

Optimizing Cover Crop Integration: Early Establishment Methods and Technological
Approaches for Enhanced Biomass and Nitrogen Management in the Mid-Atlantic

Mary Michael Lipford Zahed

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Mark S. Reiter, Chair

A. Ozzie Abaye

Joshua Mott

Kristen Hughes Evans

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ABSTRACT

The research explored strategies to improve cover crop (CC) establishment and nitrogen (N) uptake in response to the time constraints commonly faced by Mid-Atlantic farmers. The first study examined whether broadcasting CCs at corn harvest—using various incorporation techniques—can reduce nitrate leaching and enhance biomass production, compared to broadcasting or drilling CCs 4-weeks post-harvest. Four seeding methods were tested across a range of CC species, including cereal rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), rapeseed (*Brassica napus* L.), and their mixture. Over two years, data revealed that CCs planted at corn harvest achieved significantly higher fall biomass (721 to 846 kg ha⁻¹) than those seeded four weeks later (134 to 200 kg ha⁻¹). Year 2 data showed a reduction in fall soil nitrate levels with at-harvest planting (5.2 mg kg⁻¹), compared to post-harvest CC planting (11.4 to 11.8 mg kg⁻¹). Additionally, certain at-harvest treatments, particularly those with hairy vetch and the mix, increased aboveground N accumulation (181 to 208 kg ha⁻¹) and, in Year 1, improved corn yield (10,113 to 11,586 kg ha⁻¹). The second study focused on a combine-mounted seeder's capacity to address similar N management goals in corn-soybean systems, allowing for seeding CCs directly at harvest and bypassing the need for additional field passes. Results from one year demonstrated that the combine-mounted seeder produced equal or greater biomass and N accumulation compared to delayed drilling. Following corn, the combine seeded treatments increased fall biomass tenfold (205 kg ha⁻¹ vs. 1116 to 1314 kg ha⁻¹)

and nearly doubled spring biomass (2345 kg ha⁻¹ vs. 5867 to 6323 kg ha⁻¹). The effectiveness of at-harvest broadcasting was also evident even in late-season drought conditions following soybean, showing comparable results to drilling two weeks post-harvest (4528 kg ha⁻¹ vs. 4434 kg ha⁻¹). Both studies highlight that earlier CC establishment, whether by broadcast seeding with or without incorporation or utilizing combine-mounted seeders, offers a promising approach for enhancing biomass production and reducing fall nitrate leaching in Mid-Atlantic farming systems.

Optimizing Cover Crop Integration: Early Establishment Methods and Technological Approaches for Enhanced Biomass and Nitrogen Management in the Mid-Atlantic

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GENERAL AUDIENCE ABSTRACT

This research examined ways to aid Mid-Atlantic farmers in establishing earlier cover crops (CCs) and improving CC nitrogen (N) uptake. The first part of the study compared broadcasting CCs at corn harvest with waiting four weeks to either broadcast or drill them after harvest. Four species of CCs were tested, including cereal rye, hairy vetch, rapeseed, and a mixture of these. Results over two years showed that broadcasting CCs at corn harvest resulted in significantly more biomass growth in the fall, with levels ranging from 721 to 846 kg per hectare (643 to 755 lb per acre), compared to just 134 to 200 kg per hectare (120 to 178 lb per acre) with later planting. Additionally, soil nitrate levels were lower when CCs were planted at harvest—5.2 mg/kg, compared to 11.4 to 11.8 mg/kg when planted later. Certain combinations, especially those including hairy vetch, led to higher N accumulation and improved corn yields. The second part of the study evaluated a new combine-mounted seeder that allows farmers to plant CCs during cash crop harvest, reducing the number of times they need to work the fields. Results after one year showed that the combine-seeded method produced similar or greater biomass and N accumulation than conventional post-harvest drilling. Following corn, fall biomass increased tenfold and spring biomass nearly doubled compared to delayed drilling. Even with drought conditions in soybeans, the combine-seeded method yielded results comparable to drilling CCs two weeks later. The second year of the study is still in progress. Overall, both studies suggest that starting cover crops earlier, whether by

broadcasting or using the combine seeder, can significantly boost biomass growth while reducing nitrate leaching in farming systems throughout the Mid-Atlantic region. Future research is needed to test the effectiveness of the combine-mounted cover crop seeder in different soil types and climates.

Dedication

This thesis is dedicated to my former students at Ayeldu St. Augustine’s Basic School in Ghana. You were my inspiration to embark on the journey of graduate school, and I owe so much to each of you. Your curiosity, determination, and trust motivated me to keep learning, work harder, and strive to become an expert who can help bring about meaningful change in the world.

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List of Abbreviations

<u>Abbreviation</u>	<u>Definition</u>
AHI	At-harvest incorporated
AHNI	At-harvest not incorporated
BMP	Best Management Practice
CC	Cover crop
CEC	Cation Exchange Capacity
CSI	Combine-seeded incorporated
CSNI	Combine-seeded not incorporated
CSP	Conservation Stewardship Program
DCR	Department of Conservation and Recreation
DEQ	Department of Environmental Quality
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentive Program
ERS	Economic Research Service
GDD	Growing Degree Day
NASS	National Agriculture Statistics Service
NRCS	Natural Resources Conservation Service
OM	Organic matter
PHD	Post-harvest drilled
PHD	Post-harvest-drilled
PHI	Post-harvest incorporated
SARE	Sustainable Agriculture Research and Education
TMDL	Total Maximum Daily Load
USDA	United States Department of Agriculture
USGS	United States Geological Survey

1. Introduction and Literature Review

1.1 The Chesapeake Bay Conservation Challenges

The Chesapeake Bay is a vital U.S. resource, but water quality has declined due to non-point source pollutants, like agriculture (Staver & Brinsfield, 1998). Despite efforts from federal, state, and local governments, and various stakeholders to reduce pollution, little progress had been made by 2010 (Trumbower, 2021). In response, the EPA established the Chesapeake Bay Total Maximum Daily Load (TMDL) under the Clean Water Act (CWA), the largest TMDL ever developed, to limit nitrogen (N), phosphorus (P), and sediment. Virginia was allocated 24.2 million kg of N annually, with 594,000 kg for the Eastern Shore (U.S. EPA, 2010). To meet pollution reduction goals, Virginia plans to increase cover crop (CC) areas from 91,054 hectares in 2022 to 155,560 hectares by 2025 (Virginia Department of Environmental Quality (DEQ), 2024). While Virginia has met its statewide 2023 sediment reduction target, targets for N and P remain off-track (U.S. EPA, 2024). The Chesapeake Assessment Scenario Tool (CAST) helps monitor progress and estimate pollutant reductions and costs (Chesapeake Bay Program, 2020).

1.2 Current Best Management Practices (BMPs) Programs and Direction

Since the Chesapeake Bay TMDL was established, point source pollution control has kept some states on track, but non-point source pollution remains a challenge due to its complexity (U.S. EPA, 2000). Best Management Practices (BMPs), written into the 1972 Federal Water Pollution Control Act Amendments, are the primary tool for minimizing non-point source pollution. However, as Ice (2004) notes, BMP implementation is costly and often difficult to

assess due to natural variability. In a 2017 workshop, USGS reported uneven nutrient loads in Chesapeake Bay streams, with the highest concentrations linked to intensive human activity. These loads have fluctuated over the last decade (Keisman, 2018).

The USDA's Environmental Quality Incentive Program (EQIP) and Conservation Stewardship Program (CSP) provide financial aid for BMP implementation. EQIP helps new adopters of BMPs with contracts for up to 10 years (USDA-NRCS, 2017), while CSP enhances existing stewardship efforts (Wallander et al., 2021). State programs like Virginia's BMP Cost-share Program through the Virginia Department of Conservation and Recreation (DCR) also support BMPs. On the Eastern Shore of Virginia, nearly \$4 million in assistance was provided in 2023 and 16,198 hectares of CCs were planted between both counties, with a significant portion being legume CCs (Eastern Shore Soil and Water Conservation District, 2023).

1.3 BMPs Effectiveness

The effectiveness of BMPs cannot be generalized, as their success depends on the land's specific conditions. BMPs work best when combined and tailored to the land and soil type, especially on the Eastern Shore of Virginia, where sandy soils have low adsorption capacity, making strategic BMP planning essential.

The use of CCs as a BMP has many beneficial attributes including residual N scavenging, weed suppression, reduction in fertilizer costs for the following cash crop, moisture retention, and erosion control through soil stability (Blanco-Canqui, 2018; McCracken et al., 1994; Miner et al., 2020; Roesch-McNally et al., 2018; Sedghi & Weil, 2022; Snapp et al., 2005). CCs have been used by ancient civilizations through the present to enhance the soil and growth of crops (Groff, 2015). While they reduce erosion and N leaching, their impact on water quality is mixed.

In the Chesapeake Bay, winter CCs have reduced soil loss by over 70% and runoff volume by up to 96% (Dillaha, 1990). Legume CCs, in particular, can fix N and reduce the need for fertilizers. However, water quality improvements from CCs depend on factors such as the type of crop, time of establishment, and years of usage (Singh et al., 2018).

Badon et al. (2022) found that CCs combined with minimal tillage had no significant impact on surface runoff nutrient loading. Still, they reduced sediment and nutrient concentrations of N and P in runoff suggesting that BMPs can reduce nutrient loads under certain conditions.

The complex relationship between CCs and non-point source pollution is further highlighted by studies showing both positive and limited impacts on runoff and nutrient losses. Blanco-Canqui (2018) found runoff reductions of 10-98% and sediment loss reductions of up to 100%, while Singh et al. (2018) noted that two years of cover cropping did not improve water quality. This complexity reinforces the need for site-specific BMPs, where timing and conditions play critical roles (Schipanski et al., 2014). Future research should prioritize areas with high nutrient loads and consider long-term nutrient turnover in watersheds (Keisman, 2018).

1.4 Overview of Nitrogen Transformations

After carbon, hydrogen, and oxygen, N is the most limiting nutrient for photosynthesis, plant growth, phytohormone production, and protein changes within the plant (Mengesha, 2021; White et al., 2015). Aside from being vital to biological processes, such as amino acids, chlorophyll, and ATP structure and function, N is also utilized by the plant to improve root growth and mass. This root growth allows for enhanced uptake of a broad range of other

essential nutrients. High biomass and yields are partially a result of adequate plant N (Anas et al., 2020).

Plants can take up N in one of two forms, which are ammonium (NH_4^+) and nitrate (NO_3^-). Within the N cycle, N may be transformed by mineralization, which is the conversion of organic N to inorganic N, usually ammonium, and then followed by nitrification, which is the conversion of ammonium into nitrate. When there is a symbiotic legume/microorganism relationship, N gas (N_2) is converted through N-fixation into ammonia, ammonium, or organic N forms (Douglas, 2009). In many cropping systems, ammonium fertilizers are advantageous because of the plants' ability to easily assimilate ammonium. However, due to nitrifying bacteria in the soil, nitrification usually occurs rapidly, and plants will then utilize nitrates (Ward, 2008).

Nitrate and ammonium serve the plant in different ways and should not be seen as interchangeable. Bryson et al. (2014) describes that it is generally seen that ammonium *greens* the plant, while nitrate *grows* the plant. Due to ammonium being a free radical and therefore a toxin inside the plant tissues, it is combined with carbon inside the root system to create a nontoxic form of organic N. If there is a sizable amount of ammonium present in the soil, regardless of whether it is from fertilizer or rapid organic matter decomposition, it will tie up available carbon. This could stunt plant growth, starting with reduced root growth.

1.5 Factors Affecting Solubility of N Forms and Fate

Availability of N for plants is dependent on the soil carbon:nitrogen (C:N) ratio because plants are competing with microbes for soil N (Kaye et al., 1997). Microorganisms, being more effective at accessing soil N due to their ability to spread throughout the soil and utilize organic matter, often outcompete plants. When the C:N ratio exceeds 30:1, microbes immobilize N

during decomposition, making it unavailable to plants (Brust, 2019; Okopi et al., 2024). N becomes available to plants when the C:N ratio is near or below 20:1, which is why N is frequently applied in cropping systems to lower this ratio.

However, large N applications can alter soil pH. Urea and ammonium-based fertilizers acidify the soil, requiring liming to manage pH, while nitrate-based fertilizers cause a temporary rise in pH (Bryson et al., 2014). Nitrate, a highly soluble anion, moves easily through soil water without binding to soil particles, making it prone to leaching into groundwater, especially during rainfall or irrigation (Jury, 1989). Ammonium, a cation, can bind to cation exchange sites in the soil, but sandy soils with lower cation exchange capacity (CEC) are less able to retain nutrients.

1.6 The Issue of N Leaching

Nitrogen used in agricultural systems contributes to atmospheric pollution through volatilization and to water pollution by leaching, especially when used in excess. Agricultural N leaching has led to increased nitrate levels in groundwater and runoff, exceeding pre-industrial concentrations by over 100% (Ascott et al., 2017). Nitrogen losses from agricultural fields are particularly excessive in coarse-textured soils with low organic matter (OM), as nearly all soil N is associated with OM (Abdalla et al., 2019; Bryson et al., 2014).

Corn production, which uses the most N fertilizer in the U.S., has a high potential for N leaching after plants begin to senesce, particularly under limited crop uptake in late-season periods (Morris et al., 2018). In the Mid-Atlantic, crop N uptake ceases about 4 weeks before corn maturity, leaving roughly 253 kg ha⁻¹ of mineral N, including 115 kg ha⁻¹ in the nitrate form, within the upper soil profile (Hirsh et al., 2021; Hirsh & Weil, 2019). Without CC uptake, this residual N readily leaches through the soil profile (Blanco-Canqui, 2018; Staver &

Brinsfield, 1998). Cover crops are thus most effective in mitigating leaching when planted as early as cash crop N uptake ceases, particularly on the Eastern Shore, where they can reduce annual nitrate leaching losses by up to 80% (Schipanski et al., 2014; Staver & Brinsfield, 1998).

Though often studied in corn, significant nitrate leaching can also occur after soybean harvest, especially in corn-soybean rotations as shown by Blanco-Canqui (2018) and Hirsh and Weil (2019). Soybeans, as legumes, can leave more residual nitrate in the soil than corn due to N fixation and a lower C:N ratio, which accelerates residue decomposition and N release (Hirsh & Weil, 2019; Kaspar et al., 2001). Consequently, CCs planted after soybeans can effectively scavenge residual N, particularly since no synthetic N is typically added, meaning the control of excess N does not come from managing inputs as it can with corn (Kaspar et al., 2001; Staver & Brinsfield, 1998; Zhu et al., 1989).

1.7 Corn and Soybean

Corn, a major global staple, is grown in nearly every country, with the United States as the leading producer, consumer, and exporter, planting over 36 million hectares (90 million acres) annually (USDA-ERS, 2023). Other significant producers include Brazil, Mexico, Argentina, India, and Italy (Smith et al., 2004). Originally derived from the wild teosinte in central Mexico (Smith et al., 2004), corn cultivation has steadily increased in the U.S., where it is largely used for livestock feed, ethanol production, and various food and industrial products (USDA-ERS, 2023). The demand for bioethanol from 2000 to 2013 led to expanded corn acreage while soybean and wheat areas remained stable, encouraging monoculture and continuous corn rotations (Chatterjee, 2016; Plourde, 2013). Corn accounted for \$87.1 billion in

U.S. cash crop receipts in 2022, over a quarter of total crop receipts, with Virginia ranking 25th at \$325 million (USDA-ERS, 2024a; USDA-ERS, 2024b).

Corn N requirements are relatively low early in the season, with just 10% needed by V6, after which 50% of total N uptake occurs through tasseling (Frazen, 2016). Therefore, split N applications, with a side-dress closer to peak uptake, can minimize leaching risks and enhance N use efficiency.

Soybean, though smaller in scale than corn globally, is another major U.S. cash crop. Originating in China, soybean production spread, establishing the U.S. as the top producer in the 1950s, followed by Brazil and Argentina (Singh, 2010). In 2022, soybeans contributed \$61.4 billion to U.S. crop receipts, second only to corn. In Virginia, soybean outpaces corn in acreage and revenue, ranking 20th among states at \$351.7 million (USDA-ERS, 2024a; USDA-NASS, 2024). High in protein and oil, soybeans are mainly processed for oil used in foods, inks, and biodiesel; the residual meal serves as a protein source in livestock feed (Singh, 2010).

1.8 Benefits and Challenges of Chemical Fertilizer Use

Since their introduction to agriculture, chemical fertilizers have contributed to at least a 50% increase in crop yields (Stewart et al., 2005). Long-term studies indicate that N fertilizers can enhance soil microbial populations by 15% and soil organic carbon by 13% (Clay et al., 2012; Geisseler & Scow, 2014). Chatterjee (2016) asserts that chemical fertilizers support soil health and nutrient balance, echoing the USDA-NRCS definition of soil health as the capacity of soil to sustain plants, animals, and humans (USDA-NRCS, 2018). While soil health practices often promote CCs, they do not exclude synthetic fertilizer use (Miner et al., 2020; Stewart et al., 2018).

Despite the yield benefits and profitability of chemical fertilizers, rising costs, diminishing cropland, and environmental impacts challenge their long-term use (Chatterjee, 2016; Schipanski et al., 2014). NPK fertilizer prices have tripled since 2000, largely due to their fossil fuel dependency, and high-grade phosphate reserves may be depleted within 50 to 150 years (Chatterjee, 2016). These issues with synthetic fertilizers highlight the need to balance food production with ecological health through sustainable practices.

CCs present a viable alternative by scavenging N and sulfur and mining P from the soil, reducing reliance on synthetic fertilizers (Hirsh & Weil, 2019; Roley et al., 2016; Schipanski et al., 2014; Sedghi & Weil, 2022). If fossil fuel prices continue to rise, the cost savings from legume CCs may offset their management expenses (Schipanski et al., 2014).

1.9 Cover Crops

As of 2014, the USDA defines CCs as “crops, including grasses, legumes, and forbs, for seasonal cover and other conservation purposes,” primarily used for erosion control, soil health, and water quality improvement (USDA-NRCS, 2014). Historically, CCs were described as protecting soil from erosion, leaching, and freezing without necessarily being incorporated into the soil (*Soils and Men*, 1938).

According to Groff (2015), CCs were used by ancient civilizations worldwide and early American farmers, including George Washington, but declined after World War II with the rise of synthetic fertilizers and herbicides. By the mid-1960s, cover cropping was rare, except among organic farmers. The USDA’s Sustainable Agriculture Research and Education (SARE) program helped revive their use in the 1990s, promoting cereal rye (*Secale cereale*) for its flexibility and winter hardiness, alongside other species like legumes and brassicas.

The Chesapeake Bay region has been a key area for cover cropping efforts, with some success in reducing nutrient and sediment levels, though targets remain unmet (Groff, 2015). Nationally, CC adoption remains low, covering just 5% of U.S. cropland, though it grew 50% between 2012 and 2017 (Wallander et al., 2021).

Adoption rates vary, with Maryland leading the way, followed by states like Virginia and Pennsylvania. In the Midwest, states like Missouri and Indiana show moderate adoption, likely due to shorter growing seasons, fertile soils, and fewer financial incentives (Blanco-Canqui, 2018; Wallander et al., 2021). Meanwhile, states such as Colorado and New Mexico demonstrate declining use (Wallander et al., 2021).

1.10 Tradeoffs of Cover Crops

There are trade-offs with CC adoption, with both direct establishment and termination costs and indirect opportunity costs. Adoption requires altering management practices across both fall and spring, often countering the goal of minimizing production costs (Roesch-McNally et al., 2018). Direct costs in 2015 ranged from \$119 to \$198 ha⁻¹, excluding potential chemical fertilizer savings (Roley et al., 2016). Additional challenges include potential yield impacts, managing CCs as potential weeds, competing with cash crops for resources, limited equipment access, and investing in rented land (Snapp et al., 2005). A common concern among farmers is the limited time in fall to establish CCs. Corn and soybean harvests sometimes extend into late November or even early December, reducing time to plant CCs (Roesch-McNally et al., 2018). Interseeding into standing crops using ground or aerial methods could extend the CC growth window (Schipanski et al., 2014).

Cover crops vary by type—legumes, brassicas, grasses, forbs, and mixes—each offering distinct benefits. Legumes, for example, fix N (Chatterjee, 2016), with the amount depending on species, termination timing, stand health, climate, and management. A Mississippi study showed a 65% yield increase after legume CCs, with 150 kg N ha⁻¹ returned to the soil; however, N release timing may not align with cash crop needs (Zablotowicz et al., 2011).

Termination date significantly affects CC biomass, N accumulation, and economic return (Blanco-Canqui, 2018). Duggar (1899) reported that terminating hairy vetch in late April yielded 4,446 kg ha⁻¹ of biomass and 62 kg of N, while terminating in May produced 7,701 kg ha⁻¹ and 92 kg of N. To maximize benefits, growers must balance termination timing to optimize N benefits without impacting cash crop stands, especially in cooler climates where CC residue can delay soil warming and cash crop establishment (Snapp et al., 2005).

Yield response to CCs also depends on the region. Colder climates with shorter growing seasons, such as Canada and parts of the Northern U.S., often see no yield benefit from winter CCs; however, these growers may still use CCs for environmental benefits (Bich et al., 2014; Crandall et al., 2005; Kasper & Bakker, 2015). However, in Northeast and Southeast regions, winter CCs increased corn yields by mean ratios of 1.15 and 1.14, respectively (Marcillo & Miguez, 2017).

Studies often report yield increases after legumes or legume mixes (Balkcom & Reeves, 2005; Marcillo & Miguez, 2017; Zablotowicz et al., 2011), whereas grasses and brassicas, with higher C:N ratios, sometimes immobilize N and reduce yield (Brust, 2019; Okopi et al., 2024). Experiments in Georgia and Virginia revealed rye CCs reduced corn yields by 1.34% to 32%, depending on N availability and timing (Pieters & McKee, 1938). Conversely, continuous rye

cover cropping has shown no yield reduction in other studies (Ritter et al., 1998; Snapp & Surapur, 2018).

1.11 Hairy Vetch

Hairy vetch (*Vicia villosa*) is notable for its biomass production and N fixation capacity, reaching up to 300 kg N ha⁻¹ under optimal conditions (Ledgard, 2001). Across 21 U.S. studies, monocultures of hairy vetch averaged 122 kg N ha⁻¹ and 3.6 Mg ha⁻¹ aboveground biomass (Thapa et al., 2018b). Although it may establish slowly in the fall, it is winter-hardy to zone 3 and grows vigorously in spring, reaching vine lengths up to 12 feet (Clark, 2008).

A study on varying termination dates conducted on the Eastern Shore of Maryland showed terminating hairy vetch as late as May 15 (latest date for local planting period) enhanced following corn yield and production compared to the April 10th termination, and did not differ from the April 24th termination date, for all three years of the study (Clark et al., 1995). Hairy vetch has also been shown to reduce leachate nitrate concentrations compared to winter fallow (McCracken et al., 1994), conserve soil moisture, reduce weed pressure, scavenge phosphorus (Clark, 2008), be compatible in mixes, especially with cereal rye (Brainard et al., 2012), increase soil aggregation and porosity (Haruna et al., 2020), and decrease erosion and surface pooling (Folorunso et al., 1992).

Seeding rates for hairy vetch range from 28 to 112 kg ha⁻¹, though Clark (2016) recommends 17 to 22 kg ha⁻¹ when drilled or 28 to 45 kg ha⁻¹ when broadcast. Seeding depth should be 1.3 to 2.0 cm, with minimal tillage recommended if broadcasting. Planting should occur 15 to 45 days before the frost date and rhizobium inoculation is advised. Ideal germination temperatures range from 15 to 23°C, with an optimal soil pH of 5.0 to 7.5 (Chintala et al., 2023).

In the Mid-Atlantic, no-till termination methods include roller-crimping or herbicide burndown with glyphosate or a mix of other herbicides in late April or early May, ideally at the early bloom stage to maximize N benefits (Clark, 2008; Chintala et al., 2023). Hairy vetch's low C:N ratio (8:1 to 15:1) leads to fast decomposition and rapid N release, most of which occurs within two weeks after termination (Sievers & Cook, 2018). Pairing hairy vetch with cereal rye can moderate the N release to better match cash crop needs (Marcillo & Miguez, 2017). Further research could refine synchronization of cover crop nutrient release with cash crop uptake.

1.12 Cereal Rye

Cereal rye (*Secale cereale*) is one of the most widely used and resilient winter CCs in the U.S., valued for biomass production, erosion control, organic matter addition, and its ability to suppress weeds, pests, and scavenge N (Camargo Silva & Bagavathiannan, 2023; Clark, 2008). Known for nitrate leaching prevention, rye can reduce leaching by 50% compared to controls, while legumes generally do not reduce nitrate leaching as significantly (Thapa et al., 2018a). Studies show rye can uptake 50-112 kg N ha⁻¹ per season depending on climate and growth (Clark, 2008; Brandi-Dohrn et al., 1997), and in some cases, nearly eliminate nitrate leaching (McCracken et al., 1994).

Unlike legumes, rye has a high C:N ratio (35:1 in shoots, 40:1 in roots), slowing decomposition and releasing N gradually, with potential N immobilization about four weeks post-termination (Staver & Brinsfield, 1998). To manage N tie-up, rye should be terminated before flowering, although delaying until the milk to soft dough stage enhances weed suppression (Clark, 2008). For no-till systems, termination methods include roller-crimping or

herbicide applications, such as glyphosate or mixes with 2,4-D, dicamba, or saflufenacil (Cornelius & Bradley, 2017).

In Zones 3-7, rye should be planted from late summer to mid-fall, with early planting enhancing N scavenging in the fall but complicating spring termination. Recommended seeding rates vary from 67 to 135 kg ha⁻¹ when drilled to 100 to 180 kg ha⁻¹ when broadcast, with seeding depths no deeper than 5 cm (Clark, 2008; Fisher et al., 2011). Rye germinates at temperatures as low as 1°C and requires 3°C or higher for vegetative growth (Clark, 2008).

1.13 Rapeseed

Brassica CCs, such as rapeseed (*Brassica rapa*), are valued for their rapid fall growth, deep-rooted nutrient scavenging, natural tillage effects, pest suppression, and high biomass (Gieske et al., 2016; Haramoto & Gallandt, 2004). Brassicas release glucosinolates, compounds toxic to various soil pathogens and pests, including nematodes, insects, bacteria, fungi, and weeds. For effective pest suppression, brassicas must be chopped and incorporated into the soil (Clark, 2008).

Brassicas are gaining popularity in the mid-Atlantic due to their deep-rooting ability to access residual soil N unavailable to cash crops (Dean & Weil, 2009). Studies show that, if planted early, brassicas can match or exceed the N-scavenging capacity of cereal rye (Dean & Weil, 2009; Thapa et al., 2018a). Rapeseed, for instance, can capture up to 135 kg N ha⁻¹ per season (Clark, 2008) and accumulate biomass of up to 6,726 kg ha⁻¹, with an N content of 90 kg ha⁻¹ (Rife & Zeinali, 2003). With a C:N ratio between 20 to 30 in roots and 10 to 20 in shoots, brassicas decompose faster than rye but slower than hairy vetch, releasing N at a moderate pace.

To realize full benefits, brassicas should be planted at least four weeks before the first killing frost (Clark, 2008), though this timing is challenging in corn-soybean rotations unless using aerial or broadcast seeding methods (Dean & Weil, 2009). Brassicas prefer well-drained soils, pH 5.5 to 8.5, and minimum germination temperatures of 7°C. Winter-hardy rapeseed can withstand temperatures as low as -12°C (Clark, 2008; Rife & Zeinali, 2003).

