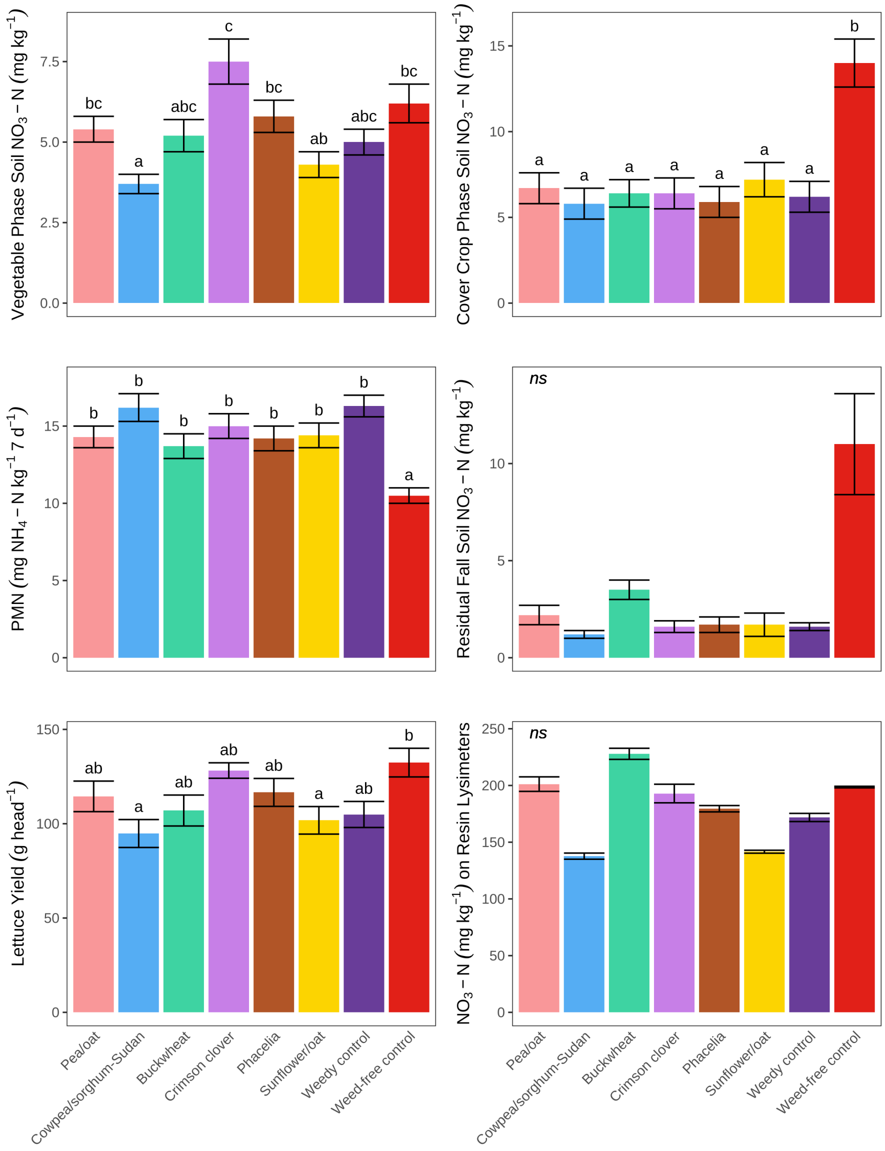

Figure 8. Indicators of N provision and retention by treatment for the VCC rotation, averaged across site-years. Indicators in the left-hand column are associated with N provision, while those in the right-hand column are associated with N retention. Within each indicator, similar letters above bars indicate no significant difference between treatments. "Ns" indicates that the effect of treatment was not significant for an indicator. Error bars represent standard error. Resin lysimeter NO_3–N represents the mean of total NO_3–N collected on resin lysimeters over the entire experiment.

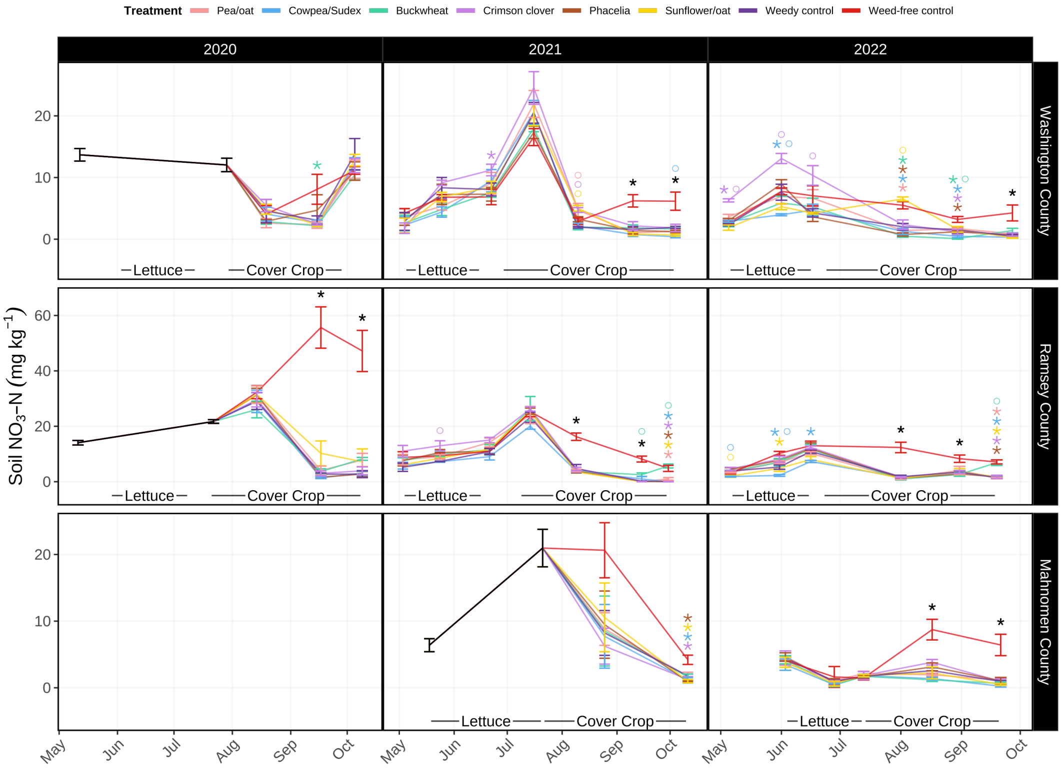

Figure 9. Mean ± standard error of soil NO_3—N in the VCC rotation at monthly intervals by treatment and site. Black data points are displayed at or before implementation of cover crop treatments and represent the grand mean. On dates where treatment had a significant effect on soil NO_3—N, symbols indicate which cover crop treatments differed from each of the two controls. Asterisks of the same color as a treatment indicate significant difference between that treatment and the weed-free control. Open circles of the same color as a treatment indicate significant difference between that treatment and the weedy control. Black asterisks indicate significant difference between all cover crop treatments and the weed-free control. Differences were considered at α=0.05. At the bottom of each panel, line segments indicate time periods in which lettuce or cover crops were growing.

