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Aerial interseeding and planting green to enhance nitrogen capture and cover crop biomass carbon

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Abstract: The US state of Maryland incentivizes farmers to plant cover crops to reduce nitrogen (N) loading to the Chesapeake Bay and to sequester carbon (C). Maryland has a greater percentage of agricultural land in cover crops than any other state, but Maryland farmers typically plant cover crops in October, after harvest and terminate them early in spring, thus severely limiting the cover crop growing time with sufficient temperatures. We hypothesized that extending the cover crop growing season, by interseeding cover crops earlier in fall and terminating them later in the spring, would increase both fall and spring cover crop biomass and N content, reduce nitrate (NO_3) leached during winter through early spring, increase soil mineral N, and increase soil moisture in early summer. We tested this hypothesis across 18 site-years by partnering with commercial farmers on the Eastern Shore of Maryland. The farmers managed a brassica-legume-cereal cover crop on their corn (*Zea mays* L.) or soybean (*Glycine max* [L.] Merr.) fields according to three treatments: (1) aerial interseed cover crop prior to cash crop harvest and terminate it at or after cash crop planting (Extended); (2) drill cover crop after cash crop harvest and terminate it several weeks before cash crop planting (Standard); and (3) a no-cover crop control in 2018 and 2019 (No Cover). For each treatment, we measured cover crop biomass + N content (fall and spring), NO_3 in 70 or 100 cm deep drainage water (fall–winter), as well as soil mineral N and moisture (in June). The Extended treatment exhibited higher fall biomass (1,700 versus 294 kg ha^{-1}) and total N content (65.3 versus 9.6 kg N ha^{-1}) only in a wet year, but produced greater spring cover crop biomass and N content than the Standard treatment every year. In the year with a very wet fall, NO_3-N leaching loss was reduced by 84% for Extended and by 45% for Standard compared to No Cover. We found no difference in NO_3 leaching between Extended and Standard in years with a dry fall (2017 and 2019). Averaged over all three years, Extended and Standard did not differ in June soil NO_3 concentration. Greater reductions in NO_3 leaching may make early aerial interseeding preferable to post-harvest drilling, while increased biomass produced in spring with later termination made Extended desirable for increased C inputs. Hence, extending the cover-cropping season can be beneficial to the farmer and to the environment due to increased fall and spring cover crop C inputs to the soil and reduced NO_3 leaching in wet years, reducing potential eutrophication of nearby waterways.

Key words: cover crops—interseeding—multispecies—nitrate leaching—planting green—soil nitrogen

Improved management of cover crops can substantially enhance their capacity to reduce nitrogen (N) loss from cropland and increase carbon (C) inputs. Excessive N loss from agricultural production contributes to eutrophication and subsequent algal blooms and hypoxia in estuaries such as the Chesapeake Bay (Testa et al. 2014), where agriculture contributes approximately 42% of the N load (Chesapeake Bay Program 2017). The principal pathway for N transport from cropland to the bay is the leaching of nitrate (NO_3) to groundwater (Phillips and Lindsey 2003) and the subsequent transport to streams, rivers, and the estuary. Cover crops have been documented to reduce groundwater N concentrations by removing soluble NO_3 from the soil profile before the leaching season and by removing water before and during the leaching season, thus reducing the volume of drainage water (Meisinger et al. 1991; Meyer et al. 2018). In addition, cover crops have been shown to substantially reduce soil erosion, improve soil structure, increase C sequestration, increase N fixation, and suppress weeds (Lal et al. 1991; Hartwig and Ammon 2002; Snapp et al. 2005; Weil and Kremen 2007). The Maryland Agricultural Water Quality and Cost Share program (MACS) pays farmers US\$100 to US\$200 ha^{-1} for planting cover crops with higher incentives given for practices thought to enhance N capture (MDA 2020a). For example, greater incentives are offered for planting cover crops earlier in autumn. Due to these incentives, Maryland has the highest level of cover crop adoption in the United States (USDA NASS 2017). Cover crops reduced N loading in 2009 to 2010 and 2019 to 2020 by an estimated 544 (MDA 2010) and 1,600 Mg of N (MDA 2020b), respectively. While this was a substantial N load reduction over a decade, greater reduction is required to improve the health of the Chesapeake Bay.

Cover crops planted in mid to late autumn may not have sufficient growing degree days (GDD) available before winter dormancy for optimal growth. For example, Hively et al. (2020) compiled 2008 to 2017 MACS enrollment data for Maryland farmers in the Tuckahoe Creek watershed, which drains many agricultural fields on Maryland's Eastern Shore. Of the 4,447 cover cropped

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fields studied, only 33% had cover crops planted before October 1, 28% between October 1 and 15, and 39% after October 15 (Hively et al. 2020). Some Maryland cover crops are planted in November or later (Hively et al. 2020) due to a variety of farm management limitations and decisions, and likely do not reduce NO_3 leaching relative to a bare fallow field (Thapa et al. 2018a). For example, a month or more before it is ready to harvest, corn (*Zea mays* L.), a common cash crop in Maryland, begins to senesce and its roots die and cease nutrient uptake (Hanway 1963; Ciampitti et al. 2013) allowing the accumulation and leaching of soluble N through the soil profile. Hirsh and Weil (2019) measured an average of 115 kg NO_3-N ha^{-1} in 210 cm soil profiles under mid-Atlantic fields at corn and soybean (*Glycine max* [L.] Merr.) maturity, 55% of which was deeper than 90 cm. If not captured by deep-rooted cover crops, this deep soil NO_3 will likely leach to groundwater over winter. Cover crops most effectively reduce NO_3 leached when given enough growing time to produce large biomass and deep roots (Kristensen and Thorup-Kristensen 2004; Thorup-Kristensen et al. 2009; Yang et al. 2014; Wahlström et al. 2015; Christopher et al. 2021; Sedghi and Weil 2022). Early planting of cover crops may therefore drive reductions in NO_3 leaching.