For monocultures, recommended seeding rates are 6 to 11 kg ha⁻¹ when drilled and 9 to 16 kg ha⁻¹ when broadcast, with a planting depth no deeper than 2 cm (Clark, 2008). No-till termination methods include roller crimping in flower or herbicide burndown; glyphosate combined with 2,4-D or Paraquat + atrazine + mesotrione are effective at later growth stages (Askew et al., 2019; Clark, 2008).

1.14 Cover Crop Mixes

Mixing multiple CC species can optimize both environmental and economic outcomes. Species selection for mixtures depends on the grower's goals and the unique benefits of each species. For instance, legumes fix N but have a low C:N ratio, grasses scavenge N effectively but have a high C:N ratio, and brassicas, with deep taproots, access nutrients in lower soil horizons but may winter-kill. Mixtures improve winter survival, especially in colder regions like Michigan (Brainard et al., 2012), enhance biomass and weed suppression (Blanco-Canqui, 2018; Brainard et al., 2012; Thapa et al., 2018b; Wortman et al., 2012), boost cash crop yield (Marcillo & Miguez, 2017), and can accelerate flowering of CCs like hairy vetch (Brainard et al., 2012). They also facilitate N accumulation comparable to grasses and retention comparable to legumes (Thapa et al., 2018b; White et al., 2017).

A meta-analysis by Thapa et al. (2018a) found that, over 55 site years, hairy vetch-cereal rye mixtures accumulated as much N as hairy vetch alone and 150% more than cereal rye alone. Additionally, this mix balances N mineralization, avoiding the rapid release from vetch or immobilization from rye. Marcillo & Miguez (2017) confirmed that mixtures typically increase cash crop yield. However, Wortman et al. (2012) observed no yield benefit in Nebraska due to soil moisture depletion by CCs before cash crop planting, underscoring climate as a key factor. Contrastingly, Thapa et al. (2018b) found that hairy vetch-rye mixtures (6.0 Mg ha^{-1}) outperformed both hairy vetch (3.6 Mg ha^{-1}) and cereal rye (5.6 Mg ha^{-1}) monocultures in biomass by 63%.

Ultimately, CC mixture efficacy depends on species choice, ratio, climate, and management, with trade-offs based on site-specific needs. For example, N leaching can be mitigated while adding N by incorporating low-seeding-rate, high-retention non-legumes and omitting winter-kill-prone legumes and brassicas (White et al., 2017).

1.15 Importance of Early Planting

Even though the benefits of cover cropping are clear, a serious limiting factor of adoption is the need for early planting. A study in Maryland discovered that for every 2-week delay in planting, there is a decrease of 160-300 growing degree days (GDD) available for CC growth and N capture drops drastically when there are fewer than 550 GDD before winter dormancy. This happens after mid-September in the mid-Atlantic region (Sedghi & Weil, 2022). Another study on the Delmarva peninsula showed that CCs should be planted by or before October 1 to maximize fall N uptake rates (Ritter et al., 1998). Thapa et al. (2018a) found that waiting until November to plant broadleaf CCs showed no reduction in nitrate leaching compared to the

control and for CCs to be effective at all, especially brassicas, planting early is critical (Dean & Weil, 2009). The classic drill is widely used for its ability to plant a range of seed sizes while ensuring the seed is placed at the appropriate depth and rate, protecting seeds from predation and improving access to soil moisture (Kientzy et al., 2023; Wofuru-Nyenke, 2023). However, waiting until after harvest to drill CCs can delay planting by weeks, which may be the difference between a good stand and a poor stand. Given this knowledge, a grower may be unwilling to sacrifice the cash crop for the success of a CC. Agricultural technology and machinery improvements that allow for earlier CC seeding are needed to create alternatives to a late drilled CC.

1.16 Alternative Planting Methods

Broadcasting or aerial seeding before cash crop harvest is an alternative to drilling CCs, with potential to increase biomass production and avoid planting later in the season (Dean & Weil, 2009; Fisher et al., 2011; Schipanski et al., 2014; Thapa et al., 2018a). Methods include aerial seeding by plane, drone, or helicopter, and ground broadcasting via combine-mounted seeders, air boom, pendulum, high-clearance or spinner spreaders, or row-based interseeders (Kientzy et al., 2023). Airplanes are commonly used for aerial seeding due to their large coverage, though this method is often costly, less precise, and limited by skilled pilot availability (Kientzy et al., 2023; Wilson et al., 2014; Wofuru-Nyenke, 2023).

Ground broadcasting is generally more precise when spreaders are calibrated for seed weight, as heavier seeds (e.g., rye) spread further than lighter ones (e.g., rapeseed) (Wofuru-Nyenke, 2023). Broadcast seeders vary in price from around \$500 to \$85,000, comparable to drill costs (Kientzy et al., 2023). Spreaders can use a blower and boom, spinner, or drop tubes.

High-clearance spreaders can be used in soybean fields anytime but are effective in corn only before the V10 growth stage (Kientzy et al., 2023).

Combine-mounted seeders have advantages, including seed coverage with chaff that boosts germination by acting as mulch, reducing labor, fuel, and equipment costs, and soil compaction by eliminating extra field passes. This method is gaining traction in the Midwest (e.g., Iowa, Minnesota, Ohio, and Indiana) and slowly spreading to the mid-Atlantic region, including Virginia (Bechman, 2021; Klessig, 2020; Practical Farmers of Iowa, 2023; Sustainable Chesapeake, 2024). Some seeders blow seed from the combine header, while others distribute from the rear. However, research on combine-mounted seeders and their effectiveness compared to other planting methods is limited.

1.17 Comparing Drill, Aerial, and Broadcast Planting Methods

There are still many limitations and risks to aerial and broadcast planting methods and researchers have many conflicting views. Laying a seed on the top of the soil leaves it vulnerable to both abiotic and biotic factors, such as predation by insects, birds, and rodents as well as wind and sun exposure (Koehler-Cole & Elmore, 2020; Wilson et al., 2014). The success of aerial or broadcasting methods is also heavily dependent on rainfall for germination, as the seed does not have access to soil moisture (Collins & Fowler, 1992; Haramoto, 2019; Koehler-Cole & Elmore, 2020; Wilson et al., 2014). A study in Minnesota reported the most important factor for success of aerially seeded crops was precipitation within one week of planting (Wilson et al., 2013).

Due to the inconsistency of precipitation, it is commonly recommended to increase seeding rates when broadcasting CCs to enhance establishment success (Koehler-Cole & Elmore, 2020). A California study on vegetable systems indicated that seeding rates would need to be

increased by 50-100% when broadcasting CCs on beds instead of drilling, although this increase was not considered cost-effective (Brennan & Leap, 2014). Conversely, research in Nebraska showed that while higher seeding rates for broadcasted CCs increased fall biomass, there was minimal effect on spring biomass (Koehler-Cole & Elmore, 2020). In South Carolina, biomass yield from hairy vetch was unaffected by the seeding method at either standard or elevated rates; however, results varied for crimson clover (St Aime et al., 2022). Additionally, Haramoto (2019) found that higher seeding rates for broadcast cereal rye in Kentucky did not impact either CC biomass or weed biomass, suggesting that current seeding recommendations may be sufficient for effective weed suppression.

Studies in Maryland have demonstrated promising results for both broadcast and aerial seeding of CCs in terms of biomass accumulation and N content. For example, a three-year study on Maryland's Eastern Shore found that aerially seeded CCs (planted by September 30) outperformed drilled CCs (planted by October 24) in wet years, with no differences observed under dry conditions. Although aerial seeding costs were higher (\$148/ha vs. \$139/ha for drilling), these costs were mitigated by Maryland's CC subsidy program (Sedghi et al., 2023). In another Maryland study, Moore & Mirsky (2020) demonstrated that while drill-interseeded CCs planted prior to cash crop harvest produced more biomass than broadcasted CCs, broadcasting seed prior to harvest also yielded significantly more biomass than drilling after harvest.

In Canada, studies on broadcasting CCs have highlighted some challenges. Collins & Fowler (1992) noted that the higher seeding rates, dependency on precipitation, and risk of failure outweighed the potential advantages of broadcasting. Yet, Edwards (1997) reported that under wetter conditions, broadcasting could be more beneficial as it avoids additional soil compaction. Ultimately, the optimal planting method appears to be context-dependent,

influenced by climate, weather, seeding rate, species, and incorporation practices (St Aime et al., 2022). Increased cost-share options for broadcasting, particularly in regions like the Corn Belt and Western states where growing seasons are shorter, could further support CC adoption (Wilson et al., 2014).

1.18 References

- Abdalla, M., Hastings, A., Cheng, K., Yue, U., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity *Wiley Global Change Biology* 25, 2530–2543. <https://doi.org/DOI: 10.1111/gcb.14644>
- Ascott, M. J., Gooddy, D. C., Wang, L., Stuart, M. E., Lewis, M. A., Ward, R. S., & Binley, A. M. (2017). Global patterns of nitrate storage in the vadose zone. *Nature Communications*, 8(1), 1416. <https://doi.org/10.1038/s41467-017-01321-w>
- Askew, M. C., Cahoon, C. W., Flessner, M. L., VanGessel, M. J., Langston, D. B., & Ferebee, J. H. (2019). Chemical termination of cover crop rapeseed. *Weed Technology*, 33(5), 686-692. <https://doi.org/doi:10.1017/wet.2019.50>
- Balkcom, K., & Reeves, D. (2005). Sunn-hemp utilized as a legume cover crop for corn Production. *Agronomy Journal*, 97. <https://doi.org/10.2134/agronj2005.0026>.
- Bechman, T. J. (2021). *Seeding behind combine gets cover crops off to good start*. <https://www.farmprogress.com/cover-crops/seeding-behind-combine-gets-cover-crops-off-to-good-start>
- Bich, A. D., Reese, C. L., Kennedy, A. C., Clay, D. E., & Clay, S. A. (2014). Corn yield is not reduced by mid-season establishment of cover crops in northern great plains Environments. *Crop Management*, 13(1), CM-2014-0009-RS. <https://doi.org/https://doi.org/10.2134/CM-2014-0009-RS>
- Blanco-Canqui, H. (2018). Cover crops and water quality. *Agronomy Journal*, 110(5), 1633-1647. <https://doi.org/https://doi.org/10.2134/agronj2018.02.0077>

- Brainard, D., Henshaw, B., & Snapp, S. (2012). Hairy vetch varieties and bi-cultures influence cover crop services in strip-tilled sweet corn. *Agronomy Journal*, *104*(3), 629-638.
<https://doi.org/https://doi.org/10.2134/agronj2011.0360>
- Brandi-Dohrn, F. M., Hess, M., Selker, J. S., Dick, R. P., Kauffman, S. M., & Hemphill Jr., D. D. (1997). Nitrate leaching under a cereal rye cover crop. *Journal of Environmental Quality*, *26*(1), 181-188.
<https://doi.org/https://doi.org/10.2134/jeq1997.00472425002600010026x>
- Brennan, E. B., & Leap, J. E. (2014). A comparison of drill and broadcast methods for establishing cover crops on beds. *HortScience horts*, *49*(4), 441-447.
<https://doi.org/10.21273/hortsci.49.4.441>
- Brust, G. E. (2019). Management strategies for organic vegetable fertility. In D. Biswas & S. A. Micallef (Eds.), *Safety and Practice for Organic Food* (pp. 193-212). Academic Press.
<https://doi.org/https://doi.org/10.1016/B978-0-12-812060-6.00009-X>
- Bryson, G. M., Mills, H. A., Sasseville, D. N., Jones, J. B., & Barker, A. V. (2014). *Plant Analysis Handbook III*. Micro-Macro Publishing.
- Camargo Silva, G., & Bagavathiannan, M. (2023). Mechanisms of weed suppression by cereal rye cover crop: A review. *Agronomy Journal*, *115*(4), 1571-1585.
<https://doi.org/https://doi.org/10.1002/agj2.21347>
- Carmona, G. I., Robinson, E., Campos, J. N. D., & McMechan, A. J. (2022). Impact of the timing and use of an insecticide on arthropods in cover-crop-corn systems. *Insects*, *13*(4), 348. <https://doi.org/https://doi.org/10.3390/insects13040348>

- Chatterjee, A. (2016). Soil fertility: current US situation and challenges. In D. Clay (Ed.), *Soil Fertility Management in Agroecosystems* (pp. 3-10). American Society of Aronomy, Inc, Crop Society of Agronomy, Inc, Soil Science Society of America, Inc.
- Chesapeake Bay Program (CBP). (2020). *Chesapeake assessment and scenario tool (CAST) Version 2019*. Chesapeake Bay Program Office. Retrieved March 26 from <https://cast.chesapeakebay.net/About>
- Chintala, R., Haller, S., & Holleman, B. (2023). Plant guide for hairy vetch (*Vicia villosa* Roth). *USDA-Natural Resources Conservation Service, Booneville Plant Materials Center* (Booneville, Arkansas 72927).
- Clark, A. (2008). *Managing cover crops profitably (3rd Ed.)*. DIANE Publishing Company. <https://books.google.com/books?id=ahxLEpn6WYwC>
- Clark, A. J., Decker, A. M., Meisinger, J. J., Mulford, F. R., & McIntosh, M. S. (1995). Hairy vetch kill date effects on soil water and corn production. *Agronomy Journal*, 87(3), 579-585. <https://doi.org/https://doi.org/10.2134/agronj1995.00021962008700030031x>
- Clay, D. E., Chang, J., Clay, S. A., Stone, J., Gelderman, R., Carlson, C. G., Retisma, K., Jones, M., Janssen, L., & Schumacher, T. (2012). Corn yields and no-tillage affects carbon sequestration and carbon footprints. *Agronomy Journal*, 104, 763-770.
- Collins, B. A., & Fowler, D. B. (1992). A comparison of broadcast and drill methods for no-till seeding winter wheat. *Canadian Journal of Plant Science*, 72(4). <https://doi.org/https://doi.org/10.4141/cjps92-126>
- Cornelius, C. D., & Bradley, K. W. (2017). Herbicide programs for the termination of various cover crop species. *Weed Technology*, 31(4), 514-522. <https://doi.org/doi:10.1017/wet.2017.20>

- Crandall, S., Ruffo, M., & Bollero, G. (2005). Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn. *Plant and Soil*, 268, 209-219.
<https://doi.org/10.1007/s11104-004-0272-x>
- Dean, J. E., & Weil, R. R. (2009). Brassica cover crops for nitrogen retention in the mid-Atlantic Coastal Plain. *Journal of Environmental Quality*, 38(2), 520-528.
<https://doi.org/https://doi.org/10.2134/jeq2008.0066>
- Dillaha, T. A. (1990). Role of best management practices in restoring the health of the Chesapeake Bay. In *Perspectives on the Chesapeake Bay, 1990: Advances in Estuarine Sciences* (Vol. CBP/TRS41/90). Chesapeake Bay Program.
- Douglas, A. E. (2009). Endosymbionts and intracellular parasites. In M. Schaechter (Ed.), *Encyclopedia of Microbiology (Third Edition)* (pp. 128-141). Academic Press.
<https://doi.org/https://doi.org/10.1016/B978-012373944-5.00257-1>.
- Duggar, F. (1899). Winter pasturage, hay and fertility afforded by hairy vetch. *Alabama Agriculture Experiment Station Bull.* 105, 129-160.
- Eastern Shore Soil and Water Conservation District. (2023). *Shore Conserver: annual report*. Eastern Shore Virginia Soil and Water Conservation District.
- Edwards, L. (1997). Comparison of two spring seeding methods to establish forage cover crops in relay with winter cereals. *Soil and Tillage Research*, 45(1998), 227-235.
- Fisher, K. A., Momen, B., & Kratochvil, R. J. (2011). Is broadcasting seed an effective winter cover crop planting method? *Agronomy Journal*, 103(2), 472-478.
<https://doi.org/https://doi.org/10.2134/agronj2010.0318>

- Folorunso, O., Rolston, D., Prichard, P., & Louie, D. (1992). Cover crops lower soil surface strength, may improve soil permeability. *Hilgardia*, 46(6), 26-27.
<https://doi.org/DOI:10.3733/ca.v046n06p26>
- Frazen, D. (2016). Crop-specific nutrient management in D. Clay & A. Chatterjee (Eds.), *Soil Fertility Management in Agroecosystems*. American Society of Aronomy, Inc, Crop Society of Agronomy, Inc, Soil Science Society of America, Inc.
- Geisseler, D., & Scow, K. M. (2014). Does long-term use of mineral fertilizers affect the soil microbial biomass? *Better Crops Plant Food*, 98(4), 13-15.
- Gieske, M. F., Ackroyd, V. J., Baas, D. G., Mutch, D. R., Wyse, D. L., & Durgan, B. R. (2016). Brassica cover crop effects on nitrogen availability and oat and corn yield. *Agronomy Journal*, 108(1), 151-161. <https://doi.org/https://doi.org/10.2134/agronj2015.0119>
- Groff, S. (2015). The past, present, and future of the cover crop industry. *Journal of Soil and Water Conservation*, 70(6), 130A-133A.
<https://doi.org/https://doi.org/10.2489/jswc.70.6.130A>
- Haramoto, E. R. (2019). Species, seeding rate, and planting method influence cover crop services prior to soybean. *Agronomy Journal*, 111(3), 1068-1078.
<https://doi.org/10.2134/agronj2018.09.0560>
- Haramoto, E. R., & Gallandt, E. R. (2004). Brassica cover cropping for weed management: A review. *Renewable Agriculture and Food Systems*, 19(4), 187-198.
<https://doi.org/10.1079/RAFS200490>
- Haruna, S. I., Anderson, S. H., Udawatta, R. P., Gantzer, C. J., Phillips, N. C., Cui, S., & Gao, Y. (2020). Improving soil physical properties through the use of cover crops: A review.

- Agrosystems, Geosciences & Environment*, 3(1), e20105.
<https://doi.org/10.1002/agg2.20105>
- Hirsh, S. M., Duiker, S. W., Graybill, J., Nichols, K., & Weil, R. R. (2021). Scavenging and recycling deep soil nitrogen using cover crops on mid-Atlantic, USA farms. *Agriculture, Ecosystems & Environment*, 309(107274). <https://doi.org/10.1016/j.agee.2020.107274>
- Hirsh, S. M., & Weil, R. R. (2019). Deep soil cores reveal large end-of-season residual mineral nitrogen pool. *Agricultural & Environmental Letters*, 4(1), 180055.
<https://doi.org/10.2134/aer2018.10.0055>
- Ice, G. (2004). History of innovative best management practice development and its role in addressing water quality limited waterbodies. *Journal of Environmental Engineering*, 130(6), 684-689. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2004\)130:6\(684\)](https://doi.org/10.1061/(ASCE)0733-9372(2004)130:6(684))
- Ji, P., Koné, D., Yin, J., Jackson, K. L., & Csinos, A. S. (2012). Soil amendments with Brassica cover crops for management of *Phytophthora* blight on squash. *Pest Management Science*, 68(4), 639-644. <https://doi.org/10.1002/ps.2308>
- Jury, W. (1989). Nitrate transport and leaching mechanisms. *Developments in Agricultural and Managed Forest Ecology*, 21C, 139-157.
- Kaspar, T. C., & Bakker, M. G. (2015). Biomass production of 12 winter cereal cover crop cultivars and their effect on subsequent no-till corn yield. *Journal of Soil and Water Conservation*, 70(6), 353-364. <https://doi.org/10.2489/jswc.70.6.353>
- Kaspar, T. C., Radke, J. K., & Laflem, J. M. (2001). Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. *Soil and Water Conservation*, 56(2), 160-164.

- Kaye, J. P., & Hart, S. C. (1997). Competition for nitrogen between plants and soil microorganisms. *Trends in Ecology & Evolution*, 12(4), 139-143.
[https://doi.org/10.1016/S0169-5347\(97\)01001-X](https://doi.org/10.1016/S0169-5347(97)01001-X)
- Keisman, J., Blomquist, J., Bohlke, J. K., Davis-Martin, J., Dennison, W., Friedrichs, C., Murphy, R., Phillips, S., Testa, J., Trentacoste, E., & Weller, D. (2018). Integrating recent findings to explain water-quality change: Support for the mid-point assessment and beyond.
- Kientzy, D., Milhollin, R., Ellis, C., & Massey, R. (2023). Understanding equipment management for planting cover crops. *Journal of Soil and Water Conservation*, 78(6), 113A-117A. <https://doi.org/10.2489/jswc.2023.0818A>
- Klessig, L. (2020). Update...combine seeded cover crop.
<https://www.youtube.com/watch?v=GUdvLpfx27g>
- Koehler-Cole, K., & Elmore, R. W. (2020). Seeding rates and productivity of broadcast interseeded cover crops. *Agronomy*, 10(11), 1723.
<https://doi.org/10.3390/agronomy10111723>
- Ledgard, S. F. (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, 228(1), 43-59.
<https://doi.org/10.1023/A:1004810620983>
- Lotter, D. W., Seidel, R., & Liebhardt, W. (2003). The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture*, 18(3), 146-154. <https://doi.org/10.1079/AJAA200345>

- Marcillo, G. S., & Miguez, F. E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. *Journal of Soil and Water Conservation*, 72(3), 226-239.
<https://doi.org/10.2489/jswc.72.3.226>
- McCracken, D. V., Smith, M. S., Grove, J. H., MacKown, C. T., & Blevins, R. L. (1994). Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Science Society of America Journal*, 58(5), 1476-1483.
<https://doi.org/10.2136/sssaj1994.03615995005800050029x>
- Mengesha, M. (2021). Effect and roles of nitrogen supply on photosynthesis. *International Journal of Photochemistry and Photobiology*, 5(2), 19-27.
<https://doi.org/10.11648/j.ijpp.20210502.12>
- Miner, G. L., Delgado, J. A., Ippolito, J. A., & Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agricultural & Environmental Letters*, 5, e20023.
<https://doi.org/10.1002/ael2.20023>
- Moore, V. M., & Mirsky, S. B. (2020). Cover crop biomass production across establishment methods in mid-Atlantic corn. *Agronomy Journal*, 112(6), 4765-4774.
<https://doi.org/10.1002/agj2.20414>
- Morris, T. F., Murrell, T. S., Beegle, D. B., Ferguson, R. B., Grove, J., Ketterings, Q., Kyveryga, P. M., Laboski, C. A. M., McGrath, J. M., Meisinger, J. J., Melkonian, J., Moebius-Clune, B. M., Nafziger, E. D., Osmond, D., Sawyer, J. E., Scharf, P. C., Smith, W., Spargo, J. T., & Yang, H. (2018). Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, 110(1), 1-37. <https://doi.org/10.2134/agronj2017.02.0112>

- Nielsen, D. C., Lyon, D. J., Higgins, R. K., Hergert, G. W., Holman, J. D., & Vigil, M. F. (2016). Cover crop effect on subsequent wheat yield in the Central Great Plains. *Agronomy Journal*, 108(1), 243-256. <https://doi.org/10.2134/agronj2015.0372>
- Okopi, S., Li, Y., & Xu, F. (2024). Biomass digestion. In M. A. Abraham (Ed.), *Encyclopedia of sustainable technologies (second edition)* (pp. 236-251). Elsevier. <https://doi.org/10.1016/B978-0-323-90386-8.00051-6>
- Pieters, A. J., & McKee, R. (1938). *Soils and men* (Vol. 1938). U.S. Department of Agriculture, National Agriculture Library.
- Plourde, J. D., Pijanowski, B. C., & Pekin, B. K. (2013). Evidence for increased monoculture cropping in the Central United States. *Agriculture, Ecosystems & Environment*, 165, 50-59. <https://doi.org/10.1016/j.agee.2012.11.011>
- Practical Farmers of Iowa. (2023). Combine seeder saves time and fuel by seeding covers during harvest - *Practical Cover Croppers*. <https://www.youtube.com/watch?v=l8AEldrAiAQ>
- Rife, C. L., & Zeinali, H. (2003). Cold tolerance in oilseed rape over varying acclimation durations. *Crop Science*, 43(1), 96-100. <https://doi.org/https://doi.org/10.2135/cropsci2003.9600>
- Ritter, W. F., Scarborough, R. W., & Chirnside, A. E. M. (1998). Winter cover crops as a best management practice for reducing nitrogen leaching *Journal of Contaminant Hydrology* 34, 1-15.
- Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems*, 33(4), 322-333. <https://doi.org/doi:10.1017/S1742170517000096>

Roley, S. S., Tank, J. L., Tyndall, J. C., & Witter, J. D. (2016). How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River Basin? *Water Resources and Economics* 15, 43-56.

<https://doi.org/https://doi.org/10.1016/j.wre.2016.06.003>.

Sanchez, I., Fultz, L. M., Lofton, J., & Haggard, B. (2019). Cover crops impacts on Louisiana corn production and soil properties. *Agrosystems, Geosciences & Environment*, 2(1),

190015. <https://doi.org/https://doi.org/10.2134/age2019.03.0015>

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P.,

Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A

framework for evaluating ecosystem services provided by cover crops in agroecosystems.

Agricultural Systems 125, 12-22.

<https://doi.org/https://doi.org/10.1016/j.agsy.2013.11.004>

Sedghi, N., Fox, R. J., Sherman, L., Gaudlip, C., & Weil, R. R. (2023). Aerial interseeding and planting green to enhance nitrogen capture and cover crop biomass carbon. *Journal of*

Soil and Water Conservation, 78(3), 282-298. <https://doi.org/10.2489/jswc.2023.00051>

Sedghi, N., & Weil, R. (2022). Fall cover crop nitrogen uptake drives reductions in winter-spring leaching. *Journal of Environmental Quality*, 51(1), 337-351. [https://doi.org/DOI:](https://doi.org/DOI:10.1002/jeq2.20342)

[10.1002/jeq2.20342](https://doi.org/DOI:10.1002/jeq2.20342)

Sievers, T., & Cook, R. L. (2018). Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Science Society of America Journal*, 82(1), 147-155.

<https://doi.org/https://doi.org/10.2136/sssaj2017.05.0139>

Singh, G. (2010). *The Soybean: Botany, Production and Uses*. CABI.