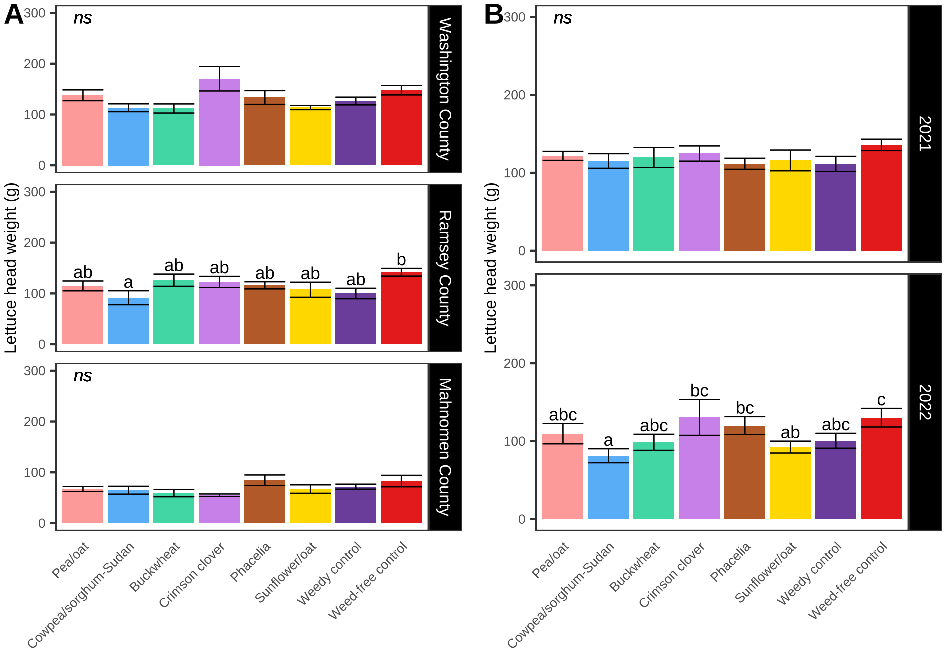

Figure 10. Lettuce yields (g head^{-1}) following summer-planted cover crops in the VCC rotation by (A) treatment and site and (B) treatment and year. Error bars indicate standard error of the mean. Similar letters above bars within the same site-year indicate no difference in lettuce yield between treatments (α=0.05). "Ns" indicates no significant effect of treatment on lettuce yield according to ANOVA.

Discussion

How much biomass do warm-season cover crops produce in the two selected rotations?

It is crucial to identify warm-season cover crop options that contribute substantial biomass in northern region vegetable rotations as biomass drives N cycling benefits. The degree of cover crop biomass production as well as biomass quality (e.g., C:N ratio, lignin content) influence when and how much N will be taken up by cover crops and subsequently released for vegetable crops, which can impact vegetable yields (Allar and Maltais-Landry, 2022; Finney et al., 2016). All cover crops in this study demonstrated potential to establish and produce substantial biomass in both rotations but did not often exceed the biomass produced in a weedy control. Variation in cover crop biomass production between site-years tended to follow similar trends to the weedy control which suggests that, even in site-years where biomass production among cover crops was low, there is still potential for N cycling benefits similar to or greater than those of weedy fallow.

Limitations in biomass production in this study were likely driven by drought conditions, seed/seedling predation, and temperatures during establishment. Small seeded cover crops were the lowest biomass producers and appeared to have the most difficulty establishing in drought-induced high temperatures. Temperatures at midsummer seeding of cover crops in VCC ranged from 25-29 °C, which exceed the optimal germination temperatures of crimson clover (11-17 °C) and phacelia (10-20 °C), explaining hinderances in establishment (Baxter et al., 2019; Tiryaki and Keles, 2012). However, these cover crops are known for extensive flowering that supports beneficial insect and pollinator populations and diversity (Rundlöf et al., 2018; Candelaria-Morales et al., 2022; Bryan et al., 2021), which could offset services lost by low biomass production. Additional limitations to biomass production may have been induced by seed predation by birds and seedling predation by deer, which we observed mainly among sunflower, buckwheat, and pea.

Cover crop mixtures tended to produce the most biomass among cover crops, which could be a result of differential resource usage by grasses and legumes that facilitates high productivity in a variety of conditions (Hooper and Vitousek, 1997). This inference is further supported by mixture expression in this study, which appeared to favor legume production in low N conditions. In the VCC rotation, cowpea comprised 27% of total biomass in the cowpea/sorghum-Sudan mixture at low fertility sites (Washington and Mahnomen Counties), yet only 6% at the high fertility site (Ramsey County). Similarly, in the CCV rotation, pea comprised 41% of total biomass in the pea/oat mixture at a low fertility site (Washington County), and only 7% at the high fertility site (Mahnomen County excluded here due to low biomass production of cover crop species in the CCV rotation). This trend is consistent with previous findings that legume-grass mixtures produce a functional response to endogenous soil N (Bukovsky-Reyes et al., 2019), proportionally expressing more grass in high N conditions and more legume in low N conditions. Additionally, drought likely had positive impacts on biomass production of the cowpea/sorghum-Sudan mixture, which was the only treatment to produce more biomass in drought years than non-drought years. This was unsurprising as cowpea is native to central Africa and thrives in hot, dry conditions, and sorghum-Sudangrass is a C4 grass that has demonstrated biomass production of more than 8 Mg ha^{-1} in the northern region (Snapp et al., 2005; Wauters et al., 2021). However, cowpea/sorghum-Sudan biomass production averaged just 1.3 Mg ha^{-1} in this study, suggesting the rotational time slots of this study did not support its full biomass potential.

Differences in biomass yield among sites can potentially be explained by SOM and GDDs. GDDs are commonly correlated with and used in predictive models of cover crop biomass production (Baraibar et al., 2020; Prabhakara et al., 2015; Mirsky et al., 2009). Ramsey County's high biomass production among sites is likely the result of high SOM (4.4%) and cumulative GDDs (Fig. 1). Contrarily, Mahnomen County's lower biomass production could be attributed to low SOM (1.2%) and cumulative GDDs. The later onset of GDDs in the spring also delayed cover crop establishment in Mahnomen County, which could be the reason for extremely low cover crop biomass production in the CCV rotation. This suggests that climates similar to those of Mahnomen County, which is located in USDA plant hardiness zone 3b, may be unsuitable for spring–summer cover crops preceding a fall vegetable. Washington County is an intermediate to other sites in relation to both SOM (2.4%) and GDDs, which could explain its mid-range cover crop productivity. However, cover crops in Washington County more frequently yielded more biomass than the weedy control than other sites, suggesting that this site had the greatest increase in potential biomass-derived benefits. Based on this result, warm-season cover crops may provide the most benefit to farms with mid-range SOM which exceeds potential nutrient deprivation but limits production of weedy biomass. Meanwhile, farms with high SOM may achieve similar biomass-derived benefits from weedy fallows as cover crops, and farms with low-range SOM may need to provide additional nutrient inputs to produce enough biomass to derive N cycling benefits from cover crops.