Early cover crop planting can be accomplished by interseeding cover crops into standing cash crops (Fisher et al. 2011; Wilson et al. 2013; Moore and Mirsky 2020). Cover crops can be broadcast interseeded using high-clearance ground-based air-seeding equipment or by airplane. Use of a seed drill usually results in more uniform stands and higher rates of seedling emergence than broadcast seeding (Collins and Fowler 1992; Kearney et al. 2006). However, drilling also usually requires waiting until the cash crop has been removed by harvest, which typically occurs a month or more after cover crops could be interseeded. Heat and shade tolerant cover crops can be interseeded into young vegetative corn early in summer using specialized high-clearance drills (Moore and Mirsky 2020), but emergence and growth may be inconsistent (Curran et al. 2018; Noland et al. 2018; Brooker et al. 2020). Cover crop seedling emergence after broadcast interseeding is dependent upon rainfall or irrigation after sowing (Fisher et al. 2011; Wilson et al. 2013; Haramoto 2019; Moore and Mirsky 2020). Late summer to early fall broadcast interseeding may be feasible in Maryland because cash crop leaf senescence occurs early enough to allow sufficient sunlight to reach the seedlings under the canopy.

Late fall planting and early spring termination are the standard cover crop practices. Interviews with farmers in the United States who used cover crops in 2019 revealed that 50% do not plant their cover crops until after cash crop harvest, and that 47.5% have never planted cash crops into living cover crops (CTIC et al. 2020). In the mid-Atlantic region, standard cover crop management practices include drilling the cover crop after fall cash crop harvest and terminating the cover crop several weeks before spring cash crop planting. The Maryland Department of Agriculture recently launched the "Healthy Soil Biomass Pilot Project" to provide farmers with an additional US\$24 ha^{-1} incentive to delay spring cover crop termination until at least May 1 (MACS 2019). Delaying cover crop termination can result in greater C inputs for soil organic matter (OM) (Huang et al. 2020; Jian et al. 2020; Blanco-Canqui 2021), retention of large quantities of soil N (Finney et al. 2016; Blesh and Martin 2018), and production of a thick mulch that can conserve soil moisture during hot, dry summer months (Alonso-Ayuso et al. 2014).

Different cover crop species provide different ecosystem services. Traditionally, single species cover crops have been utilized by farmers, but multispecies cover crops are increasingly popular (CTIC et al. 2017, 2020). In 2015, the MACS program started allowing legumes in mixtures (MACS 2015). While mixtures have become more common since 2015, the overwhelming majority (90+%) of program hectares in Maryland are still planted to single-species cereal cover crops (personal communication with Keppler, Maryland Department of Agriculture, on January 20, 2022). Single species cover crops present both advantages and disadvantages. For example, single species cereal stands can effectively reduce N leached during winter, but may also immobilize soil N in spring (Snapp et al. 2005; Rutan and Steinke 2019). Legume-only stands may fix substantial N if allowed to achieve adequate growth in spring (Tonitto et al. 2006; Poffenbarger et al. 2015; Blesh and Martin 2018). Brassicas can alleviate soil compaction (Williams and Weil 2004; Chen and Weil 2011; Chen et al. 2014) and suppress early spring weed growth (Lawley et al. 2012). Brassica roots also grow deeper and faster than cereal cover crop roots in early fall (Thorup-Kristensen 2001; Kristensen and Thorup-Kristensen 2004; Wahlstrom et al. 2015), allowing brassicas to bring subsoil nutrients to the soil surface (Wang and Weil 2018; Wang et al. 2019). Forage radish (*Raphanus sativus* L.) has been shown to reduce soil N at 180 cm deep (Dean and Weil 2009) and root to 2 m or deeper (Thorup-Kristensen 2006). While forage radish can be effective in capturing soil N in the fall, the assimilated N may again become soluble during winter as temperatures below −7°C usually kill this species, resulting in a rapid release of N from the damaged tissues (Weil and Kremen 2007; Rutan and Steinke 2019).

A multispecies cover crop may provide a wider array of ecosystem services than a single species (Finney and Kaye 2017). Legume–cereal cover crops, the most commonly used type of mixture, often increase cash crop yields when terminated late in spring (Marcillo and Miguez 2017). A meta-analysis by Thapa et al. (2018b) reported that cereal rye (*Secale cereal*)–hairy vetch (*Vicia villosa* Roth) cover crop mixtures can accumulate more spring biomass than either species planted separately, and the hairy vetch can fix as much or more N in the mixture in spring than when grown alone. When radish is planted with a winter-hardy cereal, N released by frost-kill may be taken up by the cereal, thus reducing NO_3 leached relative to a pure radish stand (Gaimaro et al. 2022; Sedghi and Weil 2022). Hirsh et al. (2021) reported that an early-planted forage radish–cereal cover crop may be more effective at cycling N than either species separately. Including a legume in the seed mixture can add biologically fixed N without increasing winter NO_3-N leaching (White et al. 2017; Kaye et al. 2019; Hirsh et al. 2021). On-farm trials in the mid-Atlantic region demonstrated that brassica–legume–cereal cover crop mixtures planted in early fall or late summer could remove most fall soil NO_3-N to a depth of 2 m without causing N immobilization problems in spring (Hirsh et al. 2021).