<https://books.google.com/books?id=EAhJUyAtsMoC>

- Singh, G., Schoonover, J. E., & Williard, K. W. J. (2018). Cover crops for managing stream water quantity and improving stream water quality of non-tile drained paired watersheds. *Water*, 10(4), 521. <https://www.mdpi.com/2073-4441/10/4/521>
- Smith, C. W., Betrán, J., & Runge, E. C. A. (2004). *Corn: origin, history, technology, and production*. Wiley. <https://books.google.com/books?id=3wvCEAAAQBAJ>
- Snapp, S. S., & Surapur, S. (2018). Rye cover crop retains nitrogen and doesn't reduce corn yields. *Soil and Tillage Research*.
- Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal*, 97(1), 322-332.
<https://doi.org/https://doi.org/10.2134/agronj2005.0322a>
- St Aime, R., Noh, E., Bridges, W. C., & Narayanan, S. (2022). A comparison of drill and broadcast planting methods for biomass production of two legume cover crops. *Agronomy*, 12(1), 79. <https://www.mdpi.com/2073-4395/12/1/79>
- Staver, K. W., & Brinsfield, R. B. (1998). Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. *Soil and Water Conservation* 53(3), 230-240.
- Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., & Strickland, M. S. (2018). What we talk about when we talk about soil health. *Agricultural & Environmental Letters*, 3(1), 180033.
<https://doi.org/https://doi.org/10.2134/aer2018.06.0033>

- Stewart, W. M., Dibb, D. W., Johnson, A. E., & Smyth, T. J. (2005). The contribution of commercial fertilizer nutrients to food production. *Agronomy Journal*, 97(1), 1-6.
<https://doi.org/doi:10.2134/agronj2005.0001>
- Sustainable Chesapeake. (2024). *Built on the farm: the combine cover crop seeder*.
<https://www.youtube.com/watch?v=qetSGZtxCCQ>
- Thapa, R., Mirsky, S. B., & Tully, K. L. (2018a). Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. *Journal of Environmental Quality*, 47(6), 1400-1411. <https://doi.org/https://doi.org/10.2134/jeq2018.03.0107>
- Thapa, R., Poffenbarger, H., Tully, K. L., Ackroyd, V. J., Kramer, M., & Mirsky, S. B. (2018b). Biomass production and nitrogen accumulation by hairy vetch–cereal rye mixtures: a meta-analysis. *Agronomy Journal*, 110(4), 1197-1208.
<https://doi.org/https://doi.org/10.2134/agronj2017.09.0544>
- Thilakarathna, M., Serran, S., Lauzon, J., Janovicek, K., & Deen, B. (2015). Management of manure nitrogen using cover crops. *Agronomy Journal*.
<https://doi.org/10.2134/agronj14.0634>.
- Trumbower, T. (2021). Treasure the Chesapeake: maintaining the Chesapeake Bay agreement TMDL requirements under the Clean Water Act in a hostile regulatory environment. *Tulane Environmental Law Journal*, 34, 209-228.
- U.S. EPA. (2010). Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. 1-93.
- U.S. EPA. (2024). EPA evaluation of Virginia’s 2022-2023 and 2024-2025 milestones. *Evaluation of Virginia’s 2022-2023 and 2024-2025 Milestones chrome-*

extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.epa.gov/system/files/docume
nts/2024-05/2024_virginia_2022_2023_2024_2025_evaluation_draft_ms.pdf

USDA-ERS. (2023). *Feed grains sector at a glance*. <https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/#:~:text=The%20United%20States%20is%20the,grown%20in%20the%20Heartland%20region.>

USDA-ERS. (2024a). *Corn, soybeans account for more than half of the 2022 U.S. crop cash receipts*. <https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=76946>

USDA-ERS. (2024b). *Cash receipts by commodity, state ranking, 2022*.

https://data.ers.usda.gov/reports.aspx?ID=17844#P7598cb95afa344669b4ba2d827a73ac5_3_251iT0R0x115

USDA-FS. (1980). *An approach to water resources evaluation on non-point silvicultural sources (a procedural handbook)*. A. U.S. Environmental Protection Agency Environmental Research Laboratory, Ga.

USDA-NASS. (2024). *2023 State agriculture overview- virginia*.

https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=VIRGINIA

USDA-NRCS. (2014). *Revised cover crop termination guidelines. NRCS National Bulletin NB 450-15-1 TCH*.

USDA-NRCS. (2017). *Title 440- Conservation Programs Manual*.

- USDA-NRCS. (2018). *Soil Health* Retrieved 4 April 2024 from <https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health>
- Virginia Department of Environmental Quality (DEQ). (2024). *Virginia's draft Chesapeake Bay 2024-2025 numeric milestones*. <https://www.deq.virginia.gov/our-programs/water/chesapeake-bay/chesapeake-bay-nutrient-sediment-reduction-milestones>
- Wallander, S., Smith, D., Bowman, M., & Claassen, R. (2021). Cover crop trends, programs, and practices in the United States.
- Wang, F., & Weil, R. (2018). The form and vertical distribution of soil nitrogen as affected by forage radish cover crop and residual side-dressed N fertilizer. *Soil Science 183*(1). <https://doi.org/0.1097/SS.0000000000000224>
- Ward, B. (2008). Nitrification. In *Encyclopedia of ecology* / (pp. 2511–2518). Elsevier,. <https://doi.org/10.1016/B978-008045405-4.00280-9>
- Weil, R., & Kremen, A. (2006). Perspective thinking across and beyond disciplines to make cover crops pay. *Journal of the Science of Food and Agriculture*. <https://doi.org/DOI:10.1002/jsfa.2742>
- White, A. C., Rogers, A., Rees, M., & Osborne, C. P. (2015). How can we make plants grow faster? A source–sink perspective on growth rate. *Journal of Experimental Botany*, *67*(1), 31-45. <https://doi.org/10.1093/jxb/erv447>
- White, C. M., DuPont, S. T., Hautau, M., Hartman, D., Finney, D. M., Bradley, B., LaChance, J. C., & Kaye, J. P. (2017). Managing the trade off between nitrogen supply and retention with cover crop mixtures. *Agriculture, Ecosystems & Environment*, *237*, 121-133. <https://doi.org/https://doi.org/10.1016/j.agee.2016.12.016>

- White, C. M., & Weil, R. R. (2010). Forage radish and cereal rye cover crop effects on mycorrhizal fungus colonization of maize roots. *Plant and Soil*, 328(1), 507-521.
<https://doi.org/10.1007/s11104-009-0131-x>
- Wilson, M. L., Allan, D. L., & Baker, J. M. (2014). Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices. *Journal of Soil and Water Conservation*, 69(3), 67A-72A. <https://doi.org/10.2489/jswc.69.3.67A>
- Wilson, M. L., Baker, J. M., & Allan, D. L. (2013). Factors affecting successful establishment of aerially seeded winter rye. *Agronomy Journal*, 105(6), 1868-1877.
<https://doi.org/https://doi.org/10.2134/agronj2013.0133>
- Wofuru-Nyenke, O. K. (2023). Mechanized cover crop farming: Modern methods, equipment and technologies *Circular Agriculture Systems* 3(6).
<https://doi.org/https://doi.org/10.48130/CAS-2023-0006>
- Wortman, S. E., Francis, C. A., Bernards, M. L., Drijber, R. A., & Lindquist, J. L. (2012). Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal*, 104(5), 1425-1435.
<https://doi.org/https://doi.org/10.2134/agronj2012.0185>
- Yadav, S. N. (1997). Formulation and estimation of nitrate-nitrogen leaching from corn cultivation. *Journal of Environmental Quality*, 26(3), 808-814.
<https://doi.org/https://doi.org/10.2134/jeq1997.00472425002600030031x>
- Zablotowicz, R. M., Reddy, K. N., Krutz, L. J., Gordon, R. E., Jackson, R. E., & Price, L. D. (2011). Can leguminous cover crops partially replace nitrogen fertilization in Mississippi delta cotton production? *International Journal of Agronomy*, Vol. 2011, 1-9.
<https://doi.org/doi:10.1155/2011/135097>

Zhu, J. C., Gantzer, C. J., Anderson, S. H., Alberts, E. E., & Beuselinck, P. R. (1989). Runoff, soil, and dissolved nutrient losses from no-till soybean with winter cover crops. *Soil Science Society of America Journal*, 53(4), 1210-1214.

<https://doi.org/https://doi.org/10.2136/sssaj1989.03615995005300040037x>

2. Early Cover Crop Establishment by Broadcast Seeding Strategies for Reducing Nitrate Leaching and Increasing Biomass Production Following Corn in the Mid-Atlantic

2.1 Abstract

Mitigating nitrogen (N) leaching from agricultural fields remains a priority in the Chesapeake Bay Watershed. Mineralization of N continues after corn uptake ceases, making it possible for substantial N leaching after harvest and before cover crop (CC) establishment. This study aims to identify the best establishment method and cover crop combination for maximizing soil nitrogen uptake, biomass production, and reducing residual soil nitrate. Four seeding methods were tested: (1) broadcasting with incorporation at corn (*Zea mays* L.) harvest, (2) broadcasting without incorporation at corn harvest, (3) broadcasting with incorporation 4 weeks post-harvest, and (4) drilling 4 weeks post-harvest. Each method was repeated with cereal rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), rapeseed (*Brassica napus* L.), and a mix of all three. While Year 1 indicated no difference between treatments, Year 2 showed fall soil nitrate levels more than double in 0 to 15 cm depth post-harvest treatments (11.4 to 11.8 mg kg⁻¹) compared to at-harvest treatments (5.2 mg kg⁻¹) and the at-harvest incorporated rye had the lowest winter soil nitrate levels (1.7 mg kg⁻¹). Planting CCs at-harvest produced up to six times more fall biomass (721 to 846 kg ha⁻¹) than CCs planted 4-weeks post-harvest (134 to 200 kg ha⁻¹) in both years. Most post-harvest treatments, especially post-harvest drilled treatments, showed comparable biomass to their at-harvest counterparts by the spring. More N was accumulated in aboveground biomass of hairy vetch and the mix, particularly when planted at corn harvest (181

to 208 kg ha⁻¹), than any other treatment combination. Corn yield increased in the first year when at-harvest hairy vetch (10,113 to 11,382 kg ha⁻¹) and at-harvest incorporated mix (11,586 kg ha⁻¹) were used compared to the control (8,894 kg ha⁻¹). However, this effect was not observed in the second year. Incorporating broadcast CC seeds at corn harvest did not significantly affect any measured data outcomes when compared to non-incorporated treatments in either year. This study demonstrates that planting cover crops at corn harvest, particularly hairy vetch or a mix, maximizes nitrogen accumulation, biomass production, and fall soil nitrate reduction, highlighting its potential as a practical strategy for mitigating nitrogen leaching in the Chesapeake Bay Watershed.

2.2 Introduction

The Chesapeake Bay is one of the most valuable natural resources in the United States, but non-point source pollutants compromise water quality (Staver & Brinsfield, 1998). Nitrate leaching from agricultural soils is a key contributor to degraded water quality, as around 60% of global groundwater contamination is linked to agriculture (Ascott et al., 2017; Rawat et al., 2022). N leaching is more pronounced in regions with coarse-textured soils, like the Eastern Shore of Virginia (Abdalla et al., 2019). Many soils on the Eastern Shore contain little organic matter, creating a situation where water remains oxic, causing nitrates to remain stable instead of denitrifying (Ator & Denver, 2015). Corn's heavy reliance on nitrogen (N) fertilizers leads to significant nitrate losses, with up to 41% of applied N lost from fields and about 15% leaching into groundwater annually (Omara et al., 2019; Yadav, 1997).

In the Mid-Atlantic, N uptake by crops ceases about four weeks before harvest maturity, leaving 253 kg ha⁻¹ of mineral N, including 115 kg ha⁻¹ in the NO₃-N form, in the top 2.1 meters

of soil (Hirsh et al., 2021; Hirsh & Weil, 2019). If not absorbed by a living plant, this N can leach from the soil profile during fall mineralization (Blanco-Canqui, 2018; Staver & Brinsfield, 1998). Cover crops provide a solution by scavenging residual N, improving weed suppression, and reducing fertilizer costs by supplying nutrients to the following crop during decomposition (Blanco-Canqui, 2018; Roesch-McNally et al., 2018). Additionally, studies in Maryland and Pennsylvania found that CCs planted during the period when cash crop N uptake ceases can reduce nitrate leaching by up to 80% (Schipanski et al., 2014; Staver & Brinsfield, 1998).

Timely planting is crucial for CC's success. Sedghi & Weil (2022) found that a two-week planting delay reduced growing degree days (GDD) by 160-to-300-degree days C°, lowering N capture potential. In the mid-Atlantic region, USA, planting CCs before October 1 is essential for optimal performance (Ritter et al., 1998). Mid-Atlantic studies indicated that delaying planting until November, particularly for brassicas, does not reduce nitrate leaching (Dean & Weil, 2009; Thapa et al., 2018a).

As identified by 29 Iowa farmers, a primary concern is the limited time after harvest to establish a successful CC stand, especially in the Midwest where harvest can extend into November (Roesch-McNally et al., 2018). Mid-Atlantic farmers share this concern, particularly following soybean harvest.

Traditional grain drills are valued for precision and seed placement but waiting until after harvest to drill CCs can delay planting by weeks, leading to poor stands (Kientzy et al., 2023; Wofuru-Nyenke, 2023). To address late planting challenges, alternative seeding methods, such as aerial or broadcast seeding, were proposed to establish CCs earlier (Dean & Weil, 2009; Fisher et al., 2011; Thapa et al., 2018a). Aerial seeding can be performed by planes, unmanned aerial vehicles (drones), or helicopters, and ground broadcasting by combine-mounted seeders,

air booms, pendulums, high-clearance spreaders, spinner spreaders, or row-based interseeders (Kientzy et al., 2023). Each seeding method has benefits and complications when used in our mid-Atlantic production systems.

Our study aims to: (1) identify the most effective establishment method and CC species for N uptake and biomass production; (2) determine if planting CCs at harvest, rather than delaying by 4 weeks, enhances N scavenging; (3) evaluate fall and spring biomass under different planting timings; (4) assess whether seed incorporation improves success after broadcast seeding; and (5) examine how at-harvest CC planting affects cash crop yields.

2.3 Materials and Methods

2.3.1 Location and Experimental Design

The experiment was conducted over two growing seasons: 2022–2023 (Year 1) and 2023–2024 (Year 2) at the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, VA (37°35' N, 75°49' W). The soil was a Bojac sandy loam, which is classified as a coarse-loamy, mixed, semiactive, thermic Typic Hapludult (Soil Series Staff, 2002). The field before the experiment was not tilled for over fifteen years and left fallow between 2015 to 2020. Soybean was planted in 2021 followed by a fallow winter field before planting corn in 2022, which received 224 kg N ha⁻¹. The experiment, conducted in no-till field corn, was arranged as a randomized complete block design with sixteen treatments plus a control, replicated four times, with each plot measuring 4.7 m in width and 9.0 m in length with 5.0 m alleys separating blocks.

2.3.2 Treatments and Cover Crop Seeding

Four methods for CC establishment were: 1) broadcast seeding at corn harvest with incorporation (AHI), 2) broadcast seeding at corn harvest without incorporation (AHNI), 3) broadcast seeding 4-weeks post corn harvest with incorporation (PHI), and 4) drilling 4-weeks post corn harvest (PHD). The at-harvest methods were chosen to simulate the use of a combine-mounted CC seeder, which is a relatively new form of CC establishment. The post-harvest methods were based on two common established methods and implemented four weeks after corn harvest, reflecting the average time needed by local farmers to return to the field for planting CCs and on USDA- Natural Resources Conservation Services (NRCS) guidelines for CC planting (Haramoto, 2019; USDA-NRCS, 2015; Wofuru-Nyenke, 2023). Four CC species used were: 1) cereal rye (*Secale cereale* L.), 2) hairy vetch (*Vicia villosa* Roth), 3) rapeseed (*Brassica napus* L.), and 4) a mix of cereal rye, hairy vetch, and rapeseed. These CCs were selected as they represent common winter CCs, all of which perform different ecosystem functions (Kühling et al., 2023). In addition to each combination of establishment method and CC species, there was a no CC control treatment.

Cover crops planting dates are shown in Table 2.1. At corn harvest, treatments were broadcasted by hand directly before corn was combined to mimic corn fodder deposited on top of CC seed. Broadcast and drill seeding rates for single CC varieties and mix calculations were sourced from the Virginia USDA-NRCS office (Table 2.2), which uses these rates to establish specifications for the EQIP 340 Cover Crop Practice Standard (USDA-NRCS, 2015). Incorporation was done by light disking and all drilled treatments were planted using a no-till drill with 19 cm row spacing (Model 3P606NT, Great Plains Ag, Saline, KS).

2.3.3 Weather data

Weather data were collected from an on-site weather station, which included maximum, minimum, and mean daily temperatures and precipitation. To assess growing conditions for each CC planting date, the number of growing degree days (GDD) was calculated with the formula:

$$GDD = \frac{(T_{max,40} + T_{min})}{2} - T_{base}$$

Where, $T_{max,40}$ represents the daily maximum air temperature, capped at 40 °C, T_{min} denotes the daily minimum air temperature, and T_{base} is the base temperature equal to 4 °C (Mirsky et al., 2017; Teasdale et al., 2004).

2.3.4 Soil Sample Collection and Analysis

Before the field trial, background soil samples were taken every 15 cm from 0 to 120 cm depth (Table 2.3). All samples were taken using a stainless-steel soil probe with a diameter of 2.86 cm. Four cores per rep, per depth, were homogenized in a plastic bucket before adding to a soil sampling box and immediately added to a forced air dryer for 5 to 10 days. Soil samples were sieved through a 2 mm sieve. Background soil samples were analyzed for water pH (1:1), buffer pH, cation exchange capacity (CEC), organic matter, and Mehlich-1 extractable phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulfur (S), boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) (Issac, 1983; McLean, 1983; Mehlich, 1953; Schulte & Hopkins, 1996; Storer, 1984). The Mehlich-1 extract was analyzed using an inductively coupled plasma-atomic emission spectrometer (ICP-AES) (Issac, 1983; Mehlich, 1953). Organic matter was determined via loss-on-ignition (Storer, 1984; Schulte & Hopkins, 1996), and soil texture was assessed at all depths for each block using the hydrometer method (Bouyoucos, 1936; Day, 1965).

Soil samples for nitrate extraction were taken from each plot from 0 to 15 cm and 15 to 30 cm. Samples were collected in the fall (October 2022 and November 2023) and in winter (January 2023 and 2024). All samples were taken following the same methods as background soil. Four grams of soil were extracted with 40 ml KCL. Solutions were shaken at 180 oscillations per minute for 30 minutes, followed by filtration through Whatman no. 42 filter paper. Extractions were analyzed on a Lachat Instruments QuickChem 8500 autoanalyzer for NO_3^- -N using QuickChem Method 12-107-04-5-A at a wavelength of 530 nm (QuickChem 8500 FIA Automated Ion Analyzer; Lachat Instruments, Hatch Company, Loveland, CO).

2.3.5 Cover Crop Biomass Collection, Processing, and Termination

A total of 0.5 m² of aboveground CC biomass was destructively sampled by collecting all living, aboveground biomass from two 0.25 m² quadrats randomly across the plot. Weed biomass was separated from CC treatment biomass. Samples were immediately dried at 55° C until reaching a constant weight. Samples were collected in winter and spring (Table 2.1). Dry biomass was weighed, then ground to pass a 1 mm screen with a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Both CC and weed biomass samples were analyzed for total C and N by dry combustion (Bremner, 1996) using a Vario EL cube elemental analyzer (Elementar Americas Inc., New York). The CC and weed C:N ratio was calculated using the percent C and N in the plant tissue. CC nutrient accumulation was calculated by multiplying % of nutrient in tissue and the dry weight of CC biomass (kg ha⁻¹). Each treatment's total biomass and nutrient content was calculated by combining the CC and weed biomass. One day before corn planting, CCs were chemically terminated with 1268 g ae ha⁻¹ glyphosate and 657 g ai ha⁻¹ glufosinate, dates listed in Table 2.1.

2.3.6 *Corn Planting, Collection, Processing, and Harvesting*

Corn planting dates varied by weather conditions (Table 2.1). A no-till planter (Monosem Inc., Edwardsville, KS) was used to plant Dekalb DKC59-81RIB corn, a variety with a 109-day relative maturity, in 4 rows per plot at a row spacing of 76 cm, with a target population density of 68,940 seeds per hectare. Corn received 56 kg N ha⁻¹ with 300 g N kg urea-ammonium nitrate (UAN) broadcasted at planting. Due to poor establishment in Year 2 from planter issues, corn was terminated with 552.51 g ai/ha of paraquat dichloride and replanted three weeks after initial planting. Ten leaves per plot were collected from the first true leaf at V5 and corn ear leaf at R1 for tissue samples (Bryson et al., 2014). Corn tissue analysis followed the same procedures as CC biomass analysis. Corn harvest dates were delayed due to rain in both seasons (Table 2.1). Corn yield was evaluated by harvesting the middle four rows with a Zürn 160 plot combine equipped with integrated weight and moisture monitoring systems (Zürn Harvesting GmbH and Co. KG, Schöntal-Westernhausen, Germany).

2.3.7 *Statistical Analysis*

Statistical analyses were performed using R version 4.4.1 (R Core Team, 2024). All significance was determined at $\alpha < 0.05$. The design is a complete factorial and ran as a two-way analysis of variance (ANOVA), with CC \times establishment method as fixed effects and block as a random effect using the aov() function. To analyze the soil N data with depth included, a three-way ANOVA was run with CC \times establishment method \times depth as fixed effects and block as a random effect. When analyzing the soil N data with the no CC control treatment, the design becomes an incomplete factorial and is analyzed as a two-way ANOVA. Depth \times treatment (which includes CC + control and establishment method combined) were run as fixed effects and

block as a random effect. A one-way ANOVA was used to analyze the inclusion of the control with biomass, corn tissue, and yield data, which combines CC species and establishment method. Comparisons were conducted using Fisher's Least Significant Difference (LSD) test to identify which groups differed using the `LSD.test()` function in the *agricolae* package (Mendiburu, 2023). Graphical data visualizations were created using the *ggplot2* package (Wickham, 2016).

2.4 Results and Discussion

2.4.1 Environmental Factors

Cumulative GDD and cumulative precipitation were summarized for each CC growing season and compared to the timing of each establishment method (Figures 2.1, 2.2). Notably, in Year 1, there was 17.3 cm more rainfall for treatments planted at-harvest compared to those planted 4 weeks post-harvest. In contrast, the difference in precipitation between at-harvest and post-harvest planting dates in Year 2 was only 3.7 cm. Although Year 1 experienced steady rainfall throughout the CC growing season, the total precipitation (61.7 cm) was lower than in Year 2 (79.7 cm), which saw heavier rainfall events, particularly in December and March. Despite the higher overall rainfall in Year 2, both at-harvest and post-harvest planting dates were followed by a week of no precipitation, likely delaying germination and establishment, particularly affecting the broadcast-seeded post-harvest treatments. The success of broadcasting methods relies heavily on sufficient rainfall for germination (Collins & Fowler, 1992; Haramoto, 2019; Koehler-Cole & Elmore, 2020; Wilson et al., 2014). Delayed post-harvest planting resulted in 338 fewer GDDs in Year 1 and 326 fewer GDDs in Year 2.

2.4.2 Soil Nitrate Levels

There was a significant depth main effect with soil N concentrations significantly higher in the 0 to 15 cm depth than the 15 to 30 cm depth across all sampling dates ($p < 0.001$; Table 2.4). Increased nitrate levels in topsoil as compared to subsoil were consistent with previous studies showing that the top 10 cm of soil tends to have higher N concentrations due to accumulation of plant residues, microbial biomass, and fertilizers across various ecosystems, including agricultural lands (Libby & Hernández, 2021; Yang et al., 2023). However, in Year 1 fall, more soil nitrates were in the 15 to 30 cm depth (7.1 mg ha^{-1}) than in Year 2 fall (3.0 mg ha^{-1}). Due to 13.6 cm more precipitation in Year 1 (Figure 2.2) between at-harvest planting and fall soil sampling date compared to Year 2, soil conditions might have been suitable for vertical movement of nitrates from deeper soil horizons by plant roots or capillarity as observed by Patel et al. (2001).

In Year 1 fall, there was no significant establishment method or CC species main or interaction effect on soil nitrate concentrations (Table 2.4), suggesting that treatments did not have a discernible effect on soil nitrate levels. There were also higher overall nitrate levels in Year 1 compared to Year 2 (Table 2.4), which can be attributed to several factors, including previous field management practices and fall precipitation. Before study establishment at corn harvest in 2022, corn was managed for grain production, receiving 224 kg N ha^{-1} total. In 2023, no sidedress N was applied to corn, as the study focused on evaluating the impact of CCs on yield without supplemental N inputs. Higher soil nitrate levels observed in Year 1 were likely due to applied fertilizer, which may have been concentrated in the 0 to 30 cm soil profile by the significant rainfall in fall 2022. However, by Year 1 winter, a significant establishment method

main effect showed post-harvest drilled treatments exhibited significantly higher soil nitrate concentrations (4.5 mg kg^{-1}) than other treatments (2.9 to 3.7 mg kg^{-1}).

In Year 2 fall, the significant establishment method \times depth interaction ($p < 0.001$) found post-harvest treatments had over double the soil nitrate levels in the 0 to 15 cm depth (11.4 to 11.8 mg kg^{-1}) compared to at-harvest treatments (5.2 mg kg^{-1} ; Table 2.4). Post-harvest treatment planting date coincided with soil N sampling in Year 2 fall, which meant CCs were only present in the at-harvest treatments at that time (Table 2.1). In both years, fall soil N concentrations exceeded winter levels. This is important for farmers located in the Chesapeake Bay Watershed, as fall soil N can mineralize into October without the use of CCs since soil temperature remains warm enough for biological activity (Blanco-Canqui, 2018; Staver & Brinsfield, 1998).

The pattern observed in Year 2 fall was less consistent by winter as CC biomass increased. The interaction effect between CC species \times establishment method showed AHI Rye had the lowest soil nitrate concentrations (1.7 mg kg^{-1} ; Table 2.4), compared to any other treatment aside from the post-harvest planted rye, reinforcing the observations of other research studies on the effectiveness of cereal rye as a N scavenger (Brandi-Dohrn et al., 1997; McCracken et al., 1994; Thapa et al., 2018a).

In Year 1, soil nitrates in treatments with CCs did not significantly differ from the control at either sampling date, based on a two-way ANOVA combining establishment method \times CC species ($p = 0.028$ and $p = 0.087$; Table 2.4 footnote). In Year 2 fall, the no CC control showed lower soil nitrate concentrations (5.7 mg kg^{-1}) compared to all post-harvest treatments within 0 to 6 cm depth (9.4 to 12.6 mg kg^{-1} ; $p < 0.001$) but was not significantly different from at-harvest treatments. By Year 2 winter, the control treatment's nitrate concentration (2.2 mg kg^{-1}) remained lower than or comparable to all CC treatments. The lower nitrate levels in the control plot likely

resulted from high fall weed biomass—1515 kg ha⁻¹ in Year 1 and 2308 kg ha⁻¹ in Year 2 (Table 2.7, Table 2.8)—contributing to significant N uptake, which was also observed by Baraibar et al. (2021) and Ritter et al. (1998). While high weed biomass can contribute to N scavenging and other agroecological benefits, such as plant diversity (Jordan & Vatovec, 2004), it can also harm the productivity of subsequent cash crops, as demonstrated by Rouge et al. (2023), and exacerbate the buildup of the weed seed bank.

The study found less conclusive results on the effects of CC species and establishment method on soil N scavenging compared to other studies (Hirsh & Weil, 2019; Schipanski et al., 2014; Sedghi & Weil, 2022; Staver & Brinsfield, 1998), but our results still support the hypothesis that broadcasting CCs at corn harvest has the potential to reduce soil nitrate levels through plant uptake.

2.4.3 *Biomass Accumulation*

When CC species were averaged over CC establishment method in Year 1, all CC species produced comparable fall biomass (501 to 629 kg ha⁻¹), except rapeseed, which only produced 248 kg ha⁻¹ ($p < 0.001$; Table 2.5). Establishment method averaged over CC species produced up to six times more fall aboveground biomass when established at-harvest (721 to 846 kg ha⁻¹) as compared to those established post-harvest (134 to 200 kg ha⁻¹) ($p < 0.001$; Table 2.5). The increase in fall biomass due to planting earlier date highlights the importance of early planting for maximizing biomass production as emphasized by multiple researchers (Akbari et al., 2019; Akbari et al., 2020; Hashemi et al., 2013; Mirsky et al., 2011). In Year 2, the CC species \times establishment method interaction showed the AHI Vetch produced more fall biomass (1654 kg ha⁻¹) than all treatments other than the at-harvest mixes ($p = 0.001$; Table 2.6). Our findings align

with Wortman et al. (2012), who found that CC mixtures did not produce more biomass than monocultures, with a mixture's effectiveness depending on establishment timing, climate, and species ratios. However, Brainard et al. (2012) found that a hairy vetch-cereal rye mix (6000 kg ha⁻¹) can outperform both monoculture hairy vetch (3,600 kg ha⁻¹) and monoculture cereal rye (5,600 kg ha⁻¹) in biomass production by 63%.