Buckwheat consistently produced substantial biomass in both rotations, which could make it a good option for reliable N cycling benefits in a variety of environmental and soil conditions, but it must be managed carefully to avoid N cycling challenges. Buckwheat is known to grow rapidly and provide floral resources for pollinators (Kumar et al., 2009; Bulan et al., 2015). In this study, buckwheat in the VCC rotation often needed to be terminated ~2–4 weeks sooner than other cover crops to avoid reseeding which could create a weed problem during subsequent lettuce growth. In several site-years, the early termination of buckwheat appeared to result in an increase in soil available NO_3–N in the late fall, which is asynchronous with vegetable demand and when vulnerability to leaching is high (Fig. 9; Table S3). Therefore, optimal N provision from a buckwheat cover crop terminated in the fall for a vegetable crop the following spring could likely be achieved by planting buckwheat several weeks later than this study. This could more consistently ensure that buckwheat seed-set does not precede fall frost, and therefore that N mineralization from buckwheat residues more likely occurs in synchrony with vegetable demand the following spring. Further investigation is needed to determine if later buckwheat planting dates present tradeoffs for biomass production or floral resources.

To what extent do warm-season cover crops impact N provision and retention services?

N PROVISION BY COVER CROPS

In the CCV rotation, N provision was evident from all cover crops through rapid increases in soil NO_3–N post-termination (Fig. 5). In the VCC rotation, it was more difficult to gauge changes in NO_3–N driven by cover crop decomposition because of the longer time gap between cover crop termination in the fall and the presumed start of N mineralization the following spring, when lettuce uptake immediately complicated our understanding of N dynamics. However, the slow but steady increases in soil NO_3–N during spring lettuce growth indicated that VCC cover crop treatments facilitated N provision (Fig. 9). Despite net increases in soil NO_3–N after cover crop termination, soil NO_3–N during vegetable growth was not consistently greater in cover crop treatments than the controls. However, in both rotations, PMN in cover crop treatments commonly exceeded the weed-free control (Fig. 4 & 8), suggesting that while cover crops may not boost N provision relative to fallows in the year following termination, they can build stores of organic N available for mineralization in subsequent years (Reussi Calvo et al., 2013; Orcellet et al., 2017). Only a portion of N in cover crop residues is mineralized in the first growing season after termination; for legume residues, this portion is estimated to be about 50%, and less for residues with higher C:N ratios (Clark, 2008). Therefore, when cover crops are used consecutively for multiple years, organic N pools available for mineralization grow, and N availability for cash crops may continue to improve (Schipanski and Drinkwater, 2011; Blesh, 2019; Kuo and Jellum, 2000).

High biomass yield did not consistently lead to greater soil NO_3–N availability for vegetables; instead, biomass C:N ratio seemed to have a stronger influence on soil NO_3–N dynamics after cover crop termination. Cover crop residues with C:N ratios below 20-25 typically facilitate net N mineralization due to ample availability of N relative to C for soil microorganisms (Reberg-Horton et al., 2012; Thomsen et al., 2016), and greater biomass yield can facilitate higher N content in residues (Clark et al., 1997). Pea/oat and crimson clover treatments facilitated greater NO_3–N availability during vegetable growth than other cover crops at multiple time points (Fig. 5 & 9), despite infrequent high biomass yields (Fig. 3 & 7). This could be explained by the leguminous pea and crimson clover residues' low C:N ratios, which typically range from 12 to 20 and tend to facilitate net N mineralization (Parr et al., 2011; Justes et al., 2009; Parton et al., 2007). While it could be true that limited cover crop biomass yields minimized N uptake, leaving greater NO_3–N available for vegetables, this inference is not supported by the observed reductions in soil NO_3–N during cover crop growth, which were similar among cover crop treatments. Instead, soil NO_3–N availability from pea/oat and crimson clover was likely sustained by substantial biomass production in the first year of the experiment, as well as stimulation of microbial activity by cover crops even in low biomass years (Strickland et al., 2019; Finney et al., 2017a).

Non-legume cover crops appeared to facilitate N provision by increasing NO_3–N availability during vegetable growth, but did so at lower levels than legumes, consistent with higher C:N ratios of non-legume residues. Buckwheat and phacelia C:N ratios typically exceed 30:1 and sorghum-Sudangrass C:N can reach as high as 53:1 (Parr et al., 2011; Candelaria-Morales et al., 2022; Creamer and Baldwin, 2000). It is uncommon for N mineralization to dominate over N immobilization when cover crop residue C:N greater than 25-40 (Poffenbarger et al., 2015; Reberg-Horton et al., 2012), but this appeared to be the case in this study. Other studies of warm-season cover crops have demonstrated net N mineralization with residue C:N exceeding 40 (O'Connell et al., 2015), which could be a result of optimal temperature and moisture conditions during summer residue decomposition (Thapa et al., 2021). Still, NO_3–N availability during vegetable growth was frequently highest in the weed-free control, suggesting limitations to N provision from cover crops.

N Retention from Cover Crops

Cover crop N retention benefits could help vegetable producers mitigate environmental problems caused by N pollution, specifically by reducing soil NO_3–N outside of periods of vegetable demand, when it is vulnerable to losses by leaching and volatilization. In this study, cover crops reduced soil NO_3–N levels relative to the weed-free control during their growth (Figs. 5 & 9), demonstrating N retention benefits that are consistent with previous studies (Nouri et al., 2022; Abdalla et al., 2019; Kaye et al., 2019). Phacelia also reduced NO_3^- leaching as indicated by resin lysimeters in the CCV rotation in Ramsey County (Figs. 4). It was unexpected that phacelia would outperform other grasses cover crops explored in this study that are known for their N scavenging capabilities (Komatsuzaki and Wagger, 2015). However, phacelia has been shown to produce greater root densities in the upper soil profile than other cover crops (Bodner et al., 2007). Because N mineralization was likely enhanced in the upper soil profile due to tillage and residue incorporation (Fernandez et al., 2019), higher root densities could have prevented leaching by assimilating NO_3^- before it had a chance to move down the soil profile.

Cover crop N retention benefits as indicated by reductions in residual fall NO_3–N and resin lysimeter NO_3–N concentrations were limited (Figs. 4 & 8), which could be a result of the rotational time slots we explored. Cover crops in either rotation of this study were not growing when vulnerability to NO_3^- leaching is highest. In MN, the most favorable conditions for NO_3^- leaching occur in early spring, when snowmelt moves large quantities of water down the soil profile just before temperatures are suitable for most plant growth. Cover crops that are planted in the fall and overwinter have an opportunity to capture this leachable NO_3^-, and their N retention benefits are well documented (Nouri et al., 2022; Abdalla et al., 2019). The warm-season cover crops in this study may not have provided the same level of N retention benefits because their NO_3^- capture occurred outside of highly vulnerable leaching windows. However, there is a gap in resin lysimeter NO_3–N measurements from the fall of 2020 to the spring of 2021 that represents a limitation of these data. Residual fall NO_3–N in the VCC rotation in 2020 at the Ramsey County site was over 9 times higher in the weed-free control than cover crop treatments (Fig. 9), which would indicate greater risks of NO_3^- leaching in the weed-free control that are not accounted for in our resin lysimeter NO_3–N data. Similarly, residual fall NO_3–N following cover crops in the VCC rotation was 70-90% lower in cover crop treatments than the weed-free control (not significant; Fig. 8), indicating differentials in potential NO_3–N that were not captured by our resin lysimeter measurements. Treatment differences in residual fall NO_3–N in later years were not as stark, likely due to drought conditions reducing N mineralization across treatments (Hunter et al., 2021).