The objectives of this study were to use farm-scale practices and multispecies (brassica–crimson clover [*Trifolium incarnatum*]–cereal) cover crops to compare cover crop management systems on working farms. We compared standard, extended season, and no cover crop treatments with respect to their performance, costs, and effects on fall and spring cover crop growth, total C and N content, deep soil macro-porewater NO_3 concentrations between December and May, plant-available soil N in June, and soil water content in June. We hypothesized that extending the cover crop growing season by interseeding cover crops earlier in fall and terminating them later in the spring would increase both fall and spring cover crop biomass and N accumulation, reduce NO_3 leaching during winter through early spring, increase soil mineral N, and increase soil moisture in early summer. We performed this research on the Eastern Shore of Maryland over three years.

Materials and Methods

Experimental Design and Site Description. The study was conducted in collaboration with four commercial grain producers in Talbot and Kent counties on the Eastern Shore of Maryland (figure S1 in the supplementary material), on fields that had a history of using cover crops. These fields were on Atlantic coastal plain sediments with primarily sandy loam or silt loam textures (identified hereafter as either sandy or silty sites). In fall of 2017, 2018, and 2019, seven (five corn and two full-season soybean), six (one corn and five full-season soybean), and five fields (four corn and one full-season soybean) were used, respectively. Farmers used their preferred crop rotation for each field. Fields (labeled A to J) used for multiple seasons alternated corn and soybean cash crops, which is a common crop rotation in Maryland. All crops and cover crops were planted with no-till or reduced tillage methods (table 1) (USDA NRCS 2016). In each field we established three cover crop management systems: (1) extended cover crop growing season by aerially interseeding the cover crop several weeks prior to cash crop harvest in fall and later cover crop termination simultaneously with or soon after cash crop planting in spring (hereafter termed Extended), (2) traditional cover crop growing season by drilling seed after cash crop harvest in fall and terminating the cover crop several weeks ahead of cash crop planting in spring (hereafter termed Standard), and (3) a no-cover crop control (hereafter termed No Cover).

Each field was divided approximately in half with each half randomly assigned to either Extended or Standard treatments. Starting in fall of 2018, a No Cover control strip (≥18.3 m wide and 200 m in length) was also established (figure S2). The cover crop was a brassica-legume-cereal mixture with a species from each group selected by the farmer (table S1). For Extended, cover crop seed was broadcast by airplane prior to September 30 into the standing cash crop at early leaf drop for soybean and at black layer for corn. Standard was seeded with a

Table 1

Cover crop treatments, cash crop planted and planting dates, tillage practices reported by farmer, and dates of cover seeding and termination for all fields used in all three years.

Field label	Fall cash crop	Extended plant date	Standard plant date	Extended termination date	Standard termination date	Spring cash crop	Cash crop plant date	Tillage practices
Fall of 2017 to spring of 2018								
A	Corn	Sept. 7	Sept. 22	May 2	Apr. 11	SB	May 11	Vertical tillage
B	Corn	Aug. 19	Oct. 18	May 8	Apr. 10	SB	May 8	No-till*
C	SB	Sept. 20	Oct. 6	May 4	May 4	SB	May 3	No-till*
D	SB	Sept. 23	Oct. 19	Apr. 30	Apr. 19	Corn	May 3	Vertical tillage
E	Corn	Sept. 7	Sept. 22	May 2	Apr. 11	SB	May 10	Chisel plow and disk
F	Corn	Aug. 19	Sept. 28	May 8	Apr. 10	SB	May 8	No-till*
G	Corn	Sept. 9	Oct. 7	Apr. 22	Apr. 22	SB	May 8	Vertical tillage
Fall of 2018 to spring of 2019								
A	SB	Sept. 26	Oct. 24	May 1	Apr. 13	Corn	May 1	Vertical tillage
B	SB	Sept. 5	Oct. 9	Apr. 23	Mar. 29	Corn	May 6	No-till*
D	Corn	Sept. 6	Sept. 21	May 2	Apr. 14	SB	May 2	None
E	SB	Sept. 25	Oct. 24	May 1	Apr. 13	Corn	May 1	Vertical tillage
H	SB	Sept. 5	Sept. 19	Apr. 23	Mar. 29	Corn	May 6	No-till*
I	SB	Sept. 4	Oct. 2	Apr. 24	Mar. 29	Corn	May 14	No-till*
Fall of 2019 to spring of 2020								
A	Corn	Aug. 21	Sept. 10	Mar. 30	Mar. 18	SB	Apr. 23	Vertical tillage
B	Corn	Aug. 22	Sept. 14	June 4	Mar. 6	SB	Apr. 21	No-till*
E	Corn	Aug. 21	Sept. 23	Mar. 27	Mar. 18	SB	May 16	Chisel plow and disk
H	Corn	Aug. 22	Sept. 13	May 13	Mar. 6	SB	Apr. 7	No-till*
J	SB	Sept. 5	Oct. 2	Mar. 6	Mar. 6	Corn	Apr. 7	No-till*

Note: SB refers to full season soybean crops.