In Year 2, treatments containing cereal rye did not show significant fall biomass differences between at-harvest and post-harvest planting dates (Table 2.6), emphasizing rye's resilience in establishment with later planting, as previously noted by Duiker (2014) and Hayden et al. (2015). In contrast, hairy vetch, rapeseed, and mix treatments exhibited vast differences in fall biomass between the two planting dates. Delayed establishment of post-harvest vetch and mix treatments aligns with vetch's slow fall growth pattern reported by Baraibar et al. (2018). The significantly higher biomass of at-harvest vetch treatments can likely be attributed to additional GGDs and sufficient autumn rainfall after seeding (Figure 2.1, Figure 2.2), which were trends also observed by Moore & Mirsky (2020) and Sedghi et al. (2023).

Fall weed biomass did not differ significantly among treatments in Year 1 ($p = 0.132$), suggesting that weed pressure from the winter fallow field was too high for any CC treatment to suppress substantial weed growth effectively (Table 2.7). However, in Year 2, at-harvest cereal rye exhibited the highest weed suppression (342 to 370 kg ha⁻¹ of weed biomass vs. 2308 kg ha⁻¹ in the control), with weeds making up only 27 to 31% of the total biomass (Table 2.8). The weed pressure in this study may have been higher than in a well-managed agricultural field due to fallow conditions in previous winters. Research indicated that 3 to 5 years of consistent cover cropping is needed to achieve significant weed suppression, depending on CC species, local

environmental conditions, and specific management practices (Pratt et al., 2023; Weisberger et al., 2023).

In this experiment, incorporation after broadcast seeding was unnecessary to achieve similar fall and spring biomass when CCs were planted at corn harvest (Table 2.5 – Table 2.10). Regardless of incorporation, lack of significance between at-harvest treatments indicated no need for additional field passes during the busy fall harvest season. When planting CCs 4 weeks after corn harvest, there was no significant difference in fall biomass between drilled and broadcast seeded with incorporation treatments. However, this was not observed in spring biomass. During Year 1, the PHD Rye transitioned from being one of the lowest fall biomass producers (385 kg ha⁻¹) (Table 2.7) to one of the highest spring biomass producers (6072 kg ha⁻¹), like at-harvest vetch and mix treatments, with only 8% total biomass being attributed to weeds (Table 2.9). PHD treatments quickly caught up to at-harvest planted counterparts in spring biomass production across all CC species ($p < 0.001$). In contrast, the PHI treatments did not achieve the same spring biomass levels as the at-harvest treatments. The overall poor performance of PHI treatments compared to at-harvest treatments in Year 1 suggested that with post-harvest planting and 17.3 cm less precipitation (Figure 2.2), drilling is more effective than broadcast seeding due to improved seed-to-soil contact, showcased by Haramoto (2019), Koehler-Cole & Elmore (2020), and Wilson et al. (2014).

In Year 2, unlike in Year 1, there were no significant differences in spring biomass across establishment methods for cereal rye (2817 to 3322 kg ha⁻¹) treatments and only the AHNI Vetch treatment differed from the post-harvest vetch treatments (Table 2.6). The PHD Mix treatment produced significantly less spring biomass than all other mix treatments, but the PHI Mix did not differ from the at-harvest treatments. The lack of significant differences in spring biomass across

establishment methods in Year 2 may be due to only a 3.7 cm difference in precipitation between at-harvest and post-harvest planting, combined with more spring rainfall than in Year 1, regardless of increased GDDs (Figure 2.2).

Treatments containing vetch, rye, or the mix had significantly less spring weed biomass than the control in both years ($p < 0.001$; Table 2.9 and 2.10). However, all rapeseed treatments were equal to the control in spring weed biomass except for the at-harvest rapeseed in Year 1 and AHI Rapeseed in Year 2 ($p < 0.001$). The small amount of fall CC biomass produced by PHI Rapeseed in Year 1 (83 kg ha^{-1}) was outcompeted by weeds and the treatment produced no spring biomass. The poor performance of the post-harvest rapeseed treatments throughout the two-year study may be due to the sensitivity of brassicas to planting timing and their competitive disadvantage when planted late as observed by Clark (2008) and Wang & Weil (2018). Some studies reported success with both aerially seeding and drilling rapeseed in terms of weed suppression and N accumulation (Dean & Weil, 2009; Kristensen & Thorup-Kristensen, 2004; Thapa et al., 2018a), but that success was not observed in this study.

2.4.4 Nitrogen Accumulation and C:N Ratio

In both years, fall CC biomass N accumulation displayed a similar pattern to biomass production (Table 2.5, Table 2.6). The interaction of CC establishment method \times CC species indicated at-harvest vetch and mix treatments had the greatest contrast between their post-harvest counterparts, with higher N accumulation in the at-harvest treatments. Furthermore, at-harvest vetch (39 to 73 kg N ha^{-1}) and at-harvest mix (43 to 59 kg N ha^{-1}) treatments displayed the greatest fall N accumulation ($p = 0.019$, $p < 0.001$).

Spring CC biomass N accumulation did not align with biomass production as strongly as the fall (Table 2.5, Table 2.6). Despite the CC establishment method \times CC species showing PHD Rye as one of the top spring biomass producers in Year 1, N accumulation was significantly lower than at-harvest and drilled vetch and mix treatments ($p = 0.046$; Table 2.5), which had the highest N accumulation in Year 1, ranging from 143 to 208 kg N ha⁻¹, and were significantly greater than all other treatments, ranging from 0 to 89 kg N ha⁻¹ ($p < 0.001$). Similarly, in CC species main effect in Year 2, CC biomass N accumulation was higher in hairy vetch and mix treatments (175 kg N ha⁻¹) compared to cereal rye (50 kg N ha⁻¹) and rapeseed treatments (16 kg N ha⁻¹) ($p < 0.001$; Table 2.6). Cover crop establishment method main effect showed AHI treatments were equal in N accumulation to AHNI treatments, but greater than both post-harvest treatments ($p < 0.001$; Table 2.6). In terms of high biomass production, substantial N accumulation, and significant weed suppression abilities, the success of hairy vetch and the hairy vetch-cereal rye-rapeseed mix in this study aligned with many other studies (Brainard et al., 2012; Hayden et al., 2014; Ledgard, 2001; Norris et al., 2020; Marcillo & Miquez, 2017; Thapa et al., 2018b).

In both years (Table 2.9 and Table 2.10), all cereal rye treatments— independent of establishment method—and AHI Rapeseed had the greatest total spring C:N ratio other than PHD Rapeseed and the control in Year 1 ($p < 0.001$). AHI Rye had a C:N ratio of 34:1 in Year 1 (26% of the total biomass was comprised of weeds) and 23:1 in Year 2 (14% weeds) (Tables 2.9 and 2.10, respectively). Similarly, PHD Rye had a C:N ratio of 31:1 in Year 1 (8% weeds) and 21:1 in Year 2 (17% weeds) (Tables 2.9 and 2.10). Even with the weed suppression capabilities of AHI and PHD Rye, there is a tradeoff as high C:N ratios cause N to be immobilized when CCs are terminated (Brust, 2019; Okopi et al., 2024; Pieters & McKee, 1938; Staver & Brinsfield,

1998) and N only becomes available for plants when the C:N ratio is around or less than 20:1 (Bryson et al., 2014).

2.4.5 *Corn Yield and Tissue Nitrogen Concentration*

Corn stage V5 leaf tissue in Year 1 showed a significant CC species main effect with hairy vetch, rye, and mix treatments having significantly more N (47.1 to 50.5 g N kg plant tissue⁻¹) than rapeseed treatments (46.8 g N kg plant tissue⁻¹) ($p = 0.011$; Table 2.11). Cover crop establishment method main effect indicated that AHNI treatments (50.4 kg g N kg plant tissue⁻¹) were significantly higher than post-harvest treatments (46.8 to 47.4 g N kg plant tissue⁻¹) ($p = 0.018$; Table 2.11). There was no significant difference between CC species main effect (29.5 kg g N kg plant tissue⁻¹ average; $p = 0.650$) or establishment method main effect (29.4 kg g N kg plant tissue⁻¹ average; $p = 0.950$) by the time corn reached R1. Sidedressing N on corn generally occurs between V6 and V8, targeting a key growth period where the plant utilizes large amounts of N beginning at V6 and lasting through V12 (Nleya et al., 2019). Early availability of N from hairy vetch treatments at V5 is critical compared to later stages like R1. No significant differences in N concentration were observed between CCs or establishment methods at V5 or R1 in Year 2.

In Year 1, corn yield was increased following the PHD Vetch and at-harvest vetch treatments (10,113 to 11,382 kg ha⁻¹) and AHI Mix (11,586 kg ha⁻¹) compared to the control (8,894 kg ha⁻¹) ($p < 0.001$; Table 2.12). In Year 2, no treatment increased yield compared to the control ($p < 0.009$). However, there was a significant CC species main effect ($p < 0.001$), with hairy vetch (9961 kg ha⁻¹) and the mix (9538 kg ha⁻¹) increasing yield compared to cereal rye (8499 kg ha⁻¹), but the mix not differing from rapeseed (9011 kg ha⁻¹; Table 2.13).

No CC species or establishment method decreased yield from the control in either year, except for AHNI Rye in Year 2 (Table 2.12). Many studies have shown that neither grass nor legume CCs decrease corn yield (Lotter et al., 2003; Snapp & Surapur, 2018; Zablotowicz et al., 2011) while other studies showed a decrease in corn yield following cereal rye, especially when cereal rye is planted early and terminated late (Martinez-feria et al., 2016; Nielsen et al., 2016; Snapp et al., 2005).

The inconsistency and lack of significance in Year 2 data for both corn tissue samples and yield were likely due to having to replant the corn in 2024 after poor stand establishment. A low C:N ratio, such as the mix and hairy vetch C:N ratio shown in Table 2.10, is associated with fast decomposition and N release into the soil after termination (Clark, 2008). Studies have indicated that most of the N release from hairy vetch residue happens in the first 2 weeks after CC termination (Sievers & Cook, 2018; Singh et al., 2020). Corn was re-planted 3 weeks after CC termination in Year 2, indicating much of the N release from hairy vetch was most likely not utilized by the re-planted corn.

2.5 Conclusions

In conclusion, broadcasting CCs, particularly cereal rye, at corn harvest has potential to reduce soil nitrates compared to delayed post-harvest planting, however, additional site years are needed to confirm these findings. High weed pressure can also effectively reduce soil nitrates, as seen in the control, although weeds do not possess as many ecosystem benefits as well-established cover crops. Broadcasting CCs at corn harvest significantly increased fall biomass, particularly with hairy vetch and mixes, and produced equal or greater spring biomass compared to drilling 4-weeks post-harvest. Post-harvest broadcasting will likely result in significantly less

CC biomass than broadcasting at harvest or drilling. Hairy vetch or mixes with hairy vetch accumulate significant N, especially when planted during corn harvest, and this N can enhance corn yields when corn is planted shortly after CC termination. Incorporation after at-harvest broadcasting was unnecessary for biomass production and N accumulation over the study's two years, potentially eliminating the need for an additional field pass. However, further research is needed to assess the necessity of incorporation in varying precipitation and climate conditions. Rapeseed struggled to establish in this experiment, leading to higher soil nitrate concentrations and lower biomass, N accumulation, and corn yields, indicating a need for further research on rapeseed establishment methods. Overall, this study demonstrated the potential of at-harvest CC broadcast seeding to improve biomass production and increase corn yield while mitigating N leaching, with ongoing investigations needed to refine these practices for broader adoption and enhanced environmental sustainability.

2.6 References

- Abdalla, M., Hastings, A., Cheng, K., Yue, U., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity *Wiley Global Change Biology* 25, 2530–2543. <https://doi.org/DOI: 10.1111/gcb.14644>
- Akbari, P., Herbert, S. J., Hashemi, M., Barker, A. V., & Zandvakili, O. R. (2019). Role of cover crops and planting dates for improved weed suppression and nitrogen recovery in no till systems. *Communications in Soil Science and Plant Analysis*, 50(14), 1722–1731. <https://doi.org/10.1080/00103624.2019.1631338>
- Akbari, P., Herbert, S., Hashemi, M., Barker, A., Zandvakili, O. R., & Emami Bistgani, Z. (2020). Winter annual rye seeding date influence on nitrogen recovery and ammonia volatilization from late fall surface-applied manure. *Agronomy*, 10(7), 931. <https://www.mdpi.com/2073-4395/10/7/931>
- Ascott, M. J., Goody, D. C., Wang, L., Stuart, M. E., Lewis, M. A., Ward, R. S., & Binley, A. M. (2017). Global patterns of nitrate storage in the vadose zone. *Nature Communications*, 8(1), 1416. <https://doi.org/10.1038/s41467-017-01321-w>
- Ator, S.W., and Denver, J.M., 2015, Understanding nutrients in the Chesapeake Bay watershed and implications for management and restoration—the Eastern Shore (ver. 1.2, June 2015): U.S. Geological Survey Circular 1406, 72 p., <http://dx.doi.org/10.3133/cir1406>.
- Balkcom, K., & Reeves, D. (2005). Sunn-hemp utilized as a legume cover crop for corn production. *Agronomy Journal*, 97. <https://doi.org/10.2134/agronj2005.0026>.
- Baraibar, B., Hunter, M.C., Finney, D.M., Barbercheck, M.E., Kaye, J.P., Curran, W.S., Bunchek, J., & Mortensen, D.A. (2021). weeds in cover crops: Context and management

- considerations. *Agriculture*, 11(3), 193. <https://doi.org/https://doi.org/10.3390/agriculture11030193>
- Baraibar, B., Hunter, M. C., Schipanski, M. E., Hamilton, A., & Mortensen, D. A. (2018). Weed suppression in cover crop monocultures and mixtures. *Weed Science*, 66(1), 121–133. doi:10.1017/wsc.2017.59
- Blanco-Canqui, H. (2018). cover crops and water quality. *Agronomy Journal*, 110(5), 1633-1647. <https://doi.org/https://doi.org/10.2134/agronj2018.02.0077>
- Bouyoucus, G. J. (1936). "Directions for making mechanical analysis of soils by the hydrometer method." *Soil Science Society of America Journal*, 42(3).
- Brainard, D., Henshaw, B., & Snapp, S. (2012). Hairy vetch varieties and bi-cultures influence cover crop services in strip-tilled sweet corn. *Agronomy Journal*, 104(3), 629-638. <https://doi.org/https://doi.org/10.2134/agronj2011.0360>
- Brandi-Dohrn, F. M., Hess, M., Selker, J. S., Dick, R. P., Kauffman, S. M., & Hemphill Jr., D. D. (1997). Nitrate leaching under a cereal rye cover crop. *Journal of Environmental Quality*, 26(1), 181-188.
- Bremner, J. M. (1996). Nitrogen-total. *Methods of Soil Analysis*: 1085-1121.
- Brust, G. E. (2019). Management strategies for organic vegetable fertility. In D. Biswas & S. A. Micallef (Eds.), *Safety and Practice for Organic Food* (pp. 193-212). Academic Press. <https://doi.org/https://doi.org/10.1016/B978-0-12-812060-6.00009-X>
- Bryson, G. M., Mills, H. A., Sasseville, D. N., Jones, J. B., & Barker, A. V. (2014). *Plant Analysis Handbook III*. Micro-Macro Publishing.
- Clark, A. (2008). *Managing cover crops profitably (3rd Ed.)*. DIANE Publishing Company. <https://books.google.com/books?id=ahxLEpn6WYwC>

- Collins, B. A., & Fowler, D. B. (1992). A comparison of broadcast and drill methods for no-till seeding winter wheat. *Canadian Journal of Plant Science*, 72(4).
<https://doi.org/https://doi.org/10.4141/cjps92-126>
- Day, P. R. (1965). "Particle fractionation and particle-size analysis in: C.A. Black (ed) *Methods of Soil Analysis, Part I.*" *Soil Science Society of America Journal*: 545-567.
- Dean, J. E., & Weil, R. R. (2009). Brassica cover crops for nitrogen retention in the Mid-Atlantic coastal plain. *Journal of Environmental Quality*, 38(2), 520-528.
<https://doi.org/https://doi.org/10.2134/jeq2008.0066>
- Duiker, S. W. (2014). Establishment and termination dates affect fall-established cover crops. *Agronomy Journal*, 106(2), 670-678.
<https://doi.org/https://doi.org/10.2134/agronj2013.0246>
- Fisher, K. A., Momen, B., & Kratochvil, R. J. (2011). Is broadcasting seed an effective winter cover crop planting method? *Agronomy Journal*, 103(2), 472-478.
<https://doi.org/https://doi.org/10.2134/agronj2010.0318>
- Frederick, L. R. (1956). The formation of nitrate from ammonium nitrogen in soils: I. Effect of Temperature. *Soil Science Society of America Journal*, 20(4), 496-500.
<https://doi.org/https://doi.org/10.2136/sssaj1956.03615995002000040012x>
- Fujita, K., Ofosu-Budu, K. G., & Ogata, S. (1992). Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and Soil*, 141(1), 155-175.
<https://doi.org/10.1007/BF00011315>
- Haramoto, E. R. (2019). Species, seeding rate, and planting method influence cover crop services prior to soybean. *Agronomy Journal*, 111(3), 1068-1078.
<https://doi.org/https://doi.org/10.2134/agronj2018.09.0560>

- Haramoto, E. R., & Gallandt, E. R. (2004). Brassica cover cropping for weed management: A review. *Renewable Agriculture and Food Systems*, 19(4), 187-198.
<https://doi.org/doi:10.1079/RAFS200490>
- Hashemi, M., Farsad, A., Sadeghpour, A., Weis, S. A., & Herbert, S. J. (2013). Cover-crop seeding-date influence on fall nitrogen recovery. *Journal of Plant Nutrition and Soil Science*, 176(1), 69-75.
- Hayden, Z. D., Ngouajio, M., & Brainard, D. C. (2014). Rye–vetch mixture proportion tradeoffs: Cover crop productivity, nitrogen accumulation, and weed suppression. *Agronomy Journal*, 106(3), 904-914. <https://doi.org/https://doi.org/10.2134/agronj2013.0467>
- Hayden, Z. D., Ngouajio, M., & Brainard, D. C. (2015). Planting date and staggered seeding of rye–vetch mixtures: Biomass, nitrogen, and legume winter survival. *Agronomy Journal*, 107(1), 33-40. <https://doi.org/https://doi.org/10.2134/agronj14.0237>
- Hirsh, S. M., Duiker, S. W., Graybill, J., Nichols, K., & Weil, R. R. (2021). Scavenging and recycling deep soil nitrogen using cover crops on mid-Atlantic, USA farms. *Agriculture, Ecosystems & Environment*, 309(107274).
<https://doi.org/https://doi.org/10.1016/j.agee.2020.107274>.
- Hirsh, S. M., & Weil, R. R. (2019). Deep soil cores reveal large end-of-season residual mineral nitrogen pool. *Agricultural & Environmental Letters*, 4(1), 180055.
<https://doi.org/https://doi.org/10.2134/acl2018.10.0055>
- Issac, R. A. (1983). *Reference soil test methods for the Southern Region of the United States* (Southern Cooperative Series Bulletin 289).
- Jordan, N., & Vatovec, C. (2004). Agroecological benefits from weeds. In *Weed Biology and Management* (pp. 137-158). Kluwer Academic Publishers.

- Kientzy, D., Milhollin, R., Ellis, C., & Massey, R. (2023). Understanding equipment management for planting cover crops. *Journal of Soil and Water Conservation*, 78(6), 113A-117A. <https://doi.org/10.2489/jswc.2023.0818A>
- Koehler-Cole, K., & Elmore, R. W. (2020). Seeding rates and productivity of broadcast interseeded cover crops. *Agronomy*, 10(11), 1723. <https://www.mdpi.com/2073-4395/10/11/1723>
- Kristensen, H. L., & Thorup-Kristensen, K. (2004). Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Science Society of America Journal*, 68(2), 529-537. <https://doi.org/https://doi.org/10.2136/sssaj2004.5290>
- Kühling, I., Mikuszies, P., Helfrich, M., Flessa, H., Schlathölter, M., Sieling, K., & Kage, H. (2023). Effects of winter cover crops from different functional groups on soil-plant nitrogen dynamics and silage maize yield. *European Journal of Agronomy*, 148. <https://doi.org/https://doi.org/10.1016/j.eja.2023.126878>
- Libbey, K., & Hernández, D. L. (2021). Depth profile of soil carbon and nitrogen accumulation over two decades in a prairie restoration experiment. *Ecosystems*, 24, 1348–1360. <https://doi.org/https://doi.org/10.1007/s10021-020-00588-3>
- Ledgard, S. F. (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, 228(1), 43-59. <https://doi.org/10.1023/A:1004810620983>
- Lotter, D. W., Seidel, R., & Liebhardt, W. (2003). The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture*, 18(3), 146–154. <https://doi.org/doi:10.1079/AJAA200345>

- Nleya, T., Chungu, C., & Kleinjan, J. (2019). Chapter 5: Corn growth and development. In *Corn best management practices*. South Dakota Board of Regents.
<https://extension.sdstate.edu/sites/default/files/2019-09/S-0003-05-Corn.pdf>
- Norris, R., Chim, B. K., Evanylo, G., Reiter, M., & Thomason, W. (2020). Corn yield and soil nitrogen following winter annual cover crops interseeded into soybean. *Crop Science*, *60*(5), 2667–2682. <https://doi.org/10.1002/csc2.20185>
- NRCS. (2015). Virginia NRCS plant establishment guide (PEG), Section Eb (cropland) cover crop establishment specifications (340). USDA. usda.gov, The U.S. Department of Agriculture 1–11.
- Marcillo, G. S., & Miguez, F. E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. *Journal of Soil and Water Conservation*, *72*(3), 226–239.
<https://doi.org/10.2489/jswc.72.3.226>
- Martinez-Feria, R., Dietzel, R., Liebman, M., Helmers, M., & Archontoulis, S. V. (2016). Rye cover crop effects on maize: A system-level analysis. *Field Crops Research*, *196*, 145–159. <https://doi.org/10.1016/j.fcr.2016.06.016>
- McCracken, D. V., Smith, M. S., Grove, J. H., MacKown, C. T., & Blevins, R. L. (1994). Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Science Society of America Journal*, *58*(5), 1476–1483.
- McLean, E. O. (1983). Soil pH and lime requirement. In A. L. Page (Ed.), *Methods of soil analysis: Part 2 chemical and microbiological properties* (2nd ed., Vol. 9, pp. 199–224). American Society of Agronomy and Soil Science Society of America.
<https://doi.org/10.2134/agronmonogr9.2.2ed.c12>
- Mehlich, A. (1953). Determination of P, Ca, Mg, K, Na, and NH₄.

- Mendiburu, F. d. (2023). agricolae: Statistical procedures for agricultural research. R package version 1.3-7. <https://CRAN.R-project.org/package=agricolae>
- Mirsky, S. B., Curran, W. S., Mortensen, D. M., Ryany, M. R., & Shumway, D. L. (2011). Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. *Weed Science*, *59*(3), 380–389. <https://doi.org/10.1614/WS-D-10-00101.1>
- Mirsky, S. B., Spargo, J. T., Curran, W. S., Reberg-Horton, S. C., Ryan, M. R., Schomberg, H. H., & Ackroyd, V. J. (2017). Characterizing cereal rye biomass and allometric relationships across a range of fall available nitrogen rates in the eastern United States. *Agronomy Journal*, *109*(4), 1520–1531. <https://doi.org/10.2134/agronj2016.09.0557>
- Moore, V. M., & Mirsky, S. B. (2020). Cover crop biomass production across establishment methods in mid-Atlantic corn. *Agronomy Journal*, *112*(6), 4765–4774. <https://doi.org/10.1002/agj2.20414>
- Nichols, V., English, L., Carlson, S., Gailans, S., & Liebman, M. (2020). Effects of long-term cover cropping on weed seedbanks. *Frontiers in Agronomy*, *2*. <https://doi.org/10.3389/fagro.2020.591091>
- Norris, R., Chim, B. K., Evanylo, G., Reiter, M., & Thomason, W. (2020). Corn yield and soil nitrogen following winter annual cover crops interseeded into soybean. *Crop Science*, *60*(5), 2667–2682. <https://doi.org/10.1002/csc2.20185>
- Okopi, S., Li, Y., & Xu, F. (2024). Biomass digestion. In M. A. Abraham (Ed.), *Encyclopedia of sustainable technologies* (Second Edition, pp. 236–251). Elsevier. <https://doi.org/10.1016/B978-0-323-90386-8.00051-6>

- Omara, P., Aula, L., Oyebiyi, F., & Raun, W. R. (2019). World cereal nitrogen use efficiency trends: Review and current knowledge. *Agrosystems, Geosciences & Environment*, 2(1), 180045. <https://doi.org/10.2134/age2018.10.0045>
- Patel, R. M., Prasher, S. O., & Broughto, R. S. (2001). Upward movement of leached nitrate with subirrigation. *American Society of Agricultural Engineers*, 44, 1521–1526.
- Pieters, A. J., & McKee, R. (1938). *Soils and men* (Vol. 1938). U.S. Department of Agriculture, National Agriculture Library.
- Pratt, R. C., Schutte, B. J., Idowu, O. J., Uchanski, M., & Grant, L. (2023). Fall-sown small grain cover crops for weed suppression and soil moisture management in an irrigated organic agroecosystem. *Renewable Agriculture and Food Systems*, 38, e1. <https://doi.org/10.1017/S174217052200028X>
- R Core Team. (2024). R: A language and environment for statistical computing. R Foundation for Statistical Computing. <https://www.R-project.org>
- Rawat, M., Sen, R., Onyekwelu, I., Wiederstein, T., & Sharda, V. (2022). Modeling of groundwater nitrate contamination due to agricultural activities—A systematic review. *Water*, 14(24), 4008.
- Ritter, W. F., Scarborough, R. W., & Chirnside, A. E. M. (1998). Winter cover crops as a best management practice for reducing nitrogen leaching. *Journal of Contaminant Hydrology*, 34, 1–15.
- Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems*, 33(4), 322–333. <https://doi.org/10.1017/S1742170517000096>

- Rouge, A., Adeux, G., Busset, H., Hugard, R., Martin, J., Matejicek, A., Moreau, D., Guillemain, J.-P., & Cordeau, S. (2023). Carry-over effects of cover crops on weeds and crop productivity in no-till systems. *Field Crops Research*, 295. <https://doi.org/10.1016/j.fcr.2023.108899>
- Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, 125, 12–22. <https://doi.org/10.1016/j.agsy.2013.11.004>
- Schulte, E. E., & Hopkins, B. G. (1996). Estimation of soil organic matter by weight loss-on-ignition. In F. R. Magdoff, M. A. Tabatabai, & E. A. Hanlon Jr. (Eds.), *Soil organic matter: Analysis and interpretation* (Special Publication No. 46, pp. 21–32). Soil Science Society of America.
- Soil Series Staff. (2002). *Official soil series descriptions*. Natural Resources Conservation Service, United States Department of Agriculture.
- Sievers, T., & Cook, R. L. (2018). Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Science Society of America Journal*, 82(1), 147–155. <https://doi.org/10.2136/sssaj2017.05.0139>
- Singh, G., Dhakal, M., Yang, L., Kaur, G., Williard, K. W. J., Schoonover, J. E., & Sadeghpour, A. (2020). Decomposition and nitrogen release of cover crops in reduced- and no-tillage systems. *Agronomy Journal*, 112(5), 3605–3618. <https://doi.org/10.1002/agj2.20268>
- Sedghi, N., Fox, R. J., Sherman, L., Gaudlip, C., & Weil, R. R. (2023). Aerial interseeding and planting green to enhance nitrogen capture and cover crop biomass carbon. *Journal of Soil and Water Conservation*, 78(3), 282–298. <https://doi.org/10.2489/jswc.2023.00051>

- Sedghi, N., & Weil, R. (2022). Fall cover crop nitrogen uptake drives reductions in winter-spring leaching. *Journal of Environmental Quality*, 51(1), 337–351.
<https://doi.org/10.1002/jeq2.20342>
- Souriol, B. F. A., & Henry, H. A. L. (2024). Short-versus long-term effects of nitrogen addition and warming on soil nitrogen mineralization and leaching in a grass-dominated old field. *Oecologia*, 205(1), 59-68. <https://doi.org/10.1007/s00442-024-05549-4>
- Snapp, S. S., & Surapur, S. (2018). Rye cover crop retains nitrogen and doesn't reduce corn yields. *Soil and Tillage Research*.
- Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal*, 97(1), 322-332.
<https://doi.org/https://doi.org/10.2134/agronj2005.0322a>
- Staver, K. W., & Brinsfield, R. B. (1998). Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. *Soil and Water Conservation*, 53(3), 230-240.
- Storer, D. A. (1984). "A Simple high sample volume ashing procedure for determining soil organic matter." *Commun. Soil Sci. Plant Anal.* 15: 759-772.
- Teasdale, J. R., Devine, T. E., Mosjidis, J. A., Bellinder, R. R., & Beste, C. E. (2004). Growth and development of hairy vetch cultivars in the Northeastern United States as influenced by planting and harvesting date. *Agronomy Journal*, 96(5), 1266-1271.
<https://doi.org/https://doi.org/10.2134/agronj2004.1266>

- Thapa, R., Mirsky, S. B., & Tully, K. L. (2018a). Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. *Journal of Environmental Quality*, 47(6), 1400-1411. <https://doi.org/10.2134/jeq2018.03.0107>
- Thapa, R., Poffenbarger, H., Tully, K. L., Ackroyd, V. J., Kramer, M., & Mirsky, S. B. (2018b). Biomass production and nitrogen accumulation by hairy vetch–cereal rye mixtures: A meta-analysis. *Agronomy Journal*, 110(4), 1197-1208. <https://doi.org/10.2134/agronj2017.09.0544>
- USDA-NRCS. (2015). Virginia Technical Note, Agronomy #10 , Virginia NRCS Cover Crop Planning Manual 1.0 chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf
- Wang, F., & Weil, R. (2018). The form and vertical distribution of soil nitrogen as affected by forage radish cover crop and residual side-dressed N fertilizer. *Soil Science*, 183(1). <https://doi.org/0.1097/SS.0000000000000224>
- Ward, B. (2008). Nitrification. In *Encyclopedia of ecology* / (pp. 2511–2518). *Elsevier*,. <https://doi.org/10.1016/B978-008045405-4.00280-9>
- Weisberger, D. A., Bastos, L. M., Sykes, V. R., & Basinger, N. T. (2023). Do cover crops suppress weeds in the U.S. Southeast? A meta-analysis. *Weed Science*, 71(3), 244–254. doi:10.1017/wsc.2023.21
- Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. <https://ggplot2.tidyverse.org>, Springer-Verlag New York.