To what extent do warm-season cover crops affect the yield of subsequent vegetable crops?

The ability of cover crops to boost vegetable yields while providing other ecological benefits could maintain profitability, which is important to producers (McCamant, 2014). In this study, trends in vegetable yields mirrored trends in NO_3–N availability during vegetable growth, reflecting a close relationship between N provision and cash crop yield that has been established previously (Finney et al., 2017b). Broccoli yields were boosted by crimson clover and pea/oat relative to the weedy control in a limited number of cases in Washington County (Fig. 6), which could be explained by greater legume biomass production and subsequent N transfer (Table S1). In the CCV rotation, crimson clover made up 76% of biomass in Washington County, while in Ramsey and Mahnomen County, crimson clover made up 52% and 1% of biomass, respectively. This suggests that vegetable yield boosts from legume cover crops are dependent on the cover crop being able to substantially outcompete weeds.

Cover crops frequently produced negative effects on vegetable yield relative to the weed-free control, especially in the CCV rotation (Figs. 6 & 10), and could be a result of residue interference with transplant establishment. In the CCV rotation, vegetables were transplanted 10-14 days after cover crop termination, at which point there were still coarse cover crop residues in the field. These coarse residues may have impeded root-soil contact of vegetable transplants, hindering establishment and yield relative to the weed-free control. This highlights a major challenge of warm-season cover crop rotations, which is optimizing the timing of cover crop termination and vegetable planting to enhance benefits. In the first year of this study, broccoli heads in the CCV rotation did not reach maturity before fall frost because we did not terminate the cover crops or transplant the broccoli soon enough for proper head maturation. This was remedied in later years at the Washington and Ramsey County sites by performing these operations sooner. In Mahnomen County, broccoli head maturation continued to be a challenge due to a limited GDDs that did not support rapid cover crop maturity in the spring–summer time slot, leaving little time for fall broccoli growth and hindering broccoli yields. Therefore, more information on these rotations is needed to clarify planting and termination times that limit cover crop residue interferences and allow enough time for vegetable maturation.

Acknowledgements

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Supplemental Materials

Table S1. Mean ± standard error of cover crop biomass production by site-year and treatment in the CCV rotation. Biomass weights (kg ha^{-1}) are presented by species or weeds along with cover crop total (grass + nongrass) and total (grass + nongrass + weeds) per treatment. Similar letters following totals indicate no differences between treatments within that site-year and rotation, with lowercase letters used for cover crop biomass total comparisons and uppercase letters used for total biomass comparisons. Four field replicates are represented in each mean ($n = 4$) unless otherwise noted.

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
Washington County					
2020					
Pea/oat	2210.0 ± 310.0	3280.0 ± 1340.0	490.0 ± 190.0	5490.0 ± 1650.0a	5980.0 ± 1460.0A (n=2)
Cowpea/sorghum-Sudan	*ND*[1]				
Buckwheat		3390.0 ± 750.0	1070.0 ± 10.0	3390.0 ± 750.0a	4460.0 ± 740.0A (n=2)
Crimson clover		3730.0 ± 630.0	1580.0 ± 1060.0	3730.0 ± 630.0a	5310.0 ± 430.0A (n=2)
Phacelia		2540.0 ± 580.0	1030.0 ± 370.0	2540.0 ± 580.0a	3570.0 ± 210.0A (n=2)
Sunflower		2746.7 ± 1017.2	1620.0 ± 504.8	2746.7 ± 1017.2a	4366.7 ± 1291.9A (n=3)
Weedy control			3430.0 ± 470.0	3430.0 ± 470.0a	3430.0 ± 470.0A (n=2)
2021					
Pea/oat	1175.0 ± 104.9	367.5 ± 86.0	440.0 ± 68.9	1542.5 ± 188.1ab	1982.5 ± 129.3A
Cowpea/sorghum-Sudan	1027.5 ± 171.3	107.5 ± 14.4	708.8 ± 76.0	1135.0 ± 175.1a	1843.8 ± 225.8A
Buckwheat		2387.5 ± 338.8	267.5 ± 44.4	2387.5 ± 338.8b	2655.0 ± 365.0A
Crimson clover		1252.5 ± 168.4	591.2 ± 38.6	1252.5 ± 168.4ab	1843.8 ± 179.1A
Phacelia		1352.5 ± 278.7	351.2 ± 86.0	1352.5 ± 278.7ab	1703.8 ± 293.7A
Sunflower/oat	1242.5 ± 214.3	890.0 ± 292.2	393.8 ± 99.2	2132.5 ± 239.5ab	2526.2 ± 142.5A

Table S1. (continued)

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
Weedy control			1700.0 ± 335.0	1700.0 ± 335.0ab	1700.0 ± 335.0A
2022					
Pea/oat	1352.5 ± 177.5	1372.5 ± 379.3	63.8 ± 19.9	2725.0 ± 292.5c	2788.8 ± 304.1C
Cowpea/sorghum-Sudan	676.1 ± 81.9	83.7 ± 42.2	861.5 ± 168.8	759.8 ± 113.9a	1621.3 ± 96.1ABC
Buckwheat		1908.7 ± 286.4	174.1 ± 32.0	1908.7 ± 286.4bc	2082.8 ± 275.1ABC
Crimson clover		2381.2 ± 194.9	166.1 ± 13.7	2381.2 ± 194.9c	2547.3 ± 200.4C
Phacelia		1197.5 ± 244.6	98.8 ± 20.6	1197.5 ± 244.6ab	1296.3 ± 240.4A
Sunflower/oat	1800.7 ± 129.4	175.1 ± 38.3	168.4 ± 65.5	1975.8 ± 163.8bc	2144.2 ± 192.2BC
Weedy control			1451.3 ± 133.7	1451.3 ± 133.7bc	1451.3 ± 133.7AB
Ramsey County					
2020					
Pea/oat	*ND*[1]				
Cowpea/sorghum-Sudan	9000.0 ± 1700.0	500.0 ± 220.0	3850.0 ± 3490.0	9500.0 ± 1920.0c	13350.0 ± 1570.0B (n=2)
Buckwheat		4670.0 ± 330.0	870.0 ± 670.0	4670.0 ± 330.0ab	5540.0 ± 340.0A (n=2)
Crimson clover		3993.3 ± 157.2	1566.7 ± 610.6	3993.3 ± 157.2a	5560.0 ± 502.1A (n=3)
Phacelia		7166.7 ± 375.5	466.7 ± 357.1	7166.7 ± 375.5bc	7633.3 ± 681.6AB (n=3)
Sunflower		8270.0 ± 730.0	1730.0 ± 250.0	8270.0 ± 730.0c	10000.0 ± 480.0AB (n=2)
Weedy control			8260.0 ± 1377.1	8260.0 ± 1377.1c	8260.0 ± 1377.1AB (n=3)
2021					
Pea/oat	78.8 ± 36.0	57.5 ± 45.2	3060.0 ± 322.7	136.2 ± 58.4ab	3196.2 ± 361.9A
Cowpea/sorghum-Sudan	1251.2 ± 587.2	5.0 ± 5.0	2395.0 ± 302.1	1256.2 ± 586.0bc	3651.2 ± 337.4A
Buckwheat		1991.2 ± 514.7	1637.5 ± 690.4	1991.2 ± 514.7c	3628.8 ± 248.9A
Crimson clover		517.5 ± 147.7	2678.8 ± 371.5	517.5 ± 147.7bc	3196.2 ± 236.5A
Phacelia		1897.5 ± 262.9	1277.5 ± 418.7	1897.5 ± 262.9c	3175.0 ± 270.0A
Sunflower/oat	32.5 ± 32.5	97.5 ± 58.1	3846.2 ± 476.8	130.0 ± 76.0a	3976.2 ± 456.4A
Weedy control			4335.0 ± 503.8	4335.0 ± 503.8c	4335.0 ± 503.8A
2022					
Pea/oat	1872.0 ± 218.4	330.0 ± 136.2	475.0 ± 67.4	2202.0 ± 151.4c	2677.0 ± 217.9D
Cowpea/sorghum-Sudan	400.4 ± 56.1	0.0 ± 0.0	1141.4 ± 51.7	400.4 ± 56.1a	1541.8 ± 105.6A
Buckwheat		449.9 ± 73.4	1217.5 ± 62.3	449.9 ± 73.4a	1667.4 ± 87.6AB
Crimson clover		1276.2 ± 120.8	946.9 ± 33.8	1276.2 ± 120.8b	2223.1 ± 126.8CD
Phacelia		1852.4 ± 169.0	257.0 ± 44.1	1852.4 ± 169.0bc	2109.4 ± 126.6BCD
Sunflower/oat	1780.6 ± 166.2	236.8 ± 117.7	414.4 ± 176.8	2017.4 ± 257.2bc	2431.9 ± 173.2CD
Weedy control			1931.4 ± 99.1	1931.4 ± 99.1bc	1931.4 ± 99.1ABC
Mahnomen County					