*Field has not had any tillage for at least 10 years.

no-till drill as soon as possible after cash crop harvest. Seeding rates (table S1) and dates (table 1) varied among farm fields according to farmer preferences. The spring cash crop was planted on the same date for all three cover crop management treatments within each field.

A transect of sampling stations was established in each treatment. Sampling stations were 6 m in diameter, approximately 50 m apart, and located in representative cover crop stands free from anomalies, such as burrows or irrigation wheel tracks. In 2017 to 2018, there were five sampling stations in each treatment (Extended and Standard), and in 2018 to 2019 and 2019 to 2020, there were four sampling stations in each treatment (Extended, Standard, and No Cover). In fall of 2019, Extended at field J did not establish a discernable cover crop stand, but Standard resulted in a normal cover crop stand. To save on labor and material costs, we did not make any measurements in the Extended treatment at field J, but instead all cover crop biomass calculations assumed that the Extended cover crop biomass was equal to the No Cover (weed) biomass.

Weather. Daily temperature, precipitation, and 40-year local weather averages were determined using Oregon State University software (PRISM 2004). Cumulative growing degree days (GDD_{cum}) with a mean daily temperature base of 4°C (Brennan and Boyd 2012; De Notaris et al. 2018) were calculated as

$$GDD_{cum} = \Sigma(\text{daily mean air temperature} - 4). \tag{1}$$

Cover Crop Biomass and Nitrogen Content. Fall cover crop biomass was measured in early December shortly before the radish winter-killed. At each sampling station, the vegetation within two randomly placed 0.5 × 0.5 m quadrats was clipped 1 cm above the soil surface and placed into brown paper bags for drying. The fleshy radish taproot, including aboveground and belowground portions, was pulled up from the soil and rinsed thoroughly with tap water to remove any soil prior to drying. The collected cover crop biomass was sorted into six components (radish roots, radish shoots, rapeseed [*Brassica napus*], legumes, cereals, and weeds), dried to constant mass for at least 48 hours at 60°C to 70°C, and then weighed. Brassica biomass means reported include the sum of radish foliage, radish fleshy taproot, and rapeseed aboveground tissues. Total biomass reported includes the sum of aboveground biomass for rapeseed, legume, cereal, and weeds and total for radish. Spring cover crop biomass was measured using the above method immediately before spring herbicide applications.

Dried tissue was ground separately (<1 mm) for each species and a 0.2 ± 0.001 g subsample analyzed for total C and N by high-temperature combustion (LECO CN628 Elemental Analyzer LECO Corp., St. Joseph, Michigan) for samples with >50 kg dry matter ha^{-1}. For samples with <50 kg ha^{-1} dry matter, the N concentration was assumed to be equal to the average for all samples of that species, an assumption that would result in negligible errors in the total N accumulated in each treatment. For spring of 2019 samples, we outsourced LECO analysis to a lab that reported N but not C data. We estimated the C concentrations for each species for spring of 2019 cover crop samples from the average C concentration of the same species in spring of 2018 and 2020. Cover crop N content for each species was calculated as dry matter (kg ha^{-1}) multiplied by N concentration (mg kg^{-1}). The total biomass and N content at each sampling station was taken as the sum of dry matter or N in cereal shoots + clover shoots + weed shoots + radish shoots + radish fleshy taproots + rapeseed shoots.

Nitrate Leaching. Soil macro-porewater samples were obtained from the bottom of the crop root zone using clean tension lysimeters made of butyrate tubes (22 mm outer diameter) with 100 kPa air entry ceramic tips (Irrometer, Riverside, California). Lysimeters were installed to depths of 100 cm deep in sandy fields or 70 cm deep in silty fields, within 1 m of the center of each sampling station, as soon as possible following cover crop drilling. This depth was chosen to measure drainage water below the plant root zone throughout the primary leaching season of November through April in Maryland (Staver and Brisfield 1998). Lysimeters were sampled approximately every two weeks during the leaching season and until lysimeters were uninstalled for spring cash crop planting. Before collecting samples, a 75 to 85 kPa vacuum was applied to the lysimeter for 1 to 24 hours. Samples were collected from lysimeters into 50 mL conical centrifuge tubes and kept cold during transport. Upon return to the lab, the samples were immediately filtered through a 2.5 μm filter paper (Whatman 42) and preserved by acidifying to pH of 1 to 2 with one drop (0.04 mL) of 6 M sulfuric acid (H_2SO_4) per 10 mL of sample volume. Preserved samples were frozen until analysis. After thawing, NO_3-N concentrations were analyzed using a LaChat Flow Injection Analyzer (Hach, Loveland, Ohio) with QuickChem 8000 manifold for NO_3-N + nitrite-N (hereafter NO_3-N) via cadmium (Cd) reduction and colorimetric determination at 520 nm using a modified method of QuikChem 12-107-04-1-H with a deionized water matrix. All NO_3-N concentrations lower than the lowest standard (0.05 mg NO_3-N L^{-1}) were reported as 0.025 mg L^{-1}.