- Wilson, M. L., Allan, D. L., & Baker, J. M. (2014). Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices. *Journal of Soil and Water Conservation*, 69(3), 67A-72A. <https://doi.org/10.2489/jswc.69.3.67A>
- Wofuru-Nyenke, O. K. (2023). Mechanized cover crop farming: Modern methods, equipment and technologies. *Circular Agriculture Systems*, 3(6).
<https://doi.org/https://doi.org/10.48130/CAS-2023-0006>
- Wortman, S. E., Francis, C. A., Bernards, M. L., Drijber, R. A., & Lindquist, J. L. (2012). Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal*, 104(5), 1425-1435.
<https://doi.org/https://doi.org/10.2134/agronj2012.0185>
- Yadav, S. N. (1997). Formulation and estimation of nitrate-nitrogen leaching from corn cultivation. *Journal of Environmental Quality*, 26(3), 808-814.
<https://doi.org/https://doi.org/10.2134/jeq1997.00472425002600030031x>
- Yang, T., Li, X., Hu, B., Li, F., Wei, D., Wang, Z., Huang, L., & Bao, W. (2023). Latitudinal patterns of soil nitrogen density across soil profiles and their driving factors in the arid valleys of southwest China. *Journal of Soils and Sediments*, 23, 2848–2861.
<https://doi.org/https://doi.org/10.1007/s11368-023-03513-y>
- Zablotowicz, R. M., Reddy, K. N., Krutz, L. J., Gordon, R. E., Jackson, R. E., & Price, L. D. (2011). Can leguminous cover crops partially replace nitrogen fertilization in Mississippi Delta cotton production? *International Journal of Agronomy*, Vol. 2011, 1-9.
<https://doi.org/doi:10.1155/2011/135097>

2.7 Figures and Tables

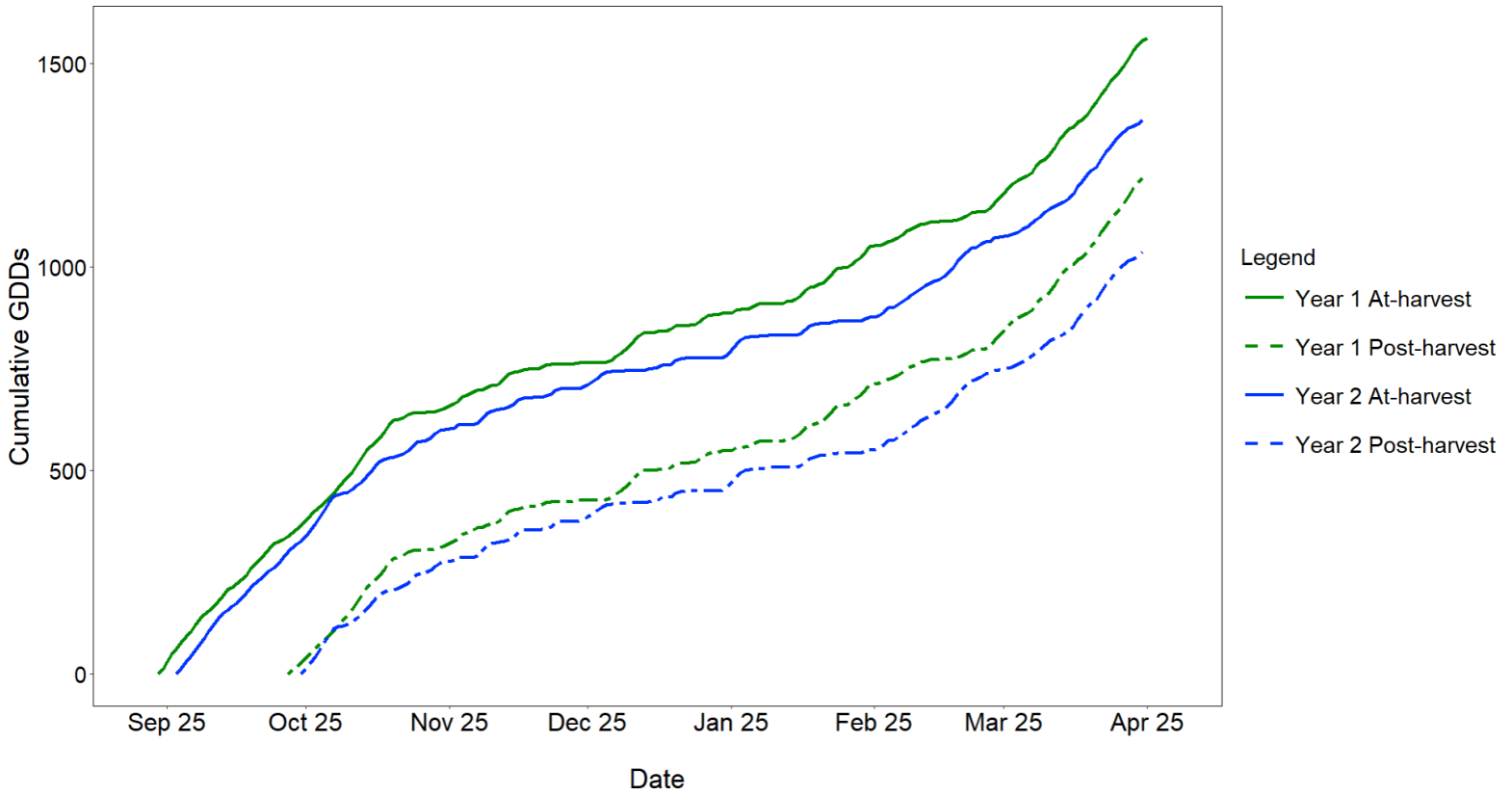


Figure 2.1 Cumulative cover crop growing degree days (GDDs) in a field trial conducted in Painter, VA in 2022-2024.

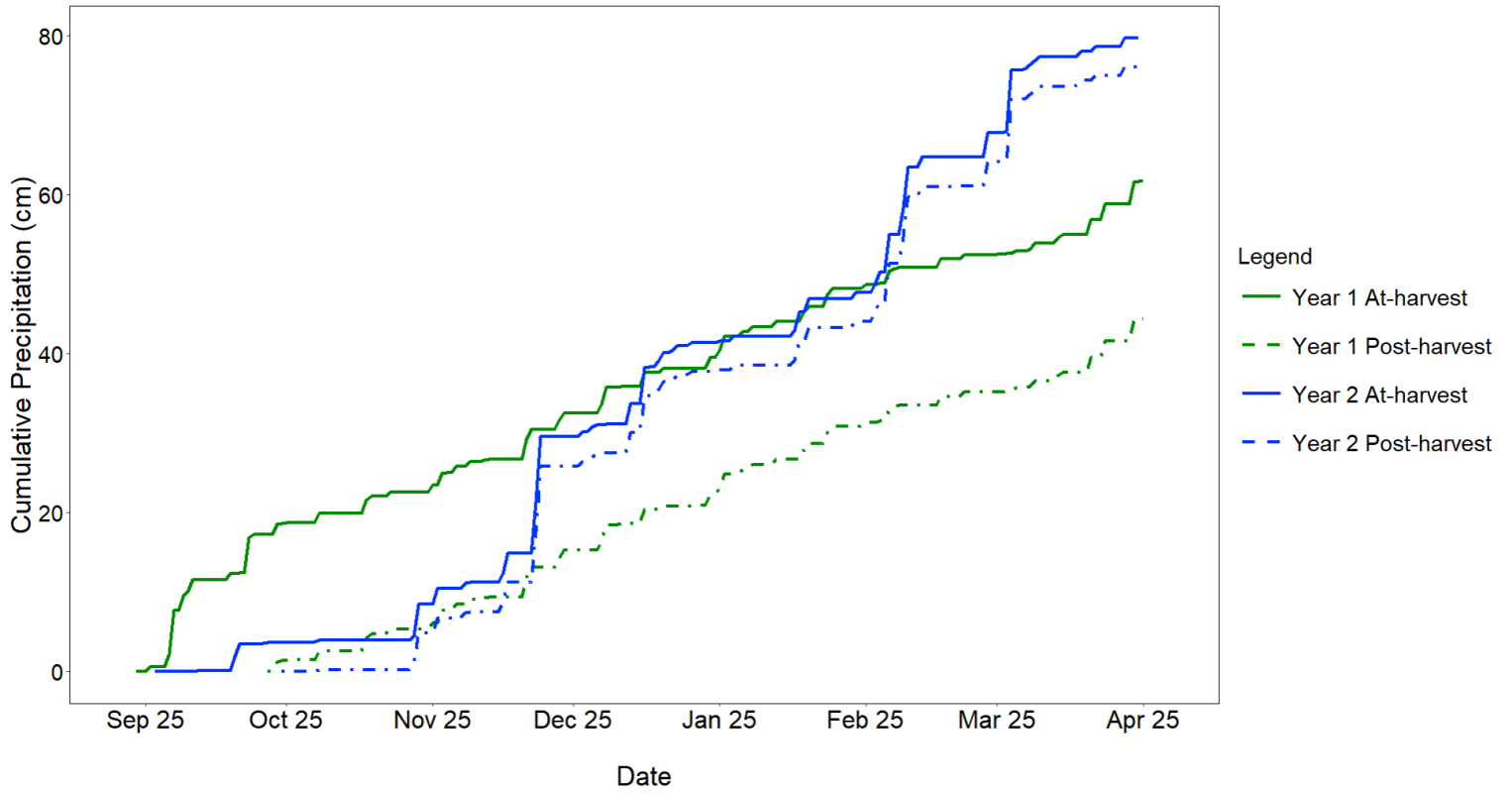


Figure 2.2 Monthly total precipitation (cm) during the cover crop growth period in a field trial conducted in Painter, VA in 2022-2024.

Table 2.1 Summary of cash crop and cover crop (CC) management practices and dates from September 2022 – September 2024.

Field Operation	Year 1	Year 2
At-harvest broadcasted CC planting	Sept. 23, 2022	Sept. 27, 2023
Corn harvest	Sept. 24, 2022	Sept. 28, 2023 & Oct. 10, 2024
At-harvest broadcasted CC incorporation	Sept. 27, 2022	Sept. 29, 2023
Post-harvest broadcasted CC planting	Oct. 21, 2022	Oct. 24, 2023
Post-harvest drilled CC planting	Oct. 21, 2022	Oct. 24, 2023
Background soil sampling	Oct. 21, 2022	-
Post-harvest CC incorporation	^a Oct. 31, 2022	Oct. 25, 2023
Fall soil sampling	Oct. 22, 2022	Nov. 7, 2023
Winter soil sampling	Jan. 5, 2023	Jan. 2, 2024
Winter biomass sampling	Jan. 4, 2023	Jan 3, 2024
Spring biomass sampling	Apr. 20, 2023	Apr. 23, 2024
CC termination	Apr. 25, 2023	Apr. 24, 2024
Corn planting	Apr. 26, 2023	^b Apr. 26, 2024 & May 17, 2024
Starter N application	May 5, 2023	May 5, 2024

^a Incorporation for late aerially seeded CC delayed due to miscommunication.

^b Initially planted corn on Apr. 26, 2024, replanted May 17, 2024, due to poor emergence.

Table 2.2 Winter cover crop (CC) treatment, functional group, species, and seeding rates planted in the Eastern Shore AREC small plot study for 2022-2024.

CC Treatment	Species	Broadcast Seeding Rate	Drill Seeding Rate
		kg ha ⁻¹	
Cereal rye	Cereal rye†	162.5	123.3
Hairy vetch	Hairy vetch	33.6	22.4
Rapeseed	Rapeseed	13.45	6.7
Mix	Cereal rye	40.4	33.3
	Hairy vetch	25.2	16.8
	Rapeseed	3.4	1.7

†Cereal rye (*Secale cereale*), Hairy vetch (*Vicia villosa*), Rapeseed (*Brassica napus*).

Table 2.3 Background soil physical and chemical properties for corn grown on sandy loam soil in Painter, VA on the Eastern Shore of Virginia in 2022.

Depth	pH	CEC	OM	Sand	Clay	Silt	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
cm		meq 100g ⁻¹	g kg ⁻¹			mg kg ⁻¹										
0-15	5.9	6.5	15.0	67.9	17.4	14.7	84.5	141.8	74.8	582.5	6.4	0.2	1.3	22.2	18.6	1.0
15-30	5.9	5.9	10.0	62.1	26.5	11.4	52.5	93.4	75.8	474.8	4.0	0.2	0.5	12.3	20.1	0.9
30-45	5.7	7.5	12.0	60.2	28.6	11.3	11.1	98.6	123.1	538.4	11.9	0.2	0.4	7.9	18.0	0.4
45-60	5.6	8.4	12.0	61.2	26.6	12.2	3.1	82.0	153.0	582.8	6.5	0.2	0.2	4.0	18.8	0.3
60-75	5.7	7.6	9.0	66.3	23.7	10.0	4.1	64.3	135.3	547.8	9.1	0.2	0.2	3.6	18.5	0.3
75-90	5.5	8.3	8.0	71.3	22.7	6.1	3.6	45.0	114.9	516.3	12.4	0.1	0.2	1.9	14.5	0.3
90-105	5.4	7.7	7.0	77.3	13.5	9.2	3.6	39.8	104.6	508.1	6.9	0.1	0.2	1.5	12.4	0.3
105-120	5.2	6.0	5.0	84.4	12.6	3.0	5.4	35.1	76.6	373.5	4.0	0.1	0.2	2.4	12.3	0.3

Table 2.4 Effect of depth, establishment method, cover crop species, and their interaction effects on soil nitrate concentrations across sampling dates on a sandy loam in Painter, VA.

		Year 1		Year 2	
		Fall	Winter	Fall	Winter
Depth (cm)		mg kg ⁻¹			
	0-15	9.1 a†	4.9 a	8.1‡	3.6 a
	15-30	7.1 b	2.3 b	3.0	1.7 b
	LSD _{0.05}	1.1	0.6	-	0.3
	<i>p</i> -value	0.001	<0.001	<0.001	<0.001
Establishment method (EM)					
	At-harvest incorporated (AHI)	8.98	2.9 b	3.9	2.6
	At-harvest not incorporated (AHNI)	7.0	3.5 b	3.8	2.5
	Post-harvest incorporated (PHI)	8.0	3.7 b	7.8	2.9
	Post-harvest drilled (PHD)	8.7	4.5 a	7.4	2.7
	LSD _{0.05}	-*	0.8	-	-
	<i>p</i> -value	0.082	0.003	<0.001	0.205
Cover Crop (CC)					
	Cereal rye	7.8	3.6	5.5	2.2
	Hairy vetch	7.7	3.4	6.1	3.0
	Rapeseed	8.6	4.0	5.4	2.9
	Mix	8.5	3.6	5.9	2.7
	LSD _{0.05}	-	-	-	-
	<i>p</i> -value	0.6124	0.585	0.288	<0.001
EM × Depth (cm)					
AHI	0-15	10.0	4.0	5.2 b	3.7
	15-30	7.8	1.8	2.6 cd	1.5
AHNI	0-15	8.1	5.1	5.2 b	3.5
	15-30	5.8	1.8	2.4 d	1.6
PHI	0-15	8.5	4.5	11.8 a	3.8
	15-30	7.6	2.8	3.7 c	2.0
PHD	0-15	9.8	6.1	11.4 a	3.6
	15-30	7.7	2.9	3.5 cd	1.7
	LSD _{0.05}	-	-	1.2	-
	<i>p</i> -value	0.803	0.139	<0.001	0.627
CC × EM					
Cereal rye	AHI	8.3 bc	3.1	3.1	1.7 f
	AHNI	7.5 c	3.8	3.1	2.5 de
	PHI	6.6 c	3.5	7.7	2.4 ef
	PHD	9.1 a-c	3.8	8.0	2.2 ef
Hairy vetch	AHI	6.5 c	2.7	4.9	3.2 a-c
	AHNI	7.2 c	3.4	4.4	2.5 c-e
	PHI	7.8 bc	3.7	7.8	2.8 a-e
	PHD	9.4 a-c	3.9	7.4	3.4 ab

Rapeseed	AHI	9.2 a-c	2.8	3.7	2.8 a-e
	AHNI	7.0 c	3.5	3.7	2.7 b-e
	PHI	10.8 ab	3.7	8.0	3.4 a
	PHD	7.5 c	5.8	6.2	2.7 b-e
Mix	AHI	11.6 a	3.1	3.9	2.7 a-e
	AHNI	6.3 c	3.3	4.0	2.5 de
	PHI	7.1 c	3.7	7.5	3.1 a-d
	PHD	8.9 a-c	4.5	8.1	2.4 de
LSD _{0.05}		3.2	-	-	0.7
<i>p</i> -value		0.037	0.639	0.403	0.043
Depth × CC		0.811	0.674	0.740	0.156
EM x depth × CC		0.995	0.467	0.853	0.266

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column followed by the same lowercase letter were not significantly different.

§Means within a column lacking a letter were not significantly different.

*Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

Note: No CC control mean was 7.4 mg kg⁻¹, 3.44 mg kg⁻¹, 4.1 mg kg⁻¹, 2.2 mg kg⁻¹ for EM + CC × depth interaction in October 2022, January 2023, November 2023, and January 2024, respectively.

Table 2.5 Effect of establishment method and cover crop (CC) species on Year 1 CC aboveground biomass and nitrogen (N) accumulation on a sandy loam in Painter, VA.

		Fall	Fall N	Spring	Spring N
		biomass	accumulation	biomass	accumulation
CC		kg ha ⁻¹			
	Cereal rye	542 a†	18‡	3899	57
	Hairy vetch	501 a	23	3641	152
	Rapeseed	248 b	10	1194	27
	Mix	629 a	26	4531	154
	LSD _{0.05}	167	-	-	-
	<i>p</i> -value	<0.001	<0.001	<0.001	<0.001
Establishment method					
	AHI	846 a	35	3849	117
	AHNI	721 a	30	4201	131
	PHI	134 b	5	1368	43
	PHD	200 b	8	3846	100
	LSD _{0.05}	167	-	-	-
	<i>p</i> -value	<0.001	<0.001	<0.001	<0.001
CC × Establishment method					
Cereal rye	AHI	844§	30 b-d	3459 bc	44 c-e
	AHNI	720	27 c-e	4469 ab	73 cd
	PHI	120	3 g	1597 ef	24 de
	PHD	385	15 e-g	6072 a	89 c
Hairy vetch	AHI	919	42 ab	4509 ab	190 ab
	AHNI	858	39 a-c	4853 ab	208 a
	PHI	166	7 g	1803 de	69 cd
	PHD	114	5 g	3398 b-d	143 b
Rapeseed	AHI	543	21 d-f	1947 c-e	41 c-e
	AHNI	313	13 e-g	1782 de	45 c-e
	PHI	83	3 g	0 f	0 e
	PHD	27	1 g	1049 ef	23 de
Mix	AHI	1079	46 a	5482 a	194 ab
	AHNI	995	43 ab	5702 a	199 a
	PHI	170	5 g	2073 c-e	78 c
	PHD	274	10 fg	4866 ab	144 b
	LSD _{0.05}	-‡	14	1636	53
	<i>p</i> -value	0.125	0.019	0.044	0.046

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column followed by the same lowercase letter were not significantly different.

§Means within a column lacking a letter were not significantly different.

‡Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡‡Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

Table 2.6 Effect of establishment method and cover crop (CC) species on Year 2 CC aboveground biomass and nitrogen (N) accumulation on a sandy loam in Painter, VA.

		Fall biomass	Fall N accumulation	Spring biomass	Spring N accumulation
CC		kg ha ⁻¹			
	Cereal rye	854†	19	4189	50 b
	Hairy vetch	772	34	874	175 a
	Rapeseed	501	11	5044	16 c
	Mix	1035	35	4186	175 a
	LSD _{0.05}	-§	-	-	16
	<i>p</i> -value	<0.001	<0.001	<0.001	<0.001
Establishment method					
	AHI	1295	43	3962	120 a
	AHNI	1039	34	3461	110 ab
	PHI	434	11	3076	99 bc
	PHD	394	9	2603	86 c
	LSD _{0.05}	-	-	-	16
	<i>p</i> -value	<0.001	<0.001	<0.001	<0.001
CC × Establishment method					
Cereal rye	AHI	939 c-f‡	19 cd	3322 ef	54‡
	AHNI	831 d-f	19 cd	3018 e-g	50
	PHI	859 d-f	19 cd	2833 fg	45
	PHD	789 d-f	19 cd	2817 fg	49
Hairy vetch	AHI	1654 a	73 a	4472 cd	188
	AHNI	1144 b-d	51 b	4806 bc	190
	PHI	193 gh	7 d-f	3648 d-f	157
	PHD	96 h	4 ef	3817 de	165
Rapeseed	AHI	1097 b-e	22 c	2211 g	39
	AHNI	833 d-f	19 cd	921 h	17
	PHI	73 h	3 ef	276 h	5
	PHD	0 h	0 f	90 h	2
Mix	AHI	1490 ab	59 b	5844 a	201
	AHNI	1350 a-c	49 b	5099 a-c	181
	PHI	611 fg	15 c-e	5549 ab	190
	PHD	691 ef	15 c-e	3687 d-f	126
	LSD _{0.05}	437	14	947	-
	<i>p</i> -value	0.001	<0.001	0.017	0.059

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

§Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column followed by the same lowercase letter were not significantly different.

‡Means within a column for lacking a letter were not significantly different.

Table 2.7 One-way ANOVA of Year 1 fall cover crop (CC) aboveground biomass, nitrogen (N) accumulation, C:N ratio, and percentage weeds within total including no CC control on a sandy loam in Painter, VA.

CC	Establishment method	CC biomass			Weed biomass			Total biomass					
		Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	Weed dry wt.	Weed N	
		_____ kg ha ⁻¹ _____			_____ kg ha ⁻¹ _____			_____ kg ha ⁻¹ _____				_____ % _____	
Cereal rye	AHI	844 a-c†	30 b-d	12 bc	1664*	35	16	2508 a	64 a-c	14 b-d	66	54	
	AHNI	720 bc	27 c-e	11 bc	879	21	15	1599 b-e	47 b-g	13 d-f	55	44	
	PHI	120 ef	3 g	14 a	1164	24	16	1284 c-e	27 gh	15 ab	91	88	
	PHD	385 de	15 e-g	11 c-e	1016	24	15	1400 c-e	39 e-h	13 c-f	73	62	
Hairy vetch	AHI	919 ab	42 ab	9 ef	842	21	16	1762 b-e	62 a-d	11 f	48	33	
	AHNI	858 a-c	39 a-c	9 f	860	20	15	1718 b-e	59 a-e	11 f	50	34	
	PHI	166 ef	7 g	10 d-f	1268	28	15	1434 c-e	35 f-h	14 b-d	88	80	
	PHD	114 ef	5 g	9 f	946	20	17	1060 e	25 gh	15 a-c	89	80	
Rapeseed	AHI	543 cd	21 d-f	11 cd	1415	33	16	1958 a-c	54 a-f	14 b-d	72	61	
	AHNI	313 d-f	13 e-g	10 def	1328	33	15	1640 b-e	46 b-g	14 b-e	81	72	
	PHI	83 ef	3 g	-§	1592	31	15	1675 b-e	34 f-h	15 a-d	95	90	
	PHD	27 f	1 g	9 f	1188	22	15	1215 de	23 h	15 a-d	98	94	
Mix	AHI	1079 a	46 a	10 d-f	1134	26	16	2213 ab	72 a	12 ef	51	36	
	AHNI	995 ab	43 ab	10 d-f	902	22	15	1897 a-d	65 ab	12 f	48	34	
	PHI	170 ef	5 g	12 b	1014	20	17	1184 de	25 gh	16 a	86	80	
	PHD	274 d-f	10 fg	11 c-e	1258	33	15	1533 b-e	43 c-h	14 b-e	82	77	
Control		-	-	-	1515	41	14	1515 b-e	41 d-h	14 a-d	100	100	
LSD _{0.05}		334	14	1	-‡	-	-	739	22	2			
<i>p</i> -value		<0.001	<0.001	<0.001	0.132	0.167	0.715	0.026	<0.001	<0.001			

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled; wt., weight.

†Means within a column lacking a letter were not significantly different.

§Due to the PHI rapeseed treatment only having biomass in one replication, the treatment was dropped from C:N analysis.

*Means within a column followed by the same lowercase letter were not significantly different.

‡Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

Table 2.8 One-way ANOVA of Year 2 fall cover crop (CC) aboveground biomass, nitrogen (N) accumulation, C:N ratio, and percentage weeds within total including no CC control on a sandy loam in Painter, VA.