Table S1. (continued)

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
2021					
Pea/oat	260.0 ± 132.0	5.0 ± 5.0	2517.5 ± 236.3	265.0 ± 131.9bc	2782.5 ± 195.5A
Cowpea/sorghum-Sudan	100.0 ± 35.8	0.0 ± 0.0	2947.5 ± 151.2	100.0 ± 35.8b	3047.5 ± 120.0A
Buckwheat		325.0 ± 107.4	2342.5 ± 350.1	325.0 ± 107.4bc	2667.5 ± 282.4A
Crimson clover		0.0 ± 0.0	2642.5 ± 181.8	0.0 ± 0.0a	2642.5 ± 181.8A
Phacelia		425.0 ± 129.8	1942.5 ± 257.3	425.0 ± 129.8c	2367.5 ± 287.7A
Sunflower/oat	485.0 ± 176.9	180.0 ± 74.5	2475.0 ± 209.1	665.0 ± 234.0c	3140.0 ± 35.8A
Weedy control			2705.0 ± 188.3	2705.0 ± 188.3d	2705.0 ± 188.3A
2022					
Pea/oat	157.2 ± 29.7	91.6 ± 10.4	551.2 ± 45.6	248.8 ± 38.1c	800.0 ± 14.7A
Cowpea/sorghum-Sudan	64.7 ± 5.7	39.1 ± 13.2	524.3 ± 186.4	103.8 ± 15.8bc	628.1 ± 197.0A
Buckwheat		133.3 ± 21.7	666.6 ± 111.7	133.3 ± 21.7bc	799.9 ± 126.6A
Crimson clover		35.1 ± 11.9	735.6 ± 68.4	35.1 ± 11.9a	770.7 ± 64.8A
Phacelia		93.8 ± 31.5	630.6 ± 27.4	93.8 ± 31.5ab	724.4 ± 47.7A
Sunflower/oat	166.8 ± 32.0	69.1 ± 15.3	474.8 ± 41.9	235.9 ± 47.3bc	710.8 ± 73.1A
Weedy control			1378.4 ± 272.8	1378.4 ± 272.8d	1378.4 ± 272.8A

[1] Not determined due to missing data.

Table S2. Mean ± standard error of cover crop biomass production by site-year and treatment in the VCC rotation. Biomass weights (kg ha^{-1}) are presented by species or weeds along with cover crop total (grass + nongrass) and total (grass + nongrass + weeds) per treatment. Similar letters following totals indicate no differences between treatments within that site-year and rotation, with lowercase letters used for cover crop biomass total comparisons and uppercase letters used for total biomass comparisons. Four field replicates are represented in each mean ($n = 4$) unless otherwise noted.

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
Washington County					
2020					
Pea/oat	1572.5 ± 220.7	547.5 ± 45.9	435.0 ± 70.3	2120.0 ± 192.1a	2555.0 ± 203.7A
Cowpea/sorghum-Sudan	185.0 ± 59.8	136.2 ± 50.4	1297.5 ± 264.7	321.2 ± 80.9a	1618.8 ± 221.5A
Buckwheat		2032.5 ± 197.6	542.5 ± 93.8	2032.5 ± 197.6a	2575.0 ± 156.3A
Crimson clover		747.5 ± 264.2	1820.0 ± 500.2	747.5 ± 264.2a	2567.5 ± 404.9A
Phacelia		531.2 ± 200.4	1387.5 ± 185.1	531.2 ± 200.4a	1918.8 ± 170.7A

Table S2. (continued)