Estimation of Field Drainage Water Volume. To determine mass of NO_3-N leached, the volume of water drained through the soil profile was estimated using a daily water balance equation provided by Allen (1998):

$$DP_i = D_i - D_{i-1} - ET_i + P_i - Q_i\ , \tag{2}$$

where DP is deep percolation, D is moisture deficit relative to field capacity, P is precipitation, Q is runoff, ET is evapotranspiration (Penman 1948), and *i* represents the *i*th calculated day. This water balance approach has been used to estimate cumulative NO_3 leaching losses (Tosti et al. 2014; Heinrich et al. 2014) and has been validated by comparisons with ET measurements (Cai et al. 2007; Mutziger et al. 2005). Following the approach of and using the moisture contents described in Allen et al. (2005), all soils were assumed to be at field capacity on the date of first lysimeter sample collection. Runoff (Q) was estimated using the curve number method (Hawkins et al. 1985):

$$Q = \frac{\left[P - 0.2 \times \left(\frac{25{,}400}{CN} - 254\right)\right]^2}{\left[P + 0.8 \times \left(\frac{25{,}400}{CN} - 254\right)\right]}\ , \tag{3}$$

where Q (cm) is water runoff loss, P (cm) is precipitation, and CN (no units) is the uncalibrated curve number determined from the soil hydrologic group (table S2) assuming "good" infiltration capacity and surface residue cover. This method can accurately predict runoff volume when the curve number is calibrated to rain events (Jin et al. 2015; Zema et al. 2017), but has been shown by Ficklin and Zhang (2013) to be reliable without calibration. In the present study, there were no measurements of rooting depth or leaf area index to justify different drainage water calculations among cover crop treatments, so a single estimate of drainage water was calculated for each site-year, beginning on the date of first lysimeter sample collection and ending when final samples were collected.

Not every lysimeter produced a porewater sample on every sampling date. Therefore, NO_3-N concentrations were aggregated by month. On each day for which the water balance predicted drainage, mean monthly NO_3-N concentration for each treatment at each field was multiplied by calculated drainage to estimate daily NO_3-N leached, which was summed to estimate cumulative NO_3-N leaching losses for each cover crop growing season:

$$\text{Cum NO}_3\text{-N leached (kg NO}_3\text{-N ha}^{-1}) = \sum DP_i \text{ (cm)} \times \text{NO}_3\text{-N}_{\text{month}} \text{ (mg L}^{-1}) \times \frac{1\text{ L}}{1 \times 10^3\text{ cm}^3} \times \frac{1 \times 10^8\text{ cm}^2}{1\text{ ha}} \times \frac{1\text{ kg}}{1 \times 10^6\text{ mg}}. \quad (4)$$

Soil Mineral Nitrogen, Moisture, and Organic Matter. Soil series and associated texture and hydrologic group were determined for each site-year using soil survey data (USDA NRCS 2020) and field observations. Composite soil samples (0 to 30 cm) were taken in June from random locations within 1 m of the center of each sampling station and analyzed for OM, pH in water, soil texture, and Mehlich 3 extractable nutrient contents (Waypoint Analytical lab, Richmond, Virginia; table S2).

When corn was at the V-4 to V-6 stage of growth (Hanway 1963), a total of six soil cores per sampling station (1.84 cm diameter × 30 cm deep) were collected for a presidedress NO_3 test (PSNT) (Meisinger et al. 1992). The cores were combined into one composite sample per sampling station, sealed in plastic bags, immediately stored on ice, transported to the lab, and weighed. On the same day when soil samples were collected from corn fields, we also collected similar soil samples from nearby study fields growing soybean crops. Composite soil samples were dried at 65°C and sieved to pass a 2 mm screen. A subsample from each composite sample was dried for 24 hours at 105°C and weighed once dry to determine gravimetric water content. Two grams of dry soil was ashed for loss on ignition at 400°C for 16 hours in porcelin crucibles to determine the percentage organic matter (%OM). Exactly 2.0 g of dry soil and 20.0 mL of 0.5 M K_2SO_4 in a 50 mL centrifuge tube were shaken horizontally (200 rpm for 30 min) and filtered through VWR 410 filter paper. The filtrate was analyzed for NO_3-N (Cd reduction method) and ammonium-nitrogen (NH_4-N; salicylate method) as described previously.

Economic Analyses. The cost of cover crop planting in each treatment was estimated for each of the 18 site-years. We used the median 2021 custom seeding rate costs for drilling or aerial seeding from a survey by University of Maryland Extension (Dill 2021). The cost of cover crop seed for the three-species cover crop mixes was estimated from Dill (2021) or local seed suppliers for the species planted and seeding rates used for each treatment. Maryland Cover Crop Program (MDA 2020a) guidelines were used to calculate the incentive payment for each seeding treatment and field. The cost-effectiveness of each treatment was calculated from both the farmer and MACS program (net planting cost) viewpoints as dollars spent per kilogram of N taken up in fall, or per kilogram of dry matter produced in spring. The cost to the farmer of implementing each treatment was the sum of the seed cost and the planting operation cost. The net planting cost was calculated as the cost to farmer minus the estimated MACS incentive payment. Termination costs were not included because farmers made the same herbicide applications whether just winter weeds or a cover crop was present.