	Establishment method	CC Biomass			Weed Biomass			Total Biomass				
		Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	Weed dry wt.	Weed N
CC		— kg ha ⁻¹ —			— kg ha ⁻¹ —			— kg ha ⁻¹ —			— % —	
Cereal rye	AHI	939 c-f†	19 cd	20 a	342 d	7 ef	20*	1280	26 c	20 ab	27	25
	AHNI	831 d-f	19 cd	19 ab	370 d	6 f	20	1201	25 c	19 ab	31	25
	PHI	859 d-f	19 cd	16 c-e	705 cd	10 d-f	17	1564	29 c	16 cd	45	33
	PHD	789 d-f	19 cd	16 cd	830 b-d	15 d-f	18	1618	33 c	18 a-c	51	44
Hairy vetch	AHI	1654 a	73 a	10 g	1026 b-d	22 b-d	18	2680	95 a	12 f	38	23
	AHNI	1144 b-d	51 b	10 fg	1013 b-d	22 b-d	21	2156	73 b	13 ef	47	30
	PHI	193 gh	7 d-f	11 fg	2154 a	31 ab	19	2346	38 c	16 cd	92	81
	PHD	96 h	4 ef	11 fg	1533 a-c	29 a-c	21	1628	32 c	18 a-c	94	88
Rapeseed	AHI	1097 b-e	22 c	17 bc	931 b-d	17 c-f	19	2028	38 c	17 a-c	46	44
	AHNI	833 d-f	19 cd	18 ab	1395 a-c	20 b-e	18	2228	39 c	20 ab	63	52
	PHI	73 h	3 ef	11 fg	1673 ab	22 b-d	18	1746	25 c	17 bc	96	88
	PHD	0 h	0 f	- δ	2107 a	37 a	18	2107	37 c	20 ab	100	100
Mix	AHI	1490 ab	59 b	11 fg	831 b-d	16 c-f	16	2321	75 b	13 ef	36	22
	AHNI	1350 a-c	49 b	12 f	760 b-d	14 d-f	20	2110	63 b	13 d-f	36	22
	PHI	611 fg	15 c-e	14 e	784 b-d	11 d-f	19	1394	26 c	15 c-e	56	42
	PHD	691 ef	15 c-e	15 de	1052 b-d	16 c-f	20	1742	31 c	18 a-c	60	51
Control		-	-	-	2309 a	39 a	18	2308	39 c	20 a	100	100
LSD _{0.05}		437	14	2	955	14	- \ddagger	-	17	3		
p-value		<0.001	<0.001	<0.001	<0.001	<0.001	0.256	0.068	<0.001	<0.001		

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled; wt., weight.

†Means within a column followed by the same lowercase letter were not significantly different.

δ Due to the PHD rapeseed treatment only having biomass in one replication, the treatment was dropped from C:N analysis.

*Means within a column lacking a letter were not significantly different.

\ddagger Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

Table 2.9 One-way ANOVA of Year 1 spring cover crop (CC) aboveground biomass, nitrogen (N) accumulation, C:N ratio, and percentage weeds within total including no CC control on a sandy loam in Painter, VA.

CC	Establishment method	CC Biomass			Weed Biomass			Total Biomass				
		Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	Weed dry wt.	Weed N
		kg ha ⁻¹			kg ha ⁻¹			kg ha ⁻¹			%	
Cereal rye	AHI	3459 cd†	44 c-e	35 a	1216 fg	18 e-g	30 a	4675 b-g	62 d	34 a	26	29
	AHNI	4469 bc	73 cd	29 b	2640 cd	41 b-e	27 a-d	7109 a	114 cd	28 bc	37	36
	PHI	1597 e	24 de	30 b	2307 c-f	40 b-e	25 a-e	3904 e-g	63 d	27 cd	59	63
	PHD	6072 a	89 c	31 ab	541 g	8 g	29 ab	6613 ab	97 d	31 ab	8	8
Hairy vetch	AHI	4509 a-c	190 ab	10 g	1376 e-g	34 c-f	17 h	5884 a-e	224 ab	11 j	23	15
	AHNI	4853 a-c	208 a	10 g	1162 fg	25 d-g	18 gh	6015 a-d	233 a	11 j	19	11
	PHI	1803 e	69 cd	12 fg	1290 e-g	23 d-g	24 b-e	3093 g	92 d	15 g-j	42	25
	PHD	3398 cd	143 b	10 g	1297 e-g	24 d-g	22 d-h	4695 b-g	167 bc	12 ij	28	14
Rapeseed	AHI	1947 de	41 c-e	21 c	2521 c-e	43 b-d	25 a-e	4468 c-g	84 d	23 de	56	51
	AHNI	1782 e	45 c-e	17 de	2419 c-f	56 a-c	20 e-h	4200 d-g	101 d	19 fg	58	56
	PHI	0 f	0 e	-§	3003 bc	59 ab	23 d-g	3003 g	59 d	23 ef	100	100
	PHD	1049 ef	23 de	19 cd	4488 a	71 a	28 a-c	5536 a-f	95 d	26 c-e	81	75
Mix	AHI	5482 ab	194 ab	13 e-g	1174 fg	24 d-g	21 e-h	6656 ab	218 ab	14 h-j	18	11
	AHNI	5702 ab	199 a	13 fg	649 g	15 fg	18 f-h	6351 a-c	213 ab	13 h-j	10	7
	PHI	2073 de	78 c	15 d-f	1575 d-g	27 d-g	25 a-e	3648 fg	105 d	16 gh	43	26
	PHD	4866 a-c	144 b	35 a	1242 fg	26 d-g	21 e-h	6108 a-d	170 bc	16 g-i	20	15
Control		-	-	-	4202 ab	78 a	23 c-f	4202 d-g	78 d	23 de	100	100
LSD _{0.05}		1588	53	4	1260	25	5	1988	58	4		
<i>p</i> -value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHD, post-harvest drilled; PHI, post-harvest incorporated; wt., weight.

†Means within a column lacking a letter were not significantly different.

§Due to the PHI rapeseed treatment having no biomass, the treatment was dropped from C:N analysis.

Table 2.10 One-way ANOVA of Year 2 spring cover crop (CC) aboveground biomass, nitrogen (N) accumulation, C:N ratio, and percent weeds within total including no CC control on a sandy loam in Painter, VA.

CC	Establishment method	CC Biomass			Weed Biomass			Total Biomass				
		Dry wt. kg ha ⁻¹	N	C:N	Dry wt. kg ha ⁻¹	N	C:N	Dry wt. kg ha ⁻¹	N	C:N	Weed dry wt. %	Weed N
Cereal rye	AHI	3322 ef	54 e	28 a	522 cd	23 c-e	10 e	3843 b-e	77 gh	23 a	14	30
	AHNI	3018 e-g	50 e	27 ab	947 b-d	41 cd	11 e	3964 b-e	91 f-h	20 a	24	45
	PHI	2833 fg	45 ef	29 a	737 b-d	31 c-e	17 c-e	3570 c-e	76 gh	23 a	21	40
	PHD	2817 fg	49 e	26 a-c	574 cd	24 c-e	15 c-e	3391 de	74 gh	21 a	17	33
Hairy vetch	AHI	4472 cd	188 a-c	10 e	89 d	2 e	16 c-e	4561 a-d	191 ab	10 e	2	1
	AHNI	4806 bc	190 ab	11 e	57 d	2 e	16 c-e	4863 a-c	192 ab	11 e	1	1
	PHI	3648 d-f	157 cd	10 e	199 d	4 e	20 a-c	3846 b-e	161 a-d	11 e	5	2
	PHD	3817 de	165 bc	10 e	266 d	7 de	18 b-d	4083 b-d	171 a-c	10 e	7	4
Rapeseed	AHI	2211 g	39 ef	25 b-d	1383 bc	47 c	15 c-e	3593 c-e	85 f-h	20 ab	38	55
	AHNI	921 h	17 fg	25 b-d	2800 a	98 b	15 c-e	3721 c-e	115 d-g	16 bc	75	85
	PHI	276 h	5 g	24 cd	1731 ab	56 c	14 c-e	2007 f	61 h	15 cd	86	92
	PHD	90 h	2 g	23 d	2676 a	95 b	12 de	2766 ef	97 e-h	13 c-e	97	98
Mix	AHI	5844 a	201 a	13 e	4 d	0 e	-§	5848 a	201 a	13 c-e	0	0
	AHNI	5099 a-c	181 a-c	12 e	53 d	1 e	15 c-e	5152 ab	182 ab	12 c-e	1	1
	PHI	5549 ab	190 ab	13 e	66 d	1 e	25 a	5614 a	191 ab	13 c-e	1	1
	PHD	3687 d-f	126 d	13 e	1426 bc	5 e	24 ab	5112 ab	131 c-f	13 c-e	28	4
Control	-	-	-	2656 a	144 a	12 de	2656 ef	144 b-e	12 de		100	100
LSD _{0.05}	947	32	3	1101	35	7	1314	48	4			
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001		

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled; wt., weight.

†Means within a column followed by the same lowercase letter were not significantly different.

§Due to the AHI Mix treatment not having weed biomass, the treatment was dropped from C:N analysis.

Table 2.11 Effect of establishment method and cover crop (CC) species on nitrogen (N) concentration in corn crop following CC treatments at V5 and R1 on a sandy loam in Painter, VA.

CC	Year 1		Year 2	
	V5	R1	V5	R1
	g N kg plant tissue ⁻¹			
Cereal rye	47.1 a†	30.0§	27.5	29.9
Hairy vetch	50.5 a	29.1	27.9	29.4
Rapeseed	46.8 b	28.5	28.5	29.6
Mix	50.0 a	29.8	27.6	29.5
LSD _{0.05}	0.3	-	-	-
<i>p</i> -value	0.011	0.650	0.720	0.868
Establishment method				
AHI	50.0 ab	29.5	28.3	29.5
AHNI	50.4 a	29.3	28.7	30.3
PHI	46.8 bc	29.0	26.6	29.1
PHD	47.4 c	29.8	27.9	29.5
LSD _{0.05}	0.3	-‡	-	-
<i>p</i> -value	0.018	0.950	0.128	0.247
CC × Establishment method	0.114	0.227	0.977	0.985

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column followed by the same lowercase letter were not significantly different.

§Means within a column lacking a letter were not significantly different.

‡Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

Note: tissue samples were collected from the first true leaf at V5 and corn ear leaf at R1.

Table 2.12 One-way ANOVA of corn yield including no cover crop (CC) control over two years on a sandy loam in Painter, VA.

		Year 1	Year 2
		Yield	
CC	Establishment Method	kg ha ⁻¹	
Cereal rye	AHI	8143 fg†	8376 cd
	AHNI	8263 fg	8157 d
	PHI	8310 e-g	8430 cd
	PHD	7893 g	9035 b-d
Hairy vetch	AHI	11021 a-c	10476 a
	AHNI	11382 ab	9766 ab
	PHI	9849 b-e	10006 ab
	PHD	10113 a-d	9595 a-c
Rapeseed	AHI	7792 g	8376 cd
	AHNI	7850 g	8157 b-d
	PHI	9817 c-e	8430 ab
	PHD	8067 fg	9035 b-d
Mix	AHI	11586 a	8940 b-d
	AHNI	9485 c-f	9910 ab
	PHI	9585 c-f	9786 ab
	PHD	9249 d-g	9516 a-c
Control		8894 d-g	9435 a-c
LSD _{0.05}		1543	1102
<i>p</i> -value		<0.001	0.009

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column for each treatment lacking a letter were not significantly different.

Table 2.13 Effects of establishment method and cover crop (CC) species on corn yield over two years on a sandy loam in Painter, VA.

		Year 1	Year 2
		Yield	
CC		kg ha ⁻¹	
	Cereal rye	8152†	8499 c
	Hairy vetch	10591	9961 a
	Rapeseed	8381	9011 bc
	Mix	9976	9538 ab
LSD _{0.05}		-8	828
<i>p</i> -value		<0.001	<0.001
Establishment method			
	AHI	9635‡	9043
	AHNI	9245	9205
	PHI	9390	9485
	PHD	8830	9276
LSD _{0.05}		-	-
<i>p</i> -value		0.218	0.531
CC × Establishment method			
Cereal rye	AHI	8143 fg‡	8376
	AHNI	8263 fg	8157
	PHI	8310 e-g	8430
	PHD	7893 g	9035
Hairy vetch	AHI	11021 a-c	10476
	AHNI	11382 ab	9766
	PHI	9849 b-e	10006
	PHD	10113 a-d	9595
Rapeseed	AHI	7792 g	8379
	AHNI	7850 g	8988
	PHI	9817 c-e	9718
	PHD	8067 fg	8960
Mix	AHI	11586 a	8940
	AHNI	9485 c-f	9910
	PHI	9585 c-f	9786
	PHD	9249 d-g	9516
LSD _{0.05}		1551	-
<i>p</i> -value		0.021	0.329

Abbreviations: AHI, at-harvest incorporated; AHNI, at-harvest not incorporated; PHI, post-harvest incorporated; PHD, post-harvest drilled.

†Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

§Dashes indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column lacking a letter were not significantly different.

‡‡Means within a column followed by the same lowercase letter were not significantly different.

3. New Technologies for an Old Solution: Utilizing a Combine-Mounted Cover Crop Seeder in a Corn-Soybean Rotation in the Mid-Atlantic Region

3.1 Abstract

Fall nitrate leaching is common after corn and soybean harvests, but well-established cover crops (CCs) offer an effective mitigation strategy. Many Mid-Atlantic farmers are challenged with limited time to establish CCs before winter, particularly after soybean harvest. Combine-mounted seeders provide a potential solution by enabling CC seeding at cash crop harvest. This study evaluated a combine-mounted seeder's effectiveness compared to drilling CCs 2-4 weeks post-harvest regarding CC biomass production and CC nitrogen (N) accumulation and examined need for CC seed incorporation after broadcasting. Cover crop treatments included cereal rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), a mix of both, and a no CC control. Results from one year demonstrated that the combine-mounted seeder produced equal or greater biomass and N accumulation compared to post-harvest drilling. After corn, there was a tenfold increase in fall biomass (1116 to 1314 kg ha⁻¹) compared to post-harvest drilled treatments (205 kg ha⁻¹), and a doubling of spring biomass (5867 to 6323 kg ha⁻¹ vs. 2345 kg ha⁻¹, respectively). Incorporated treatments after corn compared to non-incorporated treatments were not significantly different regarding biomass and N accumulation. Even under drought conditions, broadcasting at soybean harvest produced comparable results to drilling, with no statistical difference in establishment method. Findings suggested that combine-mounted

seeders can enhance N management and improve efficiency for growers by enabling earlier CC establishment. However, further multi-year research is needed to confirm these benefits.

3.2 Introduction

Winter CCs provide a wide range of agronomic and environmental advantages, such as nitrogen (N) scavenging, weed suppression, reduced fertilizer needs for subsequent crops, moisture retention, and enhanced soil stability for erosion control (Blanco-Canqui, 2018; Sedghi & Weil, 2022; Snapp et al., 2005). Research indicated that ancient civilizations used CCs, demonstrating their long-term role in improving soil fertility and crop growth (Groff, 2015). In the Chesapeake Bay region, cover cropping is critical for meeting Total Maximum Daily Load (TMDL) targets aimed at reducing nutrient and sediment pollution (EPA, 2010). Corn production, which receives the bulk of N fertilizer in the U.S., carries a higher potential for N leaching once plants begin to senesce, compared to other crops (Morris et al., 2018). Although discussions often focus on corn, research suggested that nitrate leaching from soybean fields can be equally or more significant, especially in corn-soybean rotations (Blanco-Canqui, 2018; Hirsh & Weil, 2019; Staver & Brinsfield, 1998).

Research demonstrated that CCs effectively reduce N leaching in both corn and soybean systems (Schipanski et al., 2014; Kasper et al., 2001). To support these efforts, Virginia has set an ambitious goal to cover approximately 70% of cropland with CCs (Virginia Department of Environmental Quality, 2024), and the state's General Assembly authorized record-high cost-share funding in 2022 to facilitate adoption (Virginia Department of Conservation and Recreation, 2024).

However, many Virginia farmers, especially those managing soybean fields, face time constraints in planting CCs, limiting the extent of adoption (Innovative Roundtable farmer participants, personal communication, 2022). Climate change related weather patterns, such as increased hurricanes and tropical storms, exacerbate this challenge by pushing cash crop harvests sometimes into late November or early December, further shortening the planting window. A 2017 national survey identified poor establishment as a primary barrier to widespread cover crop adoption, showing the issue extends beyond Virginia (Wayman et al., 2017).

Planting CCs with a drill ensures proper seed placement but often delays planting until after harvest, which can compromise stand quality (Kientzy et al., 2023; Wofuru-Nyenke, 2023). To address poor stand quality, broadcasting or aerial seeding CCs before summer cash crop harvest is being explored as a strategy to maximize early CC growth (Dean & Weil, 2009; Thapa et al., 2018). Although broadcasting and aerial methods carry risks, such as seed predation and reliance on rainfall for germination (Koehler-Cole & Elmore, 2020), they offer the potential for improved biomass production and N content increases if grown with favorable conditions (Moore & Mirsky, 2020; Sedghi et al., 2023).

Combine-mounted seeders are one way of broadcasting CCs, enhancing seed coverage with chaff to improve germination while reducing the need for additional field operations. Though a recently emerging solution for earlier planting, combine-mounted seeders show promise for reducing soil compaction and labor costs (Bechman, 2021; Practical Farmers of Iowa, 2023). However, more research is needed to assess the comparative effectiveness of combine-mounted CC seeders to drilling, particularly in Virginia and the broader mid-Atlantic region.

This study aims to (1) evaluate whether the use of a combine-mounted CC seeder can achieve biomass production and N accumulation comparable to post-harvest drilling after both corn and soybean; (2) assess whether incorporating seed into the soil is necessary when using a combine-mounted seeder at corn harvest; and (3) which combination of CC species and establishment method is most effective at biomass production in a no-till corn-soybean rotation.

3.3 Materials and Methods

3.3.1 Experimental location

This study was conducted in 2023-2024 as the first of a two-year study on a farmer-cooperator's farm (N.S. Farms LLC) in Charles City, Virginia. Multiple fields were used for the experiment, one following corn and two following soybeans. All fields have been no-till for 15 years, primarily in a corn-soybean rotation.

3.3.2 Site Description and Experimental Design Following Corn

Plots following corn were established on a 5.5 ha study area (37°27' N lat, 77°07' W long) mapped as 63.2% Altavista fine sandy loam, 0% to 3% slopes. Altavista soils are fine-loamy, mixed, semiactive, thermic Aquic Hapludults. The rest of the field is occupied with 19.8% Pamunkey loam (fine-loamy, mixed, semiactive, thermic Ultic Hapludalfs), 10.6% Augusta sandy loam (fine-loamy, mixed, semiactive, thermic Aeric Endoaquults), and 6.4% Craven-Remlik complex. Craven soils are fine, mixed, subactive, thermic Aquic Hapludults and Remlik soils are loamy, siliceous, subactive, thermic Arenic Hapludults (Soil Series Staff, 2002).

Treatments were arranged in a split-plot design within a randomized complete block layout with four replications. Each plot measured 14 m wide by 61 m long. Main plot treatments

consisted of four CC species, while sub-plot treatments were three planting methods, randomly assigned within each main plot. The four CC treatments were: (1) cereal rye (*Secale cereale* L.), (2) hairy vetch (*Vicia villosa* Roth), (3) a mix of cereal rye and hairy vetch, and (4) no CC control. These CCs were selected as they represent common winter CCs used by Virginia producers. The three methods for establishing CCs were: (1) combine seeded CCs with incorporation (CSI), (2) combine seeded CCs with no incorporation (CSNI), and (3) drilled CCs 4 weeks post corn harvest (PHD). The 4-week delay reflects the average time local farmers need to return to the field to plant CCs after corn.

3.3.3 *Site Description and Experimental Design Following Soybean*

Due to the limited availability of large uniform fields on-farm, plots following soybean were split between two fields, each field having two replications. Replications one and two were established on a 2 ha study area (37°25' N lat, 77°08' W long) mapped as 43.3% Craven-Caroline complex, 2% to 6% slopes, 37.9% Craven clay loam, 6% to 10% slopes, and 18.8% Slagle-Emporia complex, 2% to 6% slopes. Caroline soils are fine, mixed, subactive, thermic Typic Paleudults. Slagle soils are fine-loamy, siliceous, subactive, thermic Aquic Hapludults and Emporia soils are fine-loamy, siliceous, subactive, thermic Typic Hapludults. Replications three and four were established on a 2-ha study area (37°25' N, 77°09' W) mapped as Craven loam, 2% to 6% slopes (Soil Series Staff, 2002).

Treatments followed a similar split-plot design as after-corn treatments, with plot sizes of 15 m wide by 46 m long. Whole plot treatments used the same cover crop (CC) species as after-corn treatments, while subplots consisted of two CC establishment methods: (1) combine-seeded CCs without incorporation (CSNI) and (2) drilled CCs, planted two weeks after soybean harvest

(PHD). The two-week delay aligns with local farmers' average time to return for CC planting after soybeans. Due to the limited field size after soybeans, a treatment incorporating CCs after combine seeding was not feasible.

3.3.4 Weather Data

Hourly weather data for each field's specific latitude and longitude were obtained through the Precision Sustainable Agriculture (PSA) project's Application Programming Interface (API) (Kucek et al., 2024; Thapa et al., 2022) via <https://api.precisionsustainableag.org/weather/>. This API aggregates data from the North American Land Data Assimilation System Phase-2 (NLDAS-2) (Xia et al., 2012) and the Multi-Radar Multi-Sensor System (MRMS) for rainfall (Zhang et al., 2016). Using R packages *dplyr* (Wickham et al., 2020) and *dbplyr* (Wickham & Ruiz, 2020), hourly data were processed to calculate daily rainfall and mean air temperature. Growing degree days (GDDs) were computed for each cover crop planting date using the formula:

$$GDD = \frac{(T_{max,40} + T_{min})}{2} - T_{base}$$

Where, $T_{max,40}$ is the maximum daily temperature, limited to 40 °C, T_{min} is the daily minimum, and T_{base} is 4 °C (Mirsky et al., 2017; Teasdale et al., 2004).

3.3.5 Background Soil

Before the field trial, background soil samples were collected from all three fields at 15 cm intervals from depths of 0 to 60 cm (Table 3.3, Table 3.4) using a stainless-steel probe with a 2.86 cm diameter. Four cores per replicate at each depth were combined for homogenization. Mixed samples were dried in a forced-air system for 5–10 days. Once dried, soil was sieved

through a 2 mm mesh in preparation for chemical analysis. Waters Agricultural Laboratories (Camilla, GA) performed the analyses, assessing soil pH (1:1 in water), cation exchange capacity (CEC), organic matter content, and Mehlich 1 extractable nutrients (Issac, 1983; McLean, 1983; Mehlich, 1953; Schulte & Hopkins, 1996; Storer, 1984). Mehlich 1 extracts were analyzed using an inductively coupled plasma-atomic emission spectrometer (ICP-AES) (Issac, 1983). Organic matter was measured through the loss-on-ignition method (Storer, 1984; Schulte & Hopkins, 1996), while soil texture at all depths was determined by the hydrometer method (Bouyoucos, 1936; Day, 1965).

3.3.6 Cover Crop Seeding

Cover crop, corn, and soybean planting dates can be seen in Table 3.1. A combine-mounted CC seeder engineered by N.S. Farms was attached to a combine for treatments planted at corn and soybean harvest (Model 9760 STS, John Deere Manufacturing, Moline, IL). As the combine harvests cash crops, the CC seed drops from the hopper in a single gravity tube with an electronic flow meter onto the spreader, mixes with chaff and broadcasts the mixture out the combine's rear. The chain powered by the hydraulic motor can be calibrated for differing seeding rates. After CC seed calibration, technology within the cab allows for accurate seeding rates as the combine moves through the field by monitoring the flow meter on the yield monitor. Seeding rates for single varieties and mix calculations are shown in Table 3.2. To load the seeder, a gas-powered vacuum tube blows the seed from ground level to the hopper behind the combine's engine. Following corn, fields were mowed using a rotary cutter. Incorporation in this experiment was done by a Turbo-Till (Great Plains Ag, Saline, KS). All drilled treatments used a no-till drill (Model 750, John Deere Manufacturing, Moline, IL).

3.3.7 *Cover Crop Biomass Collection, Processing, and Termination*

Aboveground CC biomass was sampled by collecting all living plant material from two randomly placed 0.25 m² quadrats per plot, combined into a single 0.5 m² sample. Weed biomass was separated from CC biomass in the field. Samples were immediately dried at 55°C until reaching a constant weight. Biomass collections were made in both winter and spring (Table 3.1). Once dried, biomass was weighed, then ground to pass a 1 mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Both CC and weed biomass samples were then weighed to 30 mg and analyzed for total carbon (C) and N via combustion (Bremner, 1996) using a Vario EL cube elemental analyzer (Elementar Americas Inc., New York). C:N ratio was calculated by dividing total C concentration by total N concentration. Nutrient accumulation in CCs was determined by multiplying tissue nutrient percentage by dry biomass (kg ha⁻¹). Total biomass and nutrient content for each treatment were calculated by summing CC and weed biomass. CCs were chemically terminated right after corn planting, using 1471 g ae ha⁻¹ of glyphosate, 451 g ai ha⁻¹ of glufosinate, 392 g ae ha⁻¹ of 2,4-D, 1008 g ai ha⁻¹ of acetochlor and 672 g ai ha⁻¹ of atrazine. Just prior to soybean planting, CCs were chemically terminated using 1471 g ae ha⁻¹ of glyphosate, 657 g ai ha⁻¹ of glufosinate, 314 g ai ha⁻¹ paraquat dichloride, 70 g ai ha⁻¹ of flumioxazin and 89 g ai ha⁻¹ of pyroxasulfone.

3.3.8 *Corn Planting, Collection, Processing, and Harvest*

Corn variety FS 6818V RIB, with a relative maturity of 118 days, was planted in the two fields that previously had soybeans (Table 3.1). Planting was done in 76 cm rows using a twelve-row planter (Model 1760, John Deere Manufacturing, Moline, IL) equipped with Precision Planting row units, at a seeding rate of 74,132 plants ha⁻¹. Corn received 59 kg N ha⁻¹, 30 kg P

ha⁻¹, 2.7 kg S ha⁻¹, 0.28 kg B ha⁻¹, and 1.0 kg Zn ha⁻¹ on the same day. Corn was sidedressed with 112 kg N ha⁻¹ through 76 cm drop tubes on June 15, 2024. Corn ear leaf was randomly collected from 20 plants per plot at R1. Corn tissue analysis followed the same procedures as CC biomass analysis.

3.3.9 Soybean Planting, Collection, Processing, and Harvest

Soybean variety S45ES10 (4.5 relative maturity, DYNAGRO Seed) was planted in the field that previously had corn (Table 3.1). Planting was done in 76 cm rows using a twelve-row planter (Model 1760, John Deere Manufacturing, Moline, IL) equipped with Precision Planting row units, at a seeding rate of 308,881 plants ha⁻¹. Soybeans received 12 kg N ha⁻¹, 58 kg P ha⁻¹, 112 kg K ha⁻¹ on May 05, 2024. The top trifoliolate leaf was collected from 30 plants at R3, to assess N accumulation at peak requirement stage (Harper, 1974). Soybean tissue analysis followed the same procedures as CC biomass analysis.