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
Sunflower		632.5 ± 212.8	2000.0 ± 238.4	632.5 ± 212.8a	2632.5 ± 402.4A
Weedy control			2520.0 ± 384.3	2520.0 ± 384.3a	2520.0 ± 384.3A (n=3)
2021					
Pea/oat	1035.0 ± 60.2	422.5 ± 174.9	92.5 ± 39.4	1457.5 ± 124.4bc	1550.0 ± 126.7AB
Cowpea/sorghum-Sudan	3162.5 ± 381.3	1682.5 ± 207.6	592.5 ± 221.3	4845.0 ± 282.9d	5437.5 ± 266.2C
Buckwheat		2507.5 ± 341.7	557.5 ± 120.5	2507.5 ± 341.7cd	3065.0 ± 237.1BC
Crimson clover		760.0 ± 81.9	557.5 ± 86.6	760.0 ± 81.9ab	1317.5 ± 104.4A
Phacelia		450.0 ± 143.4	480.0 ± 255.4	450.0 ± 143.4a	930.0 ± 327.2A
Sunflower/oat	1155.0 ± 200.4	80.0 ± 38.1	185.0 ± 55.0	1235.0 ± 184.4bc	1420.0 ± 179.6AB
Weedy control			1622.5 ± 473.9	1622.5 ± 473.9bc	1622.5 ± 473.9AB
2022					
Pea/oat	20.0 ± 20.0	183.6 ± 55.5	1426.2 ± 349.7	203.6 ± 56.8a	1629.8 ± 327.6AB
Cowpea/sorghum-Sudan	2383.9 ± 444.4	2608.8 ± 466.6	615.2 ± 285.8	4992.7 ± 674.1c	5607.9 ± 642.2C
Buckwheat		2000.0 ± 85.0	255.0 ± 59.3	2000.0 ± 85.0c	2255.0 ± 106.1B
Crimson clover		467.6 ± 128.1	1682.8 ± 421.2	467.6 ± 128.1ab	2150.3 ± 335.9B
Phacelia		177.4 ± 84.9	1247.3 ± 199.3	177.4 ± 84.9a	1424.8 ± 144.7AB
Sunflower/oat	260.7 ± 76.0	0.0 ± 0.0	875.4 ± 85.7	260.7 ± 76.0a	1136.1 ± 103.0A
Weedy control			1882.1 ± 151.2	1882.1 ± 151.2bc	1882.1 ± 151.2AB
Ramsey County					
2020					
Pea/oat	797.5 ± 149.2	565.0 ± 172.3	1405.0 ± 455.7	1362.5 ± 85.2a	2767.5 ± 483.6A
Cowpea/sorghum-Sudan	4572.5 ± 1040.7	437.5 ± 50.7	215.0 ± 120.6	5010.0 ± 999.3b	5225.0 ± 949.1A
Buckwheat		2220.0 ± 230.7	443.3 ± 215.3	2220.0 ± 230.7ab	2663.3 ± 181.9A (n=3)
Crimson clover		1557.5 ± 293.1	1710.0 ± 657.2	1557.5 ± 293.1a	3267.5 ± 407.3A
Phacelia		3017.5 ± 458.2	445.0 ± 263.3	3017.5 ± 458.2ab	3462.5 ± 230.6A
Sunflower		3620.0 ± 1195.8	1583.3 ± 386.8	3620.0 ± 1195.8ab	5203.3 ± 996.4A (n=3)
Weedy control			2805.0 ± 321.2	2805.0 ± 321.2ab	2805.0 ± 321.2A
2021					
Pea/oat	287.5 ± 125.9	436.2 ± 178.0	3023.8 ± 342.3	723.8 ± 273.0bc	3747.5 ± 382.6A
Cowpea/sorghum-Sudan	6087.5 ± 552.4	331.2 ± 68.0	725.0 ± 180.7	6418.8 ± 484.9c	7143.8 ± 405.4B
Buckwheat		1765.0 ± 373.1	1247.5 ± 464.1	1765.0 ± 373.1c	3012.5 ± 192.8A
Crimson clover		27.5 ± 27.5	3037.5 ± 329.7	27.5 ± 27.5a	3065.0 ± 315.3A
Phacelia		172.5 ± 159.3	2973.8 ± 355.6	172.5 ± 159.3ab	3146.2 ± 220.5A
Sunflower/oat	397.5 ± 77.8	1771.2 ± 614.3	2058.8 ± 323.0	2168.8 ± 548.1c	4227.5 ± 466.0A
Weedy control			3827.5 ± 302.4	3827.5 ± 302.4c	3827.5 ± 302.4A

Table S2. (continued)

	Aboveground Biomass Weight by Species or Weeds (kg ha^{-1})				
	Grass	Nongrass	Weeds	Cover Crop Total	Total
2022					
Pea/oat	567.5 ± 178.0	62.5 ± 36.3	1841.2 ± 186.1	630.0 ± 160.5a	2471.2 ± 203.5A
Cowpea/sorghum-Sudan	4807.5 ± 433.8	258.8 ± 155.2	633.8 ± 81.0	5066.2 ± 425.0c	5700.0 ± 375.8C
Buckwheat		2908.8 ± 383.9	740.0 ± 55.1	2908.8 ± 383.9bc	3648.8 ± 343.5B
Crimson clover		1520.0 ± 219.9	2202.5 ± 243.1	1520.0 ± 219.9abc	3722.5 ± 353.1B
Phacelia		692.5 ± 310.9	2063.8 ± 162.5	692.5 ± 310.9a	2756.2 ± 277.9AB
Sunflower/oat	712.5 ± 254.6	526.2 ± 151.2	1618.8 ± 271.1	1238.8 ± 257.8ab	2857.5 ± 86.9AB
Weedy control			3621.2 ± 389.8	3621.2 ± 389.8bc	3621.2 ± 389.8B
Mahnomen County					
2021					
Pea/oat	2652.5 ± 255.0	395.0 ± 214.7	500.0 ± 171.6	3047.5 ± 429.5b	3547.5 ± 416.9A
Cowpea/sorghum-Sudan	1665.0 ± 468.9	87.5 ± 7.5	637.5 ± 209.3	1752.5 ± 476.0b	2390.0 ± 525.8A
Buckwheat		1615.0 ± 437.1	1322.5 ± 482.7	1615.0 ± 437.1b	2937.5 ± 772.5A
Crimson clover		512.5 ± 233.8	1062.5 ± 501.0	512.5 ± 233.8a	1575.0 ± 425.7A
Phacelia		1510.0 ± 130.6	960.0 ± 205.5	1510.0 ± 130.6b	2470.0 ± 172.6A
Sunflower/oat	1755.0 ± 264.7	1145.0 ± 538.7	517.5 ± 142.3	2900.0 ± 364.2b	3417.5 ± 440.0A
Weedy control			2260.0 ± 288.5	2260.0 ± 288.5b	2260.0 ± 288.5A
2022					
Pea/oat	1487.9 ± 135.1	350.0 ± 78.6	218.8 ± 85.3	1837.9 ± 171.6b	2056.6 ± 120.7AB
Cowpea/sorghum-Sudan	791.2 ± 207.6	888.8 ± 244.1	312.5 ± 39.8	1680.0 ± 263.3b	1992.5 ± 242.8AB
Buckwheat		685.0 ± 128.0	810.3 ± 242.5	685.0 ± 128.0a	1495.3 ± 148.0A
Crimson clover		691.2 ± 88.7	724.4 ± 125.5	691.2 ± 88.7a	1415.6 ± 77.8A
Phacelia		711.2 ± 80.2	946.0 ± 138.4	711.2 ± 80.2a	1657.2 ± 100.3AB
Sunflower/oat	1240.4 ± 173.5	590.2 ± 158.9	616.2 ± 266.3	1830.7 ± 284.9b	2446.9 ± 210.8B
Weedy control			1861.2 ± 317.8	1861.2 ± 317.8b	1861.2 ± 317.8AB

[1] Not determined due to missing data.

Table S3. Summary of monthly soil NO_3–N ANOVA statistics and pairwise treatment comparisons by rotation, site, and date. F values are presented with subscript numerator and denominator degrees of freedom. F and P values are derived from ANOVA performed on models of soil NO_3–N by treatment with block as a random effect. Letter summaries are derived from post-hoc pairwise treatment comparisons using Tukey's HSD and Sidak p-value adjustments for multiple comparisons. Similar letters between treatments within a row indicate no differences at α=0.05.