Statistical Analyses. Data were analyzed using R Studio version 1.2.5042 and Microsoft Excel (Office 365, Microsoft Corporation, Redmond, Washington). The Shapiro-Wilk test was used to assess normality, and power transformations were applied to satisfy assumptions of normality and homogeneity of variances. The experimental design was unbalanced due to different numbers of fields each year and the lack of a no cover control in year one. Therefore, the data were analyzed by creating a multilevel partially nested, mixed effects model in R with the lmer package (Kuznetsova et al. 2017). The effect of year, fall cash crop, and field were random effects and the soil texture and cover crop treatment were fixed effects. We performed an F test on the lmer model using the type III Satterthwaite method (Hrong-Tai Fai and Cornelius 1996). When the F test indicated a significant cover management treatment effect, the results were subsequently subjected to lsmeans post-hoc analysis with Tukey adjustment to differentiate among treatment levels.

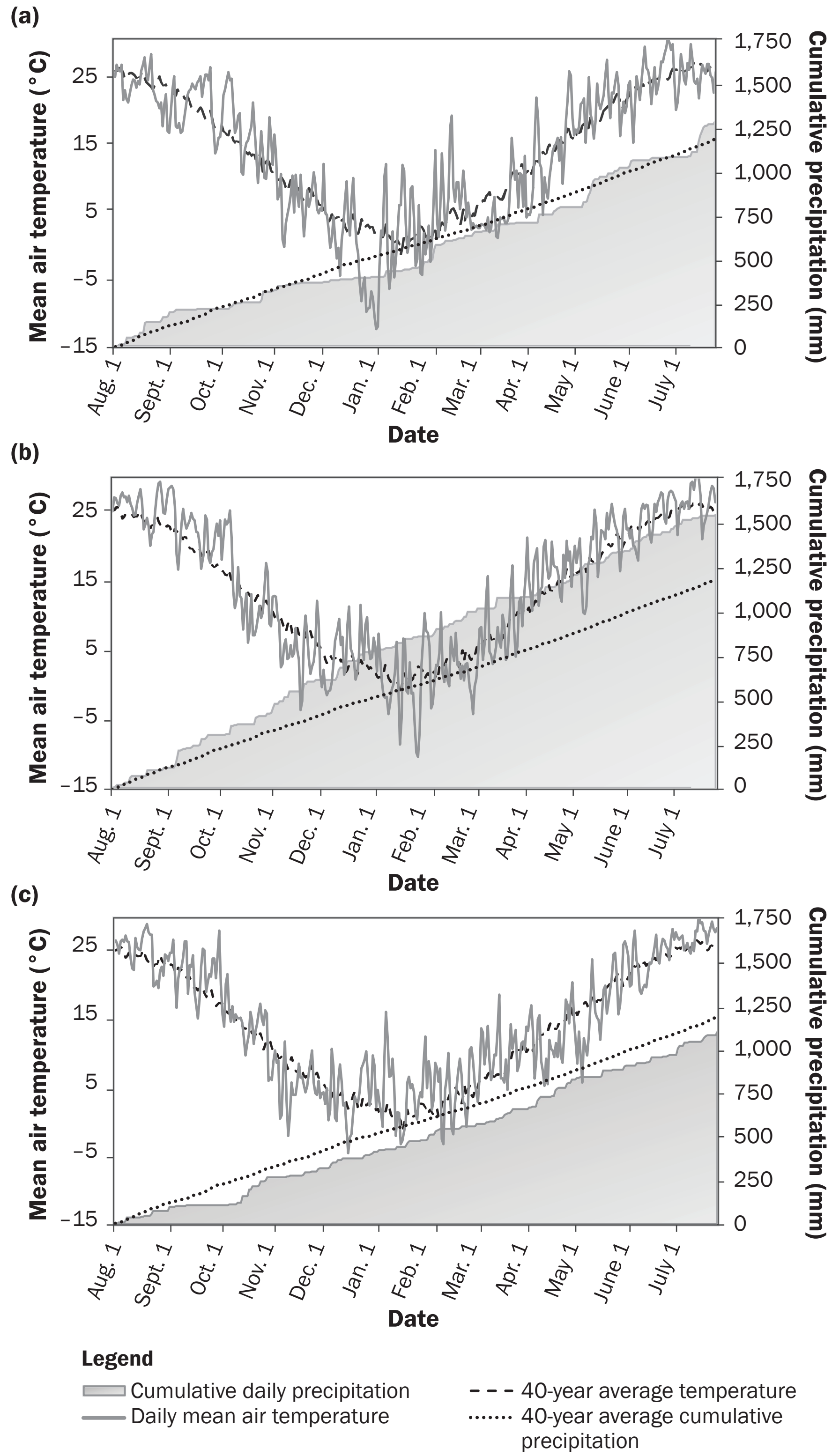
The Microsoft Excel data analysis add-in was used to perform all regression analyses. The relationship between crop biomass or N content with accumulated GDD available was analyzed via regression separately for each year. Fall cover crop N content and estimated cumulative NO_3-N leached were averaged for each treatment by year combination, and a regression analysis was performed. The soil porewater NO_3-N concentrations were analyzed for each year separately using repeated measures analysis with the lmer command to test for effects of cover management treatment and sample collection month, as well as their interactions. The fall cover crop N content and spring cover crop biomass per dollar spent by MACS or spent by farmers were analyzed using the lmer command to test for the differences due to year and cover management treatment, with each field used as a random blocking factor.