3.3.10 Statistical Analysis

Statistical analyses were performed using R version 4.4.1 (R Core Team, 2024). All significance was determined at alpha < 0.05. A split-plot ANOVA was conducted to evaluate cover crop species and treatment effects on biomass production using the `sp.plot()` function in R. CC species was considered the main plot factor, establishment method the subplot factor, and biomass, N accumulation or N tissue content the response variable. The model accounted for variability within and between replicates and was structured to appropriately test the main plot and subplot effects, as well as the interaction. If applicable, post-hoc comparisons were conducted using Fisher's Least Significant Difference (LSD) test to identify which groups

differed using the `LSD.test()` function in the *agricolae* package (Mendiburu, 2023). Graphical data visualizations were created using the *ggplot2* package (Wickham, 2016).

3.4 Results and Discussion

3.4.1 *Environmental Factors and Background Soil*

Cumulative GDDs and total precipitation were analyzed for the CC growing season (Figures 3.1, 3.2). A notable difference in precipitation occurred between at-harvest and post-harvest planting dates after corn, with 10.0 cm more rainfall for at-harvest plantings compared to those planted 4 weeks later. In contrast, the difference following soybean was only 1.3 cm within the 2 weeks. A moderate month-long drought from mid-October to mid-November weakened germination and establishment of all treatments planted after October 16th, including drilled treatments after soybean (United States Drought Monitor, 2024). Delayed post-harvest planting dates resulted in 407 fewer GDDs after corn and 175 fewer GDDs after soybean than at-harvest planting.

For the cornfield, soil pH averaged 5.9 across reps from 0 to 60 cm (Table 3.3). Organic matter (OM) averaged 12.0 g kg⁻¹ from 0 to 15 cm and 8.3 g kg⁻¹ from 15 to 60 cm. For the soybean fields, soil pH averaged 5.8 across reps from 0 to 30 cm and 4.9 from 30 to 60 cm (Table 3.4). OM averaged 19.2 g kg⁻¹ in the 0 to 15 cm horizon and 10.8 g kg⁻¹ in 15 to 60 cm.

3.4.2 *Fall Biomass Accumulation Following Corn*

The establishment method × CC interaction was not significant for fall CC biomass production ($p = 0.168$); however, the establishment main effect was important (Table 3.5; $p < 0.001$). Both combine-seeded treatments produced significantly higher fall biomass (1116 to

1314 kg ha⁻¹) compared to post-harvest drilled treatments (205 kg ha⁻¹), but did not differ significantly from each other. Using a combine-mounted seeder after corn can increase fall CC biomass by more than sixfold compared to drilling 4-weeks post-harvest and incorporation was unnecessary. The success of early planted CCs combined with rainfall aligns with findings from Sedghi et al. (2023) who found that aerial interseeded CCs outperformed post-harvest drilled CCs in biomass (1,700 versus 294 kg ha⁻¹) and N content (65.3 versus 9.9 kg N ha⁻¹) when there was adequate rainfall. A better-established CC with higher biomass aids in its ability to scavenge N with more established roots and a greater N uptake (Finney et al., 2016; Ritter et al., 1998). Therefore, increased fall biomass produced by the early planting date of the combine-mounted seeder has significant potential to capture more soil N after corn harvest compared to post-harvest drilling.

When total biomass (CC + weed biomass) was analyzed, control weed biomass (2023 to 2698 kg ha⁻¹) was not significantly different from the combine-seeded treatments (1973 to 2996 kg ha⁻¹), although all combine-seeded treatments were greater in total fall biomass than post-harvest counterparts (1028 to 1509 kg ha⁻¹), demonstrating greater weed suppression (Table 3.5). Post-harvest drilled hairy vetch (1028 kg ha⁻¹) produced the lowest total biomass, contrasting the combine-seeded hairy vetch (2817 to 2996 kg ha⁻¹; LSD_{0.05} = 733 kg ha⁻¹), indicating that hairy vetch is slow to establish in late fall under dry conditions, even when drilled, compared to the less drastic change in cereal rye (Baraibar et al., 2018; Clark, 2008).

The establishment method × CC interaction for fall cover crop N accumulation was significant (p = 0.002) showing combine-seeded hairy vetch treatments had the highest fall N accumulation (104 to 106 kg N ha⁻¹) and were significantly higher than all other treatments (Table 3.5). All post-harvest drilled treatments were significantly lower than any other CC and

establishment method treatment combinations with N accumulation ranging from 1 to 8 kg N ha⁻¹ ($p = 0.002$; $LSD_{0.05} = 25 \text{ kg N ha}^{-1}$). Seeding CC with the combine-mounted seeder increased N accumulation by 212 times in hairy vetch, 17 times in the mix, and 7 times in cereal rye compared to 4 weeks post-harvest drilling. Dramatic increases in N accumulation with earlier planting dates align with the findings of Cottney et al. (2022) who found early sowing date significantly increased N accumulation for all species, including the control. The increase in N accumulation from earlier planted CCs demonstrates substantial potential for cash crop yield increases and fertilizer cost savings according to Haymaker et al., 2024. The establishment method \times CC interaction for total N accumulation showed that only combine-seeded hairy vetch had significantly more N accumulation than all control plots, equal to or greater than any post-harvest drill treatment (Table 3.5; $p < 0.001$).

3.4.3 *Spring Biomass Accumulation Following Corn*

Similar to fall, analysis of spring CC biomass production showed a significant establishment method main effect (Table 3.6; $p < 0.001$). Both combine-seeded treatments produced significantly higher spring biomass (5867 to 6323 kg ha⁻¹) compared to post-harvest drilled treatments (2345 kg ha⁻¹), but did not differ significantly from each other ($LSD_{0.05} = 755 \text{ kg ha}^{-1}$). Considering the total biomass establishment method \times CC interaction (Table 3.6), all combine-seeded treatments, regardless of CC, had higher spring biomass (5492 to 7017 kg ha⁻¹) than all post-harvest drilled (2138 to 3377 kg ha⁻¹) and no CC control treatments (1422 to 2101 kg ha⁻¹; $p < 0.001$). The only post-harvest treatment that demonstrated more biomass than the no CC control treatments in total spring biomass was post-harvest drilled vetch (3377 kg ha⁻¹), due to significantly more weed biomass (853 kg ha⁻¹) than any other treatments containing CCs (17 to

340 kg ha⁻¹; Table 3.6). All treatments containing CCs have significantly lower spring weed biomass than all no CC control treatments ($p < 0.001$). Significant weed biomass in post-harvest vetch treatments indicated that poor fall establishment has a negative impact on hairy vetch, which was also observed by Teasdale et al. (2004).

In spring, as in the fall, combine-seeded hairy vetch treatments exhibited the highest N accumulation, along with combine-seeded incorporated mix (207 to 250 kg N ha⁻¹), both of which were significantly greater than all other treatments (Table 3.6; $p = 0.029$). Unlike fall, all hairy vetch and mix treatments, except for the PHD mix, accumulated significantly more N (122 to 251 kg N ha⁻¹) than the no CC control plots (29 to 46 kg N ha⁻¹; Table 3.6). Hairy vetch and mix planted with the combine-seeder accumulated 2.4 and 2.6 times more N than post-harvest drilled counterparts ($p < 0.001$). While cereal rye produced higher biomass than the control, it had equal or very similar N accumulation, as it relies solely on soil N and cannot fix atmospheric N like legumes, according to Finney et al. (2016).

Both establishment method and CC had significant main effects on spring C:N ratio for CC and total biomass (Table 3.6). Cereal rye had the highest CC biomass C:N ratio of 34:1 compared to hairy vetch and mix, which were 10:1 and 17:1, respectively, with the mix being significantly higher than vetch ($p < 0.001$). Cereal rye total biomass C:N ratio was also significantly higher than the no CC control plots, which had a C:N of 22:1 and were similar to the total mix C:N ratio (18:1). For the establishment method main effect, combine-seeded not-incorporated treatments had a significantly higher C:N ratio (24:1) than drilled treatments (18:1) but combine-seeded incorporated treatments did not differ from either (20:1) (Table 3.6; $p = 0.030$). Cereal rye treatments with high C:N ratios may lead to N immobilization as shown by Brust (2019) and Okopi et al. (2024) which is almost always the case with early planted and late

terminated cereal rye. Nitrogen becomes available to plants only when the C:N ratio is around or below 20:1 (Bryson et al., 2014). Our findings demonstrate when paired, cereal rye and hairy vetch mixtures have a lower C:N ratio and faster N release than cereal rye alone, which aligns with studies by Ranells & Wagger (1996) and Sadra et al (2023). However, Lacey et al. (2020) found that hairy vetch and cereal rye mix did not release N any faster than cereal rye, although planting date was not factored into the study.

Combine-seeded incorporated treatments showed no significant differences compared to non-incorporated combine-seeded treatments following corn. According to Licht (2019), incorporating broadcast CC seeds is typically recommended to improve seed-to-soil contact, however, this study suggested that additional field passes may not be necessary. Similarly, although increased seeding rates for broadcast seeding are commonly advised (Brennan & Leap, 2014; USDA-NRCS, 2015), our findings, consistent with Koehler-Cole & Elmore (2020) and Haramoto (2019), suggest this adjustment may not be needed (Table 3.2). Balcom et al. (2023) found that planting dates impacted biomass production more than the seeding rate.

3.4.4 Nitrogen Content in R3 soybeans Following Cover Crops

The R3 soybean tissue samples following CCs planted behind corn showed a significant interaction effect for N (Table 3.7; $p < 0.001$). Soybeans following CSNI vetch had the highest N concentration within the plant ($53 \text{ g N kg plant tissue}^{-1}$). This N was significantly higher than that of combine-seeded cereal rye, combine-seeded not incorporated and drilled mix, and the incorporated control (47 to $50 \text{ g N kg plant tissue}^{-1}$), but not significantly different than any other treatment. As the CSNI vetch treatment proved to accumulate some of the most N within the CC biomass planted before soybean (Table 3.6), the higher N within the soybean for CSNI vetch is

evidence that the soybean plant assimilated the N within the vetch. However, N concentration of 35 to 55 g N kg plant tissue⁻¹ is considered optimal for the R3 stage, meaning no treatments had N deficiencies at R3 (Bryson et al., 2014; Pal & Saxena, 1976). Overall, there was not a strong consistency in soybean tissue data, but due to soybean needing little to no additional N, soybean N demand and yield are not frequently affected by CCs (Liebl, et al., 1992; Yang et al., 2024).

3.4.5 Fall Biomass Accumulation Following Soybean

Neither CC species nor establishment method had a significant effect on fall CC, weed, or total biomass following soybean (Table 3.8). Total fall biomass (weeds + CC) ranged from 2051 to 3444 kg ha⁻¹, with weeds accounting for 74 to 97% of total biomass. Similarly, N accumulation in fall biomass showed no significant differences, ranging from 40 to 62 kg ha⁻¹, with weeds contributing 63 to 95% of total N.

No CC impact on total biomass or N assimilation is likely attributed to the extended drought, which persisted from at-harvest planting on October 17 through November 20 (Figure 3.2). Combine-seeded treatments received only 1.3 cm of rainfall within 36 days, 4 days after planting, while drilled treatments received no rain until 21 days after planting. Although lack of precipitation limits broadcasted CC performance, especially late fall, as observed by Collins & Fowler (1992), Haramoto (2019), Koehler-Cole & Elmore (2020), and Wilson et al. (2014), this drought inhibited growth equally across all treatments, including drilled CCs.

3.4.6 Spring Biomass Accumulation Following Soybean

Similar to fall, spring CC biomass showed no significant differences due to establishment method or species and averaged 4,480 kg ha⁻¹ (Table 3.9). However, unlike the fall, weed biomass in the control (2629 kg ha⁻¹) was significantly higher than in CC treatments (465 to 1102

kg ha⁻¹), indicating some weed suppression by CCs. In the establishment method × CC interaction, total biomass revealed that combine-seeded mix (6902 kg ha⁻¹) was significantly higher than all other treatment combinations, followed by the drilled mix (5639 kg ha⁻¹; Table 3.9). All treatments containing CCs produced more total biomass than the control treatments (2379 to 2879 kg ha⁻¹), though no significant differences were found between combine-seeded and drilled treatments, except for the mix. Previous research indicated that legume CCs must produce 4,000 to 4,500 kg ha⁻¹ of dry biomass to meet the following corn crop's demand (Parr et al., 2011; Teasdale et al., 2004). Despite the drought, hairy vetch treatments, regardless of establishment method, achieved this target biomass weight.

Cover crop main effect, averaged over establishment method, indicated higher N with higher in hairy vetch (191 kg N ha⁻¹) and mix (189 kg N ha⁻¹) compared to cereal rye (67 kg N ha⁻¹), but there was no significant establishment method effect ($p = 0.619$). The same significance was observed for total N accumulation, with the control being comparable to cereal rye (55 kg N ha⁻¹).

While not impacted by establishment method ($p = 0.170$), the C:N ratio was significantly higher ($p < 0.001$) in cereal rye (24:1) than in other species, with hairy vetch being the lowest (10:1), averaged across establishment method (Table 3.9). Total spring C:N ratio (CC + weeds) showed cereal rye remained the highest (24:1), followed by the control (20:1), compared to the mix and hairy vetch, which were 14:1 and 10:1, respectively. The C:N ratio of CCs at termination has a large influence on N release rates from the biomass according to Otte et al. (2019), Siever & Cook (2018) and Thapa et al. (2022). Cover crops after soybean did not accumulate as many GDDs as those following corn due to the late planting date, and therefore

had a lower overall C:N ratio when terminated, even in cereal rye, which may increase N mineralization across all treatments as seen in a study by Balkcom et al. (2023).

3.4.7 Nitrogen Content in R1 Corn Following Cover Crops

Growth stage R1 corn tissue samples following CCs planted behind soybeans showed no significant main or interaction effects (Table 3.7). Nitrogen concentration ranged from 25 to 28 g N kg plant tissue⁻¹. Optimum range for the silking stage is 28 to 40 g N kg plant tissue⁻¹ (Bryson et al., 2014), indicating the corn was slightly N deficient after CCs following soybeans, even though corn received 59 kg N ha⁻¹ as a starter fertilizer and 112 kg N ha⁻¹ at sidedress. The lack of any CC species or establishment method treatment effect is likely due to minimal differences in CC biomass and N accumulation across treatments. More research through varying precipitation is needed to draw any conclusions.

3.5 Conclusions

After one year, preliminary data indicated that planting CCs at cash crop harvest enhances both biomass production and N accumulation. Broadcasting seeds with the combine-mounted seeder generated comparable or greater CC biomass than drilling seeds 2-4 weeks post-harvest, following both corn and soybean. Due to adequate rainfall and added GDDs, CC biomass after corn increased tenfold when planted at harvest using the seeder, compared to drilling 4 weeks post-harvest, and more than doubled spring biomass. Nitrogen accumulation in fall CC biomass rose dramatically, increasing 212 times in hairy vetch, 17 times in the CC mix, and 7 times in cereal rye due to early planting. By spring, N accumulation more than doubled in combine-seeded mix and hairy vetch treatments relative to drilled treatments. These findings

underscore the negative effects of delayed planting on CC performance. Furthermore, broadcasting CCs at corn harvest without incorporation proved effective, eliminating the need for additional field operations. However, early planting increased C:N ratio, which could raise concerns about N immobilization, particularly in cereal rye CC.

Even during a drought year, broadcasting at soybean harvest resulted in biomass production and N accumulation equivalent to post-harvest drilling. However, additional site years are required to solidify these findings and assess the treatments' impacts on cash crop yield. The combine-mounted seeder in the Mid-Atlantic region has the potential to significantly reduce N leaching after corn harvest by facilitating substantial fall biomass production, enabling earlier CC planting after soybeans, and reducing labor and costs for growers.

3.6 References

- Balkcom, K. S., Read, Q. D., & Gamble, A. V. (2023). Rye planting date impacts biomass production more than seeding rate and nitrogen fertilizer. *Agronomy Journal*, 115(5), 2351-2368. doi.org/10.1002/agj2.21418
- Baraibar, B., Hunter, M. C., Schipanski, M. E., Hamilton, A., & Mortensen, D. A. (2018). Weed suppression in cover crop monocultures and mixtures. *Weed Science*, 66(1), 121–133. doi.org/10.1017/wsc.2017.59
- Bechman, T. J. (2021). Seeding behind combine gets cover crops off to good start. farmprogress.com/cover-crops/seeding-behind-combine-gets-cover-crops-off-to-good-start
- Blanco-Canqui, H. (2018). Cover crops and water quality. *Agronomy Journal*, 110(5), 1633-1647. doi.org/10.2134/agronj2018.02.0077
- Bouyoucus, G. J. (1936). Directions for making mechanical analysis of soils by the hydrometer method. *Soil Science Society of America Journal*, 42(3).
- Bremner, J. M. (1996). Nitrogen-total. *Methods of Soil Analysis*: 1085-1121.
- Bryson, G. M., Mills, H. A., Sasseville, D. N., Jones, J. B., & Barker, A. V. (2014). *Plant analysis handbook III*. Micro-Macro Publishing.
- Clark, A. (2008). *Managing cover crops profitably* (3rd ed.). DIANE Publishing Company. books.google.com/books?id=ahxLEpn6WYwC
- Collins, B. A., & Fowler, D. B. (1992). A comparison of broadcast and drill methods for no-till seeding winter wheat. *Canadian Journal of Plant Science*, 72(4). doi.org/10.4141/cjps92-126

- Cottney, P., Black, L., Williams, P., & White, E. (2022). How cover crop sowing date impacts upon their growth, nutrient assimilation, and the yield of the subsequent commercial crop. *Agronomy*, 12(2), 369. [mdpi.com/2073-4395/12/2/369](https://doi.org/10.3390/agr12020369)
- Day, P. R. (1965). "Particle Fractionation and Particle-Size Analysis In: C.A. Black (ed) *Methods of Soil Analysis, Part I.*" *Soil Science Society of America Journal*: 545-567.
- Day, P. R. (1965). Particle fractionation and particle-size analysis. In C. A. Black (Ed.), *Methods of soil analysis, part I* (pp. 545–567). *Soil Science Society of America Journal*.
- Dean, J. E., & Weil, R. R. (2009). Brassica cover crops for nitrogen retention in the mid-Atlantic coastal plain. *Journal of Environmental Quality*, 38(2), 520-528.
doi.org/10.2134/jeq2008.0066
- Environmental Protection Agency (EPA). (2010). Chesapeake Bay total maximum daily load for nitrogen, phosphorus and sediment. (pp. 1–93).
- Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal*, 108(1), 39–52. doi.org/10.2134/agronj15.0182
- Groff, S. (2015). The past, present, and future of the cover crop industry. *Journal of Soil and Water Conservation*, 70(6), 130A–133A. doi.org/10.2489/jswc.70.6.130A
- Haramoto, E. R. (2019). Species, seeding rate, and planting method influence cover crop services prior to soybean. *Agronomy Journal*, 111(3), 1068–1078.
doi.org/10.2134/agronj2018.09.0560
- Harper, J. E. (1974). Soil and symbiotic nitrogen requirements for optimum soybean production. *Crop Science*, 14(2). doi.org/10.2135/cropsci1974.0011183X001400020026x

- Haymaker, J. (2024). Cultivating sustainability: Analyzing soil health dynamics and economics of cover crops in the mid-Atlantic (Publication No. 112216298). Virginia Tech.
- Hirsh, S. M., & Weil, R. R. (2019). Deep soil cores reveal large end-of-season residual mineral nitrogen pool. *Agricultural & Environmental Letters*, 4(1), 180055.
doi.org/10.2134/aer2018.10.0055
- Isaac, R. A. (1983). Reference soil test methods for the Southern Region of the United States. Southern Cooperative Series Bulletin, 289.
- Kaspar, T. C., Radke, J. K., & Laflem, J. M. (2001). Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. *Soil and Water Conservation*, 56(2), 160-164.
- Kientzy, D., Milhollin, R., Ellis, C., & Massey, R. (2023). Understanding equipment management for planting cover crops. *Journal of Soil and Water Conservation*, 78(6), 113A-117A. <https://doi.org/10.2489/jswc.2023.0818A>
- Koehler-Cole, K., & Elmore, R. W. (2020). Seeding rates and productivity of broadcast interseeded cover crops. *Agronomy*, 10(11), 1723.
<https://doi.org/10.3390/agronomy10111723>
- Kucek, L. K., Muller, K., Martins, L. B., Moore, V. M., Reberg-Horton, C., Mirsky, S. B., Englert, J., Drinkwater, L. E., Douglas, J., Eagen, S. S., Butler, T., Ryan, M. R., Casey, A., Clark, K., Ehlke, N., Hendrickson, J., Guretzky, J., Johnson, H., Archer, D., . . .
- Riday, H. (2024). Genetic and environmental drivers of legume cover crop performance: Hairy vetch. *Crop Science*. <https://doi.org/10.1002/csc2.21318>
- Lacey, C., Nevins, C., Camberato, J., Kladviko, E., Sadeghpour, A., & Armstrong, S. (2020). Carbon and nitrogen release from cover crop residues and implications for cropping

- systems management. *Journal of Soil and Water Conservation*, 75, 505–514.
<https://doi.org/10.2489/jswc.2020.00102>
- Licht, M. (2019). A look at cover crop seeding methods. *Iowa State University Extension and Outreach*. <https://crops.extension.iastate.edu/blog/mark-licht/look-cover-crop-seeding-methods>
- Liebl, R., Simmons, F. W., Wax, L. M., & Stoller, E. W. (1992). Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). *Weed Technology*, 6, 838–846. <https://doi.org/10.1017/S0890037X00036356>
- Nelson, D. W., & Sommers, L. E. (2020). Total nitrogen analysis of soil and plant tissues. *Journal of Association of Official Analytical Chemists*, 63(4), 770–778.
<https://doi.org/10.1093/jaoac/63.4.770>
- NRCS. (2015). Virginia NRCS plant establishment guide (PEG), section Eb (cropland) cover crop establishment specifications (340). *USDA*. <https://www.nrcs.usda.gov>
- McCracken, D. V., Smith, M. S., Grove, J. H., MacKown, C. T., & Blevins, R. L. (1994). Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Science Society of America Journal*, 58(5), 1476–1483.
<https://doi.org/10.2136/sssaj1994.03615995005800050029x>
- McLean, E. O. (1983). Soil pH and lime requirement. In A. L. Page (Ed.), *Methods of soil analysis: Part 2 chemical and microbiological properties* (2nd ed., Vol. 9, pp. 199–224). *American Society of Agronomy and Soil Science Society of America*.
<https://doi.org/10.2134/agronmonogr9.2.2ed.c12>
- Mehlich, A. (1953). Determination of P, Ca, Mg, K, Na, and NH₄. *North Carolina Agricultural Experiment Station Bulletin*.

- Mendiburu, F. d. (2023). agricolae: statistical procedures for agricultural research. *R package version 1.3-7*. <https://CRAN.R-project.org/package=agricolae>
- Miner, G. L., Delgado, J. A., Ippolito, J. A., & Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agricultural & Environmental Letters*, 5(e20023). <https://doi.org/10.1002/ael2.20023>
- Moore, V. M., & Mirsky, S. B. (2020). Cover crop biomass production across establishment methods in mid-Atlantic corn. *Agronomy Journal*, 112(6), 4765–4774. <https://doi.org/10.1002/agj2.20414>
- Morris, T. F., Murrell, T. S., Beegle, D. B., Camberato, J. J., Ferguson, R. B., Grove, J., Ketterings, Q., Kyveryga, P. M., Laboski, C. A. M., McGrath, J. M., Meisinger, J. J., Melkonian, J., Moebius-Clune, B. M., Nafziger, E. D., Osmond, D., Sawyer, J. E., Scharf, P. C., Smith, W., Spargo, J. T., . . . Yang, H. (2018). Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, 110(1), 1–37. <https://doi.org/10.2134/agronj2017.02.0112>
- Otte, B., Mirsky, S., Schomberg, H., Davis, B., & Tully, K. (2019). Effect of cover crop termination timing on pools and fluxes of inorganic nitrogen in no-till corn. *Agronomy Journal*, 111(6), 2832–2842. <https://doi.org/10.2134/agronj2018.10.0699>
- Pal, U. R., & Saxena, M. C. (1976). Relationship between nitrogen analysis of soybean tissues and soybean yields. *Agronomy Journal*, 68(6), 927–932. <https://doi.org/10.2134/agronj1976.00021962006800060021x>
- Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C., & Crozier, C. (2011). Nitrogen delivery from legume cover crops in no-till organic corn production. *Agronomy Journal*, 103(6), 1578–1590. <https://doi.org/10.2134/agronj2011.0007>

- Practical Farmers of Iowa. (2023). Combine seeder saves time and fuel by seeding covers during harvest - practical cover croppers. [YouTube video].
<https://www.youtube.com/watch?v=l8AEldrAiAQ>
- R Core Team (2024). R: a language and environment for statistical computing. *R Foundation for Statistical Computing*. <https://www.R-project.org>
- Ranells, N. N., & Waggener, M. G. (1996). Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agronomy Journal*, 88(5), 777–882.
<https://doi.org/10.2134/agronj1996.00021962008800050015x>
- Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems*, 33(4), 322–333. <https://doi.org/10.1017/S1742170517000096>
- Sadra, S., Mohammadi, G., & Mondani, F. (2023). Nitrogen release dynamics and carbon sequestration by legume and non-legume cover crops under pure and mixed planting conditions. *Agriculture (Pol'nohospodárstvo)*, 69(1), 13–26. <https://doi.org/10.2478/agri-2023-0002>
- Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, 125, 12–22
- Schulte, E. E., & Hopkins, B. G. (1996). Estimation of soil organic matter by weight loss-on-ignition. In F. R. Magdoff, M. A. Tabatabai, & E. A. Hanlon Jr. (Eds.), *Soil organic*

- matter: Analysis and interpretation*. Special Publication No. 46. *Soil Science Society of America Journal*.
- Sedghi, N., Fox, R. J., Sherman, L., Gaudlip, C., & Weil, R. R. (2023). Aerial interseeding and planting green to enhance nitrogen capture and cover crop biomass carbon. *Journal of Soil and Water Conservation*, 78(3), 282-298. <https://doi.org/10.2489/jswc.2023.00051>
- Sedghi, N., & Weil, R. (2022). Fall cover crop nitrogen uptake drives reductions in winter-spring leaching. *Journal of Environmental Quality*, 51(1), 337-351. <https://doi.org/DOI:10.1002/jeq2.20342>
- Sievers, T., & Cook, R. L. (2018). Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Science Society of America Journal*, 82(1), 147–155. <https://doi.org/10.2136/sssaj2017.05.0139>
- Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal*, 97(1), 322-332. <https://doi.org/https://doi.org/10.2134/agronj2005.0322a>
- Soil Series Staff. (2002). *Official Soil Series Descriptions*. Natural Resources Conservation Service. United States Department of Agriculture.
- Staver, K. W., & Brinsfield, R. B. (1998). Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlanticcoastal plain. *Soil and Water Conservation* 53(3), 230-240.
- Storer, D. A. (1984). "A Simple high sample volume ashing procedure for determining soil organic matter." *Commun. Soil Sci. Plant Anal.* 15: 759-772.