			Treatment							
Date	$F_{Ndf,Ddf}$	P	Pea/oat	Cowpea/sorghum-Sudan	Buckwheat	Crimson clover	Phacelia	Sunflower/oat	Weedy control	Weed-free control
CCV Rotation										
Washington County										
2020-05-12	$1.0_{7,21}$	0.433	a	a	a	a	a	a	a	a
2020-06-02	$5.3_{7,21}$	0.001	a	b	ab	ab	ab	b	b	b
2020-06-27	$2.0_{7,21}$	0.109	a	a	a	a	a	a	a	a
2020-07-13	$4.7_{7,21}$	0.002	a	a	a	ab	a	a	a	b
2020-08-19	$6.4_{7,21}$	<0.001	c	abc	ab	bc	ab	a	ab	bc
2020-09-15	$2.2_{7,20}$	0.082	a	a	a	a	a	a	a	a
2020-10-05	$2.7_{7,21}$	0.037	ab	ab	ab	b	ab	ab	a	ab
2021-05-04	$1.1_{7,21}$	0.399	a	a	a	a	a	a	a	a
2021-05-25	$1.1_{7,24}$	0.395	a	a	a	a	a	a	a	a
2021-06-22	$10.2_{7,21}$	<0.001	ab	b	a	ab	ab	ab	b	c
2021-07-16	$18.9_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-08-10	$3.9_{7,21}$	0.008	ab	ab	a	b	ab	ab	ab	b
2021-09-10	$2.5_{7,21}$	0.050	a	a	a	a	a	a	a	a
2021-10-04	$0.7_{7,21}$	0.639	a	a	a	a	a	a	a	a
2022-05-05	$0.2_{7,21}$	0.982	a	a	a	a	a	a	a	a
2022-06-01	$21.7_{7,23}$	<0.001	ab	c	bc	c	c	a	c	c
2022-06-23	$48.8_{7,21}$	<0.001	a	ab	ab	ab	ab	a	b	c
2022-07-06	$125.4_{7,24}$	<0.001	a	a	a	a	a	a	a	b
2022-08-02	$24.8_{7,21}$	<0.001	bc	ab	a	cd	a	a	a	d
2022-08-30	$0.9_{7,21}$	0.506	a	a	a	a	a	a	a	a
2022-09-27	$0.9_{7,21}$	0.549	a	a	a	a	a	a	a	a
Ramsey County										
2020-05-11	$1.1_{7,19}$	0.396	a	a	a	a	a	a	a	a
2020-06-01	$1.2_{7,23}$	0.318	a	a	a	a	a	a	a	a

Table S3. (continued)

Date	$F_{Ndf,Ddf}$	P	Pea/oat	Cowpea/sorghum-Sudan	Buckwheat	Crimson clover	Phacelia	Sunflower/oat	Weedy control	Weed-free control
2020-06-27	$66.2_{7,24}$	<0.001	bc	ab	ab	c	a	c	bc	d
2020-07-15	$34.0_{7,24}$	<0.001	a	a	a	a	a	a	a	b
2020-08-14	$4.2_{7,21}$	0.005	ab	a	a	ab	a	a	ab	b
2020-09-17	$2.1_{7,24}$	0.084	a	a	a	a	a	a	a	a
2020-10-09	$3.3_{7,21}$	0.016	ab	ab	a	ab	ab	ab	a	b
2021-05-03	$1.3_{7,21}$	0.294	a	a	a	a	a	a	a	a
2021-05-24	$0.6_{7,24}$	0.782	a	a	a	a	a	a	a	a
2021-06-21	$14.4_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-07-14	$42.3_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-08-09	$3.5_{7,21}$	0.013	ab	a	a	ab	ab	ab	ab	b
2021-09-15	$0.2_{7,21}$	0.991	a	a	a	a	a	a	a	a
2021-10-07	$1.0_{7,21}$	0.463	a	a	a	a	a	a	a	a
2022-05-04	$1.4_{7,21}$	0.262	a	a	a	a	a	a	a	a
2022-05-31	$3.0_{7,21}$	0.023	ab	ab	b	ab	ab	a	ab	b
2022-06-21	$33.8_{7,21}$	<0.001	ab	c	c	ab	a	ab	bc	d
2022-07-05	$33.5_{7,21}$	<0.001	ab	ab	b	ab	a	ab	ab	c
2022-08-01	$7.9_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2022-08-31	$2.0_{7,21}$	0.097	a	a	a	a	a	a	a	a
2022-09-26	$1.8_{7,21}$	0.139	a	a	a	a	a	a	a	a
Mahnomen County										
2021-06-18	$0.3_{7,21}$	0.960	a	a	a	a	a	a	a	a
2021-07-21	$10.3_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-08-25	$1.4_{7,21}$	0.250	a	a	a	a	a	a	a	a
2021-10-11	$2.3_{7,21}$	0.066	a	a	a	a	a	a	a	a
2022-06-03	$3.2_{7,21}$	0.019	ab	ab	ab	ab	ab	a	b	ab
2022-06-28	$0.7_{7,21}$	0.651	a	a	a	a	a	a	a	a
2022-07-13	$11.4_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2022-08-17	$1.1_{7,21}$	0.378	a	a	a	a	a	a	a	a
2022-10-05	$0.5_{7,24}$	0.833	a	a	a	a	a	a	a	a
VCC Rotation										
Washington County										
2020-07-29	$2.0_{7,21}$	0.101	a	a	a	a	a	a	a	a

Table S3. (continued)

Date	$F_{Ndf,Ddf}$	P	Pea/oat	Cowpea/sorghum-Sudan	Buckwheat	Crimson clover	Phacelia	Sunflower/oat	Weedy control	Weed-free control
2020-08-19	$1.3_{7,21}$	0.313	a	a	a	a	a	a	a	a
2020-09-15	$2.5_{7,24}$	0.043	ab	ab	a	ab	ab	ab	ab	b
2020-10-05	$0.7_{7,21}$	0.690	a	a	a	a	a	a	a	a
2021-05-04	$1.9_{7,21}$	0.129	a	a	a	a	a	a	a	a
2021-05-25	$3.0_{7,24}$	0.022	ab	a	ab	b	ab	ab	ab	ab
2021-06-22	$3.7_{7,21}$	0.009	ab	ab	ab	b	a	ab	ab	a
2021-07-16	$2.3_{7,21}$	0.067	a	a	a	a	a	a	a	a
2021-08-10	$9.8_{7,21}$	<0.001	b	a	a	b	ab	b	a	ab
2021-09-10	$8.6_{7,20}$	<0.001	a	a	a	a	a	a	a	b
2021-10-04	$13.4_{7,21}$	<0.001	ab	a	b	b	ab	ab	b	c
2022-05-05	$11.9_{7,21}$	<0.001	b	ab	ab	c	ab	a	ab	ab
2022-06-01	$9.6_{7,21}$	<0.001	ab	a	ab	c	bc	ab	b	bc
2022-06-17	$3.4_{7,24}$	0.012	ab	ab	ab	b	a	a	a	ab
2022-08-02	$13.8_{7,24}$	<0.001	ab	ab	a	bc	ab	d	ab	cd
2022-08-30	$11.1_{7,21}$	<0.001	cd	ab	a	bc	bc	bcd	bcd	d
2022-09-27	$13.3_{7,21}$	<0.001	ab	a	b	ab	ab	a	ab	c
Ramsey County										
2020-07-22	$0.7_{7,21}$	0.679	a	a	a	a	a	a	a	a
2020-08-14	$0.5_{7,21}$	0.813	a	a	a	a	a	a	a	a
2020-09-17	$22.8_{7,20}$	<0.001	ab	a	ab	ab	a	b	ab	c
2020-10-09	$14.5_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-05-03	$1.1_{7,24}$	0.380	a	a	a	a	a	a	a	a
2021-05-24	$4.9_{7,21}$	0.002	ab	a	ab	b	ab	a	a	ab
2021-06-21	$3.9_{7,21}$	0.007	b	a	ab	b	ab	ab	ab	ab
2021-07-14	$0.8_{7,24}$	0.575	a	a	a	a	a	a	a	a
2021-08-09	$15.9_{7,21}$	<0.001	a	a	a	a	a	a	a	b
2021-09-15	$24.1_{7,24}$	<0.001	a	a	b	a	a	a	a	c
2021-09-30	$39.8_{7,24}$	<0.001	b	a	c	a	ab	ab	ab	c
2022-05-06	$10.1_{7,21}$	<0.001	b	a	b	b	b	a	b	ab
2022-05-31	$14.9_{7,21}$	<0.001	bcd	a	bcd	cd	bcd	b	bc	d
2022-06-16	$3.3_{7,24}$	0.013	ab	a	ab	ab	ab	ab	ab	b
2022-08-01	$15.4_{7,21}$	<0.001	a	a	a	a	a	a	a	b