Results and Discussion

Weather Variations by Year. Extreme weather variation characterized the three field seasons of this project (figure 1). In 2017 to 2018 heavy rainfall occurred in August of 2017 and April of 2018. Mid-July of 2018 through fall of 2018 was also characterized by heavy rainfall, but September to October of 2017 and early June through mid-July of 2018 were extremely dry (figures 1a and 1b). In 2017 to 2018, the rainfall patterns resulted in an estimated 24.2 to 30.7 cm of drainage water from each field between mid-February and late April, which represents the time period for which we took lysimeter samples. In 2018 to 2019, cumulative rainfall was ~300 mm greater than the 40 year average (figure 1b). However, dry periods occurred in July to October of 2019. Between December of 2018 and April of 2019, we estimated 39.9 to 44.1 cm of drainage water from each field. The 2019 to 2020 field season was dry in mid-August through October of 2019, and rainfall was consistently lower than the 40-year average (figure 1c). Between November of 2019 and March of 2020, we estimated 24.5 to 25.6 cm of drainage water for each field. The 40-year average (mean for 1981 to 2020) September rainfall, prior to

Figure 1

Daily mean air temperature and cumulative daily precipitation for (a) 2017 to 2018, (b) 2018 to 2019, and (c) 2019 to 2020. The 40-year local averages are included for comparison. When the filled, grey gradient area is below the dashed black 40-year average line, rainfall was below normal for that time period. When the filled, grey gradient area is above the dashed black 40-year average line, rainfall was above normal for that time period.



or at cover crop interseeding, for Talbot and Kent counties was 10.3 cm (PRISM 2004). The September rain for 2017 (4.3 cm) and 2019 (2.2 cm) was far below the 40-year average, while September of 2018 was far wetter (19.5 cm). In late January of 2018 and 2019, lowest mean daily air temperatures were −12.3°C and −10.3°C, respectively, which was sufficiently cold to winter-kill the forage radish (figure 1). Temperatures in the winter of 2019 to 2020 were unusually warm, and not low enough to winter-kill the forage radish (lowest mean daily temperature was −4.5°C; figure 1c).

Fall Cover Crop Total Biomass and Species Distribution. Averaged across 18 site-years, mean fall biomass for Extended was 1,500 kg ha^{-1}, which was 1.7 times that for Standard (880 kg ha^{-1}), and both were significantly greater than No Cover biomass (173 kg ha^{-1}). There was no difference in fall cover crop biomass between fields planted into soybeans or corn (table S3). However, the year by cover crop management interaction was significant due to increased effectiveness of broadcasting early in the wet conditions of 2018, while there was no difference between Extended and Standard in the dry years of 2017 or 2019 (table 2). Regression of fall of 2018 GDD against biomass was significant, with GDD accounting for 90.6% of variation in fall biomass (regression, $p < 0.001$), with a sharp increase in biomass after a 700 GDD threshold, which occurred for Extended (figure 2a). In contrast, this relationship did not exist in the dry years of 2017 and 2019. On average, Extended was aerially sown 26 days earlier than the late-drilled Standard (table 1), leading to an average of 380 additional GDD before expected winter dormancy (December 1). Germination of broadcast cover crop seed has been shown to be dependent on rainfall after sowing and likely explains the difference in fall biomass between the years (Fisher et al. 2011; Wilson et al. 2013; Moore and Mirsky 2020). The weather in fall of 2017 and fall of 2019 was unfavorable to early broadcast interseeding (Extended) because the dry conditions likely delayed seed germination in Extended and simultaneously allowed for earlier fall harvest and cover crop sowing in Standard (figure 1). Thus, GDD between seeding and December 1 did not significantly influence fall biomass in 2017 or 2019 (figure 2a). In the wet fall of 2018, the Extended cover crop seed quickly germinated while wet conditions

Table 2
Late fall dry matter for total cover crop and cover crop components, tissue carbon to nitrogen (C/N) ratio, tissue N concentration, and cover crop N content for cover crops at 18 site-years on commercial farms in Maryland.

Source of variability			Cereal (kg dry matter ha^{-1})	Clover (kg dry matter ha^{-1})	Brassica (kg dry matter ha^{-1})	Weeds (kg dry matter ha^{-1})	Total biomass (kg dry matter ha^{-1})	Cover crop N content (kg N ha^{-1})	Cover tissue C/N ratio	Cover tissue N conc. (g N kg^{-1})
Year (Y)	2017		510a*	24.1b	494ns	61.6ns	1,090ns	33.5ns	13.8ns	30.8b
	2018		352b*	156a	419ns	103ns	1,030ns	41.8ns	15.7ns	40.6a
	2019		480a*	49.5b	899ns	107ns	1,540ns	41.6ns	15.1ns	27.1b
Management treatment (M)	Extended		450ns	139a	815a	97.0b	1,500a	48.8a	14.5b*	32.5b
	Standard		440ns	22.2b	381b	37.3c	880b	28.2b	13.5b*	31.9b
	No Cover		—	—	—	173a	173c	6.44c	18.1a*	37.3a
Y × M	2017	Extended	393b	29.2c*	665ns	109ns	1,200a	36.6b	13.9ns	30.6b
		Standard	628a	19.0c*	279ns	14.7ns	941a	29.1b	13.8ns	30.9b
		No Cover	—	—	—	—	—	—	—	—
	2018	Extended	491ab	290a*	805ns	117ns	1,700a	65.3a	15.6ns	38.4b
		Standard	212b	21.6c*	33.9ns	26.9ns	294b	9.62c	13.5ns	32.7b
		No Cover	—	—	—	165ns	165b	8.35c	18.0ns	50.7a
	2019	Extended	470ab	67.4b*	1,010ns	59.5ns	1,610a	44.7ab	14.0ns	27.8bc
		Standard	489ab	27.2c*	809ns	77.0ns	1,400a	45.4ab	13.1ns	32.4b
		No Cover	—	—	—	183ns	183b	3.86c	18.1ns	21.1c

Notes: Means within an effect followed by the same letter do not differ significantly. * significant at $p < 0.1$; all other letter differences are significant at $p < 0.05$. ns is not significant at $p < 0.1$. A more detailed version of this table is available in the supplementary materials (table S3).

delayed cash crop harvest and cover crop drilling for the Standard treatment. Similarly, over three years, Sandler et al. (2015) only measured a consistent relationship between early planting and radish biomass in a year with adequate rainfall when they broadcast-interseeded radish into soybeans and corn in Missouri. When the dry fall weather benefitted Standard in the present study we detected no significant difference in fall biomass between Extended and Standard.

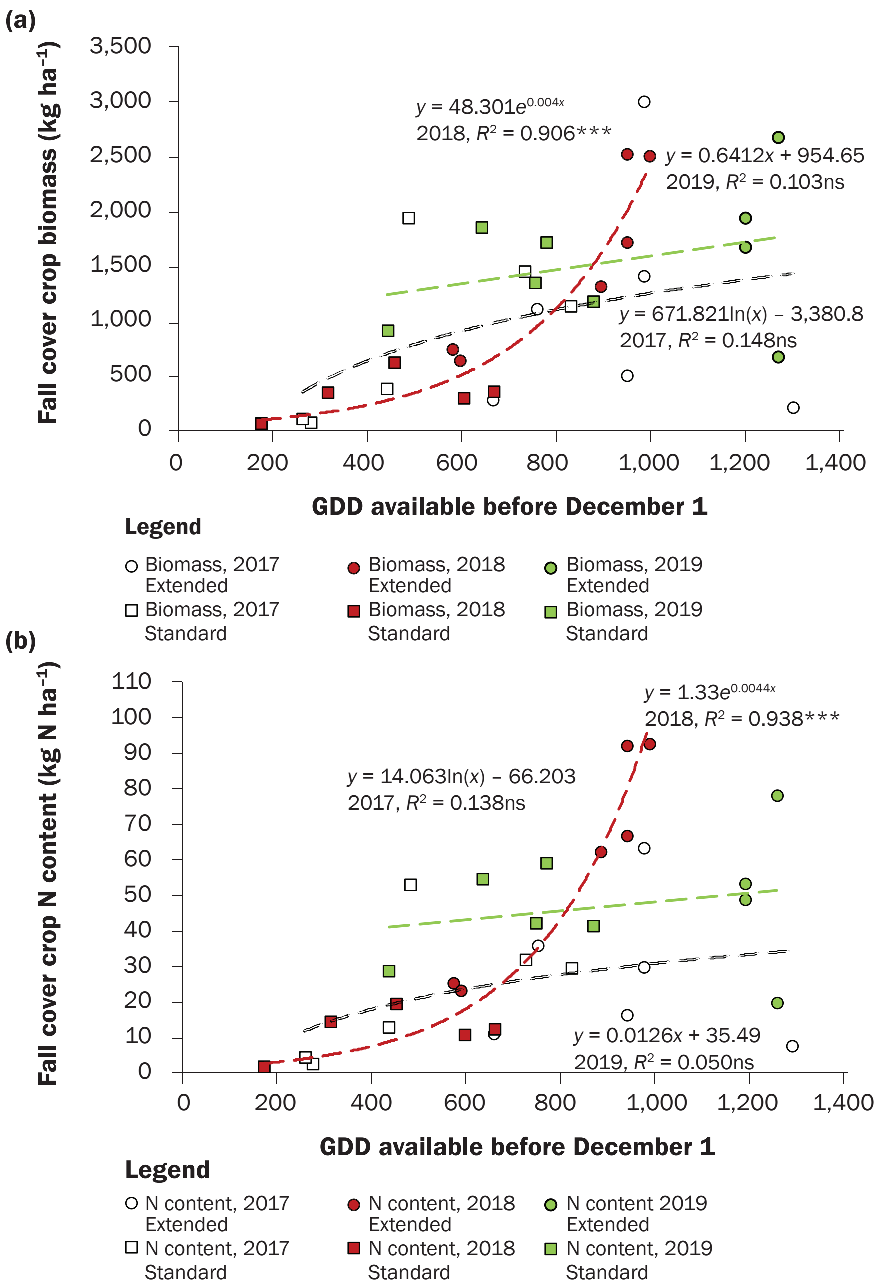
Cover crop planting treatment impacted species proportions in fall (table 2). Across all 18 site-years, the fall biomass for Extended was 54% brassica, 30% cereal, and 9% legume, whereas Standard was 43% brassica, 50