- Teasdale, J. R., Devine, T. E., Mosjidis, J. A., Bellinder, R. R., & Beste, C. E. (2004). Growth and development of hairy vetch cultivars in the Northeastern United States as influenced by planting and harvesting date. *Agronomy Journal*, *96*(5), 1266-1271.
<https://doi.org/https://doi.org/10.2134/agronj2004.1266>
- Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. *Journal of Environmental Quality*, *47*(6), 1400-1411. <https://doi.org/https://doi.org/10.2134/jeq2018.03.0107>
- Thapa, R., Tully, K. L., Reberg-Horton, C., Cabrera, M., Davis, B. W., Fleisher, D., Gaskin, J., Hitchcock, R., Poncet, A., Schomberg, H. H., Seehaver, S. A., Timlin, D., & Mirsky, S. B. (2022). Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. *Agriculture, Ecosystems & Environment*, *326*, 107823. <https://doi.org/10.1016/j.agee.2021.107823>
- USDA-NRCS. (2015). *Virginia Technical Note, Agronomy #10 , Virginia NRCS Cover Crop Planning Manual 1.0*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf
- Virginia Department of Conservation and Recreation (DCR). (2024). *Agricultural BMP cost-share program: FY 2025 Overview*.
- Virginia Department of Environmental Quality (DEQ). (2024). *Virginia's draft Chesapeake Bay 2024-2025 numeric milestones*. <https://www.deq.virginia.gov/our-programs/water/chesapeake-bay/chesapeake-bay-nutrient-sediment-reduction-milestones>
- Wayman, S., Kissing Kucek, L., Mirsky, S. B., Ackroyd, V., Cordeau, S., & Ryan, M. R. (2017). Organic and conventional farmers differ in their perspectives on cover crop use and

- breeding. *Renewable Agriculture and Food Systems*, 32(4), 376–385.
doi:10.1017/S1742170516000338
- Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. <https://ggplot2.tidyverse.org>, Springer-Verlag New York.
- Wickham, H., and E. Ruiz (2020). *dbplyr: A ‘dplyr’ back end for databases*. R package version 1.4.3. <https://CRAN.R-project.org/package=dbplyr>.
- Wickham, H., R. Francois, L. Henry, K. Muller (2020). *dplyr: A Grammar of data manipulation*. R package version 0.8.5. <https://CRAN.R-project.org/package=dplyr>.
- Wilson, M. L., Allan, D. L., & Baker, J. M. (2014). Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices. *Journal of Soil and Water Conservation*, 69(3), 67A-72A. <https://doi.org/10.2489/jswc.69.3.67A>
- Wofuru-Nyenke, O. K. (2023). Mechanized cover crop farming: Modern methods, equipment and technologies *Circular Agriculture Systems* 3(6).
<https://doi.org/https://doi.org/10.48130/CAS-2023-0006>
- Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., Luo, L., Alonge, C., Wei, H., Meng, J., Livneh, B., Lettenmaier, D., Koren, V., Duan, Q., Mo, K., Fan, Y., & Mocko, D. (2012). Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. *Journal of Geophysical Research: Atmospheres*, 117(D3). <https://doi.org/https://doi.org/10.1029/2011JD016048>
- Yang, X., Drury, C. F., Dan Reynolds, W., & Reeb, M.-A. D. (2024). Legume cover crop as a primary nitrogen source in an organic crop rotation in Ontario, Canada: impacts on corn,

soybean and winter wheat yields. *Organic Agriculture*, 14(1), 19-31.

<https://doi.org/10.1007/s13165-023-00452-3>

Zhang, J., Howard, K., Langston, C., Kaney, B., Qi, Y., Tang, L., Grams, H., Wang, Y., Cocks, S., Martinaitis, S., Arthur, A., Cooper, K., Brogden, J., & Kitzmiller, D. (2016). Multi-radar multi-sensor (MRMS) quantitative precipitation estimation: Initial operating capabilities. *Bulletin of the American Meteorological Society*, 97(4), 621-638.

<https://doi.org/https://doi.org/10.1175/BAMS-D-14-00174.1>

Zhu, J. C., Gantzer, C. J., Anderson, S. H., Alberts, E. E., & Beuselinck, P. R. (1989). Runoff, soil, and dissolved nutrient losses from no-till soybean with winter cover crops. *Soil Science Society of America Journal*, 53(4), 1210-1214.

<https://doi.org/https://doi.org/10.2136/sssaj1989.03615995005300040037x>

3.7 Figures & Tables

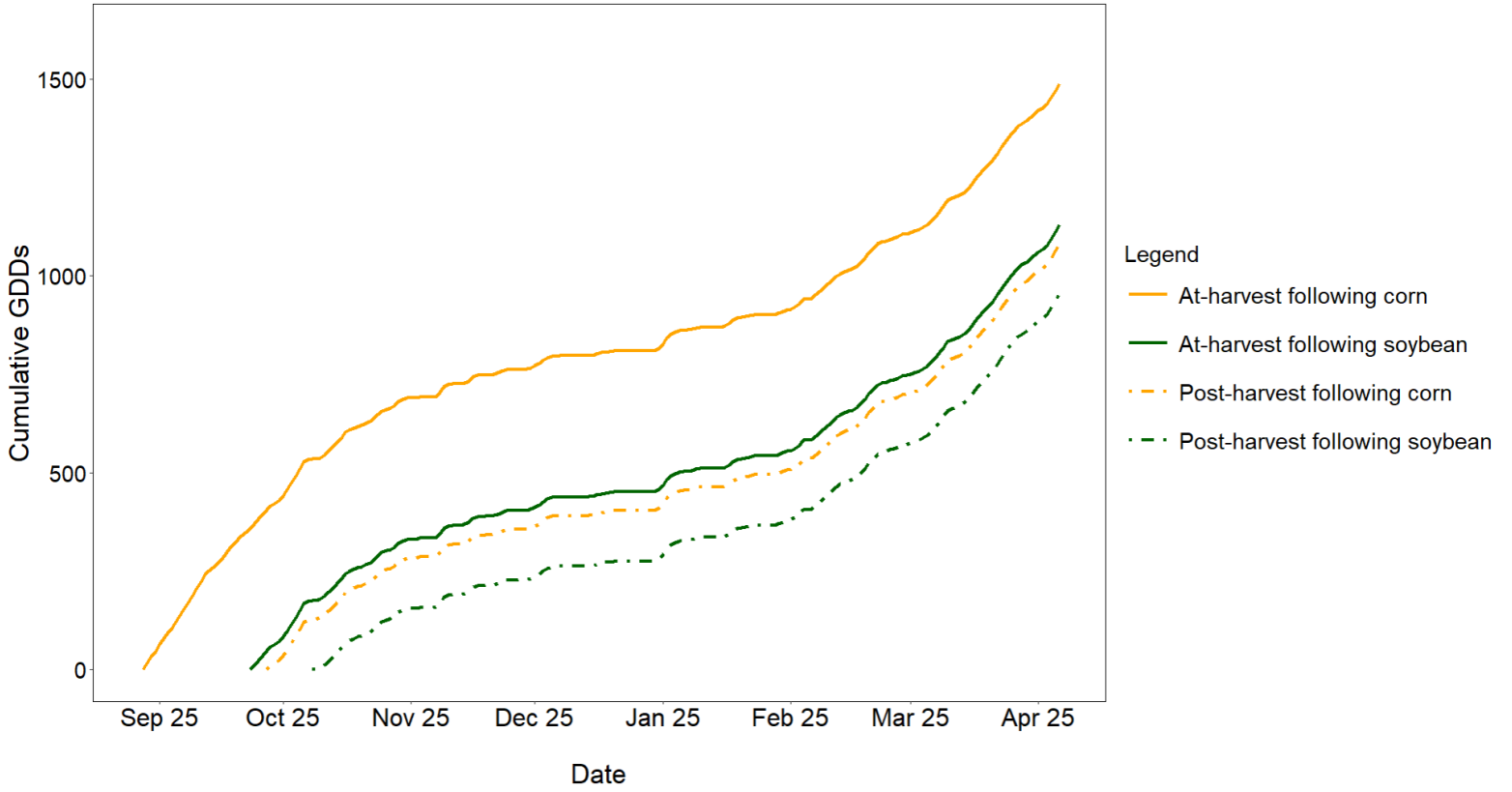


Figure 3.1 Cumulative cover crop Growing Degree Days (GDDs) in a field trial conducted in Charles City, VA in 2023-2024.

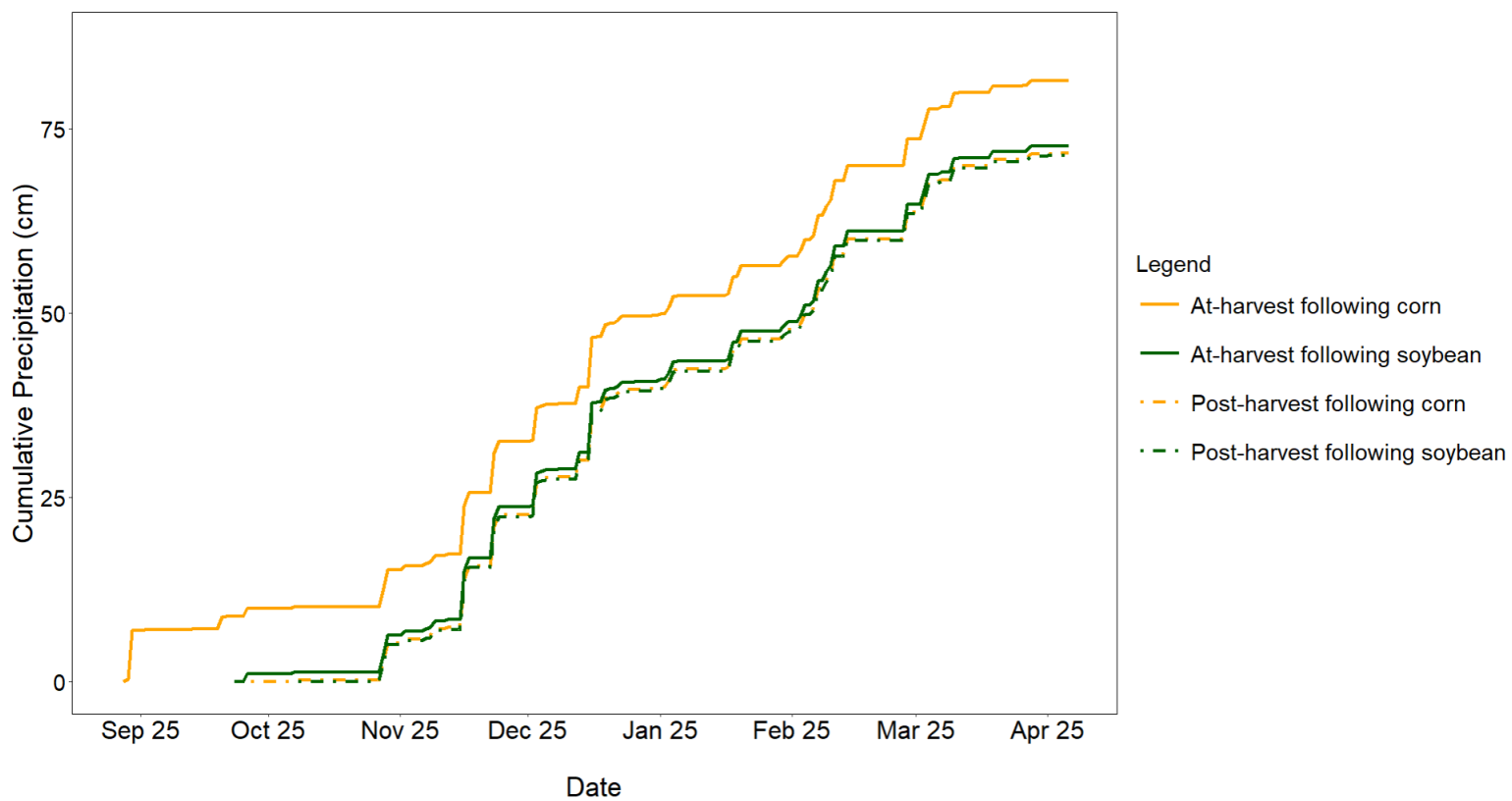


Figure 3.2 Monthly total precipitation (cm) during cover crop growth period in a field trial conducted in Charles City, VA in 2023-2024.

Table 3.1 Cash crop and cover crop (CC) management practices summary and dates from September 2023 – May 2024.

Field Operation	Date		Date
Following corn		Following soybean	
Combine-seeded CC planting	Sept. 21, 2023	Combine-seeded CC planting	Oct. 17, 2023
Corn harvest	Sept. 21, 2023	Soybean harvest	Oct. 17, 2023
Combine-seeded CC incorporation	Sept. 21, 2023	Combine-seeded CC incorporation	-†
Post-harvest drilled CC planting	Oct. 21, 2023	Post-harvest drilled CC planting	Nov. 1, 2023
Winter biomass sampling	Jan. 8, 2024	Winter biomass sampling	Jan. 11, 2024
Spring biomass sampling	May 1, 2024	Spring biomass sampling	May 2, 2024
CC termination	May 7, 2024	Corn planting	May 3, 2024
Soybean planting	May 15, 2024	CC termination	May 7, 2024

†There were no combine-seeded with incorporation treatments following soybean harvest.

Table 3.2 Winter cover crop (CC) treatment, species, and seeding rates planted on N.S. Farms in Charles City, VA in 2023-2024.

CC Treatment	Species	Broadcast seeding rate	Drill seeding rate	VA NRCS recommended aerial seeding rate [§]
				kg ha ⁻¹
Cereal rye	Cereal rye [†]	84	84	163
Hairy vetch	Hairy vetch	28	28	34
Mix	Cereal rye	45	45	81
	Hairy vetch	15	15	17

[†]Cereal rye (*Secale cereale*), Hairy vetch (*Vicia villosa*).

[§]USDA-NRCS. (2015). *Virginia NRCS Cover Crop Planning Manual 1.0*.

Table 3.3 Background soil physical and chemical properties in field following corn grown on sandy loam soil at N.S. Farms in Charles City, Virginia in 2023.

Depth	pH	CEC	OM	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
cm		meq 100g ⁻¹	g kg ⁻¹	mg kg ⁻¹									
0-15	5.9	4.5	12.0	26.4	49.9	60.4	453.8	7.9	0.2	4.1	7.9	43.3	0.6
15-30	5.8	3.8	6.6	4.9	45.5	46.3	265.6	12.5	0.1	0.7	4.3	15.5	0.2
30-45	6.0	5.0	8.8	3.5	50.8	101.1	391.8	2.5	0.1	0.6	2.3	14.8	0.2
45-60	5.8	5.9	9.5	1.5	38.5	120.6	394.1	7.6	0.1	0.2	0.6	12.0	0.1

Table 3.4 Background soil physical and chemical properties in fields following soybean grown on sandy loam soil at N.S. Farms in Charles City, Virginia in 2023.

Depth	pH	CEC	OM	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
cm		meq 100g ⁻¹	g kg ⁻¹	mg kg ⁻¹									
0-15	6.0	8.1	19.2	41.8	41.7	136.1	774.0	2.4	0.3	3.3	3.8	41.1	2.3
15-30	5.5	6.9	10.9	6.9	19.5	117.8	553.0	10.8	0.3	0.7	1.5	19.9	0.8
30-45	5.0	7.6	10.8	3.6	15.9	87.4	409.9	15.3	0.2	0.5	0.9	19.5	0.4
45-60	4.8	9.5	10.6	1.4	16.5	77.1	352.9	11.1	0.2	0.4	0.6	13.8	0.3

Table 3.5 Effect of establishment method and cover crop (CC) species on 2023 fall aboveground biomass, Nitrogen accumulation, and C:N ratio following corn on a sandy loam soil in Charles City, VA.

CC	CC biomass			Weed biomass			Total biomass			
	Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	
	_____ kg ha ⁻¹ _____			_____ kg ha ⁻¹ _____			_____ kg ha ⁻¹ _____			
Cereal rye	1532 [†]	34 [□]	20	337	4	24 a	1869	38	20	
Hairy vetch	1733	70	13	548	8	20 b	2280	77	15	
Mix	1370	35	18	607	7	25 a	1977	43	19	
Control	-8	-	-	2421	31	24 a	2421	31	24	
LSD _{0.05}	-*	-	-	-	-	4	-	-	-	
<i>p</i> -value	0.511	0.025	<0.001	<0.001	<0.001	0.035	0.356	0.006	<0.001	
Establishment method										
CSI	2115 a [‡]	64	16	734	9	23	2320	57	18	
CSNI	2314 a	71	15	773	11	23	2508	64	17	
PHD	205 b	4	20	1428	17	24	1582	20	23	
LSD _{0.05}	386	-	-	-	-	-	-	-	-	
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	0.379	<0.001	<0.001	<0.001	
Establishment method × CC										
Cereal rye	CSI	1859	36 b	21 a	115 f	1 f	26	1973 c-e	38 bc	21 c
	CSNI	2321	57 b	18 b	66 f	1 f	23	2387 a-c	58 b	18 d
	PHD	416	8 c	22 a	832 de	10 c-e	23	1248 ef	18 cd	22 bc
Hairy vetch	CSI	2560	106 a	11 c	436 ef	6 d-f	20	2996 a	112 a	11 e
	CSNI	2618	104 a	11 c	199 f	3 ef	18	2817 ab	107 a	11 e
	PHD	20	1 c	17 b	1008 cd	13 cd	22	1028 f	14 d	22 bc
Mix	CSI	1928	51 b	16 b	361 ef	4 ef	26	2289 a-c	56 b	17 d
	CSNI	2003	51 b	16 b	130 f	2 f	26	2132 b-d	53 b	17 d
	PHD	180	3 c	21 a	1329 c	16 c	24	1509 d-f	19 cd	24 ab
Control	CSI	-	-	-	2023 b	25 b	23	2023 cd	25 cd	23 a-c
	CSNI	-	-	-	2698 a	38 a	23	2698 a-c	38 bc	23 a-c
	PHD	-	-	-	2542 a	31 b	25	2542 a-c	31 cd	25 a
LSD _{0.05}	-	25	3	488	7	-	732	22	3	
<i>p</i> -value	0.168	0.002	0.048	0.016	0.004	0.058	0.003	<0.001	<0.001	

Abbreviations: CSI, combine-seeded incorporated; CSNI, combine-seeded not incorporated; PHD, post-harvest drilled; wt, weight.

†Means within a column lacking a letter were not significantly different.

§Dashes in the control row indicate there was no CC biomass to analyze.

*Dashes in LSD row indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column followed by the same lowercase letter were not significantly different.

□Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

Table 3.6 Effect of establishment method and cover crop (CC) species on 2024 spring aboveground biomass, Nitrogen accumulation, and C:N ratio following corn on a sandy loam soil in Charles City, VA.

CC	CC biomass			Weed biomass			Total biomass			
	Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	
	— kg ha ⁻¹ —			— kg ha ⁻¹ —			— kg ha ⁻¹ —			
Cereal rye	4625†	61 [□]	34 a	140	2 b	32	4765	63	34 a	
Hairy vetch	4507	195	10 c	311	7 b	19	4818	202	11 c	
Mix	5404	150	17 b	100	2 b	28	5504	151	18 b	
Control	-§	-	-	1755	36 a	22	1755	36	22 b	
LSD _{0.05}	-*	-	7	-	14	-	-	-	7	
<i>p</i> -value	0.326	0.002	<0.001	<0.001	0.001	-	<0.001	<0.001	<0.001	
Establishment method										
CSI	5867 a‡	178	20 ab	471	8	24	4872	141	21 ab	
CSNI	6323 a	158	24 a	560	12	26	5302	130	24 a	
PHD	2345 b	71	18 b	699	15	25	2458	68	18 b	
LSD _{0.05}	755	-	4	-	-	-	-	-	4	
<i>p</i> -value	<0.001	<0.001	0.030	0.005	0.114	-	<0.001	<0.001	0.022	
Establishment method × CC										
Cereal rye	CSI	5495	75 cd	35	64 f	1	30	5558 b	76 e	35
	CSNI	6584	79 c	39	17 f	0	35	6600 ab	80 e	39
	PHD	1798	29 d	28	340 e	5	32	2138 de	34 f	28
Hairy vetch	CSI	5539	250 a	10	46 f	1	16	5585 b	251 a	10
	CSNI	5457	232 a	10	35 f	1	18	5492 b	233 ab	10
	PHD	2525	104 c	11	853 d	18	21	3377 c	122 cd	12
Mix	CSI	6568	207 ab	15	33 f	1	-	6601 ab	208 b	15
	CSNI	6930	162 b	22	87 ef	2	-	7017 a	164 c	22
	PHD	2714	79 c	15	181 ef	3	28	2895 cd	82 de	16
Control	CSI	-	-	-	1743 b	29	25	1743 e	29 f	25
	CSNI	-	-	-	2101 a	46	24	2101 de	46 ef	24
	PHD	-	-	-	1422 c	33	18	1422 e	33 f	18

LSD _{0.05}	-	46	-	257	-	-	1130	42	-
<i>p</i> -value	0.326	0.029	0.166	<0.001	0.088	-	<0.001	<0.001	0.150

Abbreviations: CSI, combine-seeded incorporated; CSNI, combine-seeded not incorporated; PHD, post-harvest drilled; wt, weight.

†Means within a column lacking a letter were not significantly different.

§Dashes in the control row indicate there was no CC biomass to analyze.

*Dashes in LSD row indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column followed by the same lowercase letter were not significantly different.

□Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

↓Due to only having weed biomass in one replication of CSI and CSNI mix treatments, statistical analysis was not performed on weed C:N ratio.

Table 3.7 Effect of establishment method and cover crop (CC) species on Nitrogen concentration in corn at R1 and soybean at R3 following CC treatments on a sandy loam soil in Charles City, Virginia.

		R1 corn	R3 soybean
CC		g N kg plant tissue ⁻¹	
Cereal rye		27†	48
Hairy vetch		25	52
Mix		28	50
Control		28	51
<i>p</i> -value		0.269	0.089
Establishment method			
CSI		-8	50
CSNI		27	50
PHD		27	50
<i>p</i> -value		0.558	0.751
Establishment method × CC			
Cereal rye	CSI	-	49 cd‡
	CSNI	28	47 d
	PHD	27	50 a-d
Hairy vetch	CSI	-	52 ab
	CSNI	23	53 a
	PHD	26	50 a-d
Mix	CSI	-	51 a-c
	CSNI	28	50 b-d
	PHD	29	48 cd
Control	CSI	-	50 b-d
	CSNI	28	52 ab
	PHD	27	52 ab
LSD _{0.05}		-*	0.2
<i>p</i> -value		0.085	<0.001

Abbreviations: CSI, combine-seeded incorporated; CSNI, combine-seeded not incorporated; PHD, post-harvest drilled.

†Means within a column lacking a letter were not significantly different.

‡There was no CSI treatment following soybean.

*Dashes in LSD row indicate no LSD was run due to either no significance or a significance in the interaction effect.

‡Means within a column followed by the same lowercase letter were not significantly different.

Table 3.8 Effect of establishment method and cover crop (CC) species on 2023 fall aboveground biomass, Nitrogen accumulation, and C:N ratio following soybean on a sandy loam soil in Charles City, VA.

	CC biomass			Weed biomass			Total biomass		
	Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N
	— kg ha ⁻¹ —			— kg ha ⁻¹ —			— kg ha ⁻¹ —		
CC									
Cereal rye	596†	18	14	2372	37	18	2968	55	17
Hairy vetch	82	2	12	2264	38	18	2346	40	17
Mix	540	15	13	1511	25	18	2051	40	16
Control	-§	-	-	3445	62	19	3445	62	19
<i>p</i> -value	0.077	0.063	0.288	0.179	0.093	0.935	0.386	0.113	0.680
Establishment method									
CSNI	515	15	13	2512	42	18	2899	54	17
PHD	297	7	13	2284	38	18	2506	44	17
<i>p</i> -value	0.059	0.050	0.531	0.537	0.512	0.939	0.253	0.522	0.763
Establishment method × CC	0.203	0.274	0.884	0.392	0.494	0.451	0.386	0.522	0.394

Abbreviations: CSI, combine-seeded incorporated; CSNI, combine-seeded not incorporated; PHD, post-harvest drilled; wt, weight.

†Means within a column lacking a letter were not significantly different.

§The no CC control plots contained only weed biomass.

Table 3.9 Effect of establishment method and cover crop (CC) species on 2024 spring aboveground biomass, Nitrogen accumulation, and C:N ratio following soybean on a sandy loam soil in Charles City, VA.

	CC biomass			Weed biomass			Total biomass			
	Dry wt.	N	C:N	Dry wt.	N	C:N	Dry wt.	N	C:N	
	kg ha ⁻¹			kg ha ⁻¹			kg ha ⁻¹			
CC										
Cereal rye	3526 [†]	67 b [‡]	24 a	1102 b	19 b	24	4628 [□]	86 b	24 a	
Hairy vetch	4276	191 a	10 c	465 b	10 b	21	4742	201 a	10 c	
Mix	5640	189 a	13 b	631 b	12 b	24	6270	201 a	14 c	
Control	-§	-	-	2629 a	56 a	20	2629	55 b	20 b	
LSD _{0.05}	-*	79	2	777	12	-	-	64	4	
<i>p</i> -value	0.288	0.013	<0.001	<0.001	<0.001	0.213	0.029	<0.001	<0.001	
Establishment method										
CSNI	4528	145	16	1308	25	22	4704	134	18	
PHD	4434	153	15	1105	23	22	4431	137	17	
<i>p</i> -value	0.773	0.619	0.170	0.212	0.448	0.862	0.180	0.771	0.197	
Establishment method × CC										
Cereal rye	CSNI	3525	66	25	1032	17	25	4557 c	83	25
	PHD	3528	70	23	1172	21	23	4699 c	90	23
Hairy vetch	CSNI	3909	165	10	568	13	20	4477 c	178	11
	PHD	4644	217	9	363	7	21	5006 bc	224	10
Mix	CSNI	6149	205	13	754	14	23	6902 a	220	14
	PHD	5131	173	13	508	9	24	5639 b	181	14
Control	CSNI	-	-	-	2879	57	21	2879 d	57	21
	PHD	-	-	-	2379	54	19	2379 d	54	20
LSD _{0.05}	-	-	-	-	-	-	-	835	-	-
<i>p</i> -value	0.128	0.108	0.554	0.554	0.716	0.753	0.030	0.078	0.923	

Abbreviations: CSI, combine-seeded incorporated; CSNI, combine-seeded not incorporated; PHD, post-harvest drilled; wt, weight.

[†]Means within a column lacking a letter were not significantly different.

[§]Dashes in the control row indicate there was no CC biomass to analyze.

^{*}Dashes in LSD row indicate no LSD was run due to either no significance or a significance in the interaction effect.

[‡]Means within a column followed by the same lowercase letter were not significantly different.

[□]Means within a column lacking a letter but with $p < 0.05$ had a significant interaction effect.

4. Conclusions

This study demonstrated that early CC establishment through broadcasting at cash crop harvest, regardless of seed incorporation, offers a promising strategy for reducing nitrate leaching and improving both CC biomass production and N accumulation in Mid-Atlantic farming systems. Broadcasting CCs, especially using the mix, vetch, or rye, at corn harvest consistently yielded greater fall biomass than delayed post-harvest planting. However, depending on precipitation, post-harvest drilled CCs showed potential to produce similar spring biomass to at-harvest planted CCs. Preliminary data also supports the effectiveness of using a combine-mounted seeder to broadcast CCs at cash crop harvest, generating comparable or greater CC biomass and N accumulation than drilling several weeks later, following both corn and soybeans. Hairy vetch and the mix accumulated particularly high N, especially when planted at-harvest, leading to potential yield benefits for subsequent corn crops. However, at-harvest establishment increased the C:N ratio at CC termination, which could have impacted N availability for the following corn, particularly with cereal rye. While rapeseed establishment challenges resulted in lower biomass and N accumulation, continued research on optimal seeding methods for rapeseed could address this gap. These findings underscore that at-harvest CC establishment through broadcast seeding can effectively mitigate nitrate leaching, enhance biomass production, and increase corn yields comparable to or greater than those achieved with post-harvest drilling in a corn-soybean rotation. Further multi-year research is essential to confirm these results across varied climate and soil conditions, refine seeding strategies, and fully assess their long-term impacts on cash crop yields.