Table S3. (continued)

Date	$F_{Ndf,Ddf}$	P	Pea/oat	Cowpea/sorghum-Sudan	Buckwheat	Crimson clover	Phacelia	Sunflower/oat	Weedy control	Weed-free control
2022-08-31	$4.8_{7,21}$	0.002	a	a	a	a	a	a	a	b
2022-09-19	$12.7_{7,24}$	<0.001	a	a	b	a	a	a	a	b
Mahnomen County										
2021-08-25	$0.8_{7,21}$	0.578	a	a	a	a	a	a	a	a
2021-10-11	$4.4_{7,21}$	0.004	ab	a	ab	a	a	a	ab	b
2022-06-03	$0.4_{7,21}$	0.889	a	a	a	a	a	a	a	a
2022-06-28	$0.3_{7,21}$	0.921	a	a	a	a	a	a	a	a
2022-07-13	$0.4_{7,21}$	0.893	a	a	a	a	a	a	a	a
2022-08-17	$12.6_{7,21}$	<0.001	ab	a	a	b	ab	ab	ab	c
2022-09-21	$16.3_{7,21}$	<0.001	a	a	a	a	a	a	a	b

Table S4. Mean ± standard error of resin lysimeter NO_3—N (kg ha^{-1}) by treatment and burial period in the CCV rotation. Bolded column is the cumulative sum of PLN measured in the entire study, though this is not a continuous sum as PLN was not measured overwinter in 2020. Similar lowercase letters following means indicate no differences between treatments within the same rotational system and burial period. Similar uppercase letters following cumulative sums indicate no treatment differences between cumulative sums within the same rotational system.

Treatment	Resin Lysimeter NO_3—N (kg ha^{-1})				
	8/03/20–10/29/20	4/30/21–7/13/21	7/23/21–4/28/22	5/4/22–7/5/22	Cumulative Sum
	Broccoli	*Cover Crop*	*Broccoli + Overwinter*	*Cover Crop*	
Pea/oat	29.5 ± 10.3ab	66.0 ± 14.3a	58.1 ± 4.3a	17.5 ± 3.3a	**171.2 ± 25.6AB**
Cowpea/sorghum-Sudan	11.5 ± 1.6a	76.9 ± 25.0a	52.0 ± 14.3a	11.6 ± 3.5a	**152.0 ± 23.2AB**
Buckwheat	14.8 ± 2.9a	75.3 ± 22.0a	49.0 ± 12.5a	15.5 ± 7.7a	**154.6 ± 25.6AB**
Crimson clover	20.8 ± 1.8ab	80.9 ± 25.0a	55.9 ± 8.9a	18.9 ± 6.8a	**176.4 ± 30.6AB**
Phacelia	20.0 ± 10.9a	66.4 ± 14.4a	48.5 ± 11.5 (3) a	15.4 ± 5.1a	**138.2 ± 38.4A**
Sunflower	17.1 ± 6.2a	80.8 ± 10.2a	51.4 ± 13.3a	21.1 ± 6.1a	**170.4 ± 12.5AB**
Weedy fallow	26.7 ± 5.0ab	91.3 ± 20.1a	33.0 ± 7.0a	13.0 ± 4.7a	**164.1 ± 16.8AB**
Weed-free fallow	53.5 ± 8.9b	131.6 ± 13.0a	70.4 ± 5.9a	33.5 ± 1.7a	**289.1 ± 6.7B**

Table S5. Mean ± standard error of resin lysimeter NO_3—N (kg ha^{-1}) by treatment and burial period in the VCC rotation. Bolded column is the cumulative sum of PLN measured in the entire study, though this is not a continuous sum as PLN was not measured overwinter in 2020. Similar lowercase letters following means indicate no differences between treatments within the same rotational system and burial period. Similar uppercase letters following cumulative sums indicate no treatment differences between cumulative sums within the same rotational system.

Treatment	Resin Lysimeter NO_3—N (kg ha^{-1})				
	7/17/20–10/29/20	4/30/21–7/1/21	7/8/21–4/28/22	5/4/22–6/20/22	Cumulative Sum
	Cover Crop	*Lettuce*	*Cover Crop + Overwinter*	*Lettuce*	
Pea/oat	42.9 ± 20.1a	70.6 ± 10.5a	54.4 ± 20.5a	33.4 ± 4.0a	**201.2 ± 36.4A**
Cowpea/sorghum-Sudan	47.4 ± 14.2a	33.5 ± 8.1a	44.4 ± 22.4 (3) a	23.5 ± 8.9a	**137.7 ± 42.7A**
Buckwheat	21.4 ± 7.1a	90.2 ± 13.3a	81.3 ± 20.3a	35.0 ± 9.1a	**227.9 ± 34.9A**
Crimson clover	53.4 ± 22.4a	57.0 ± 15.8a	48.3 ± 15.4a	34.2 ± 4.8a	**192.9 ± 18.2A**
Phacelia	31.7 ± 4.5a	78.4 ± 11.7a	30.1 ± 16.2a	39.3 ± 14.0a	**179.5 ± 22.8A**
Sunflower	13.6 ± 5.8a	62.4 ± 12.8a	31.2 ± 20.6a	34.5 ± 11.7a	**141.6 ± 21.3A**
Weedy fallow	49.9 ± 13.9a	60.3 ± 11.7a	44.0 ± 4.2 (3) a	28.5 ± 5.6a	**171.8 ± 23.6A**
Weed-free fallow	51.2 ± 16.4a	79.0 ± 15.8a	48.0 ± 11.4 (3) a	32.4 ± 7.6a	**198.6 ± 40.7A**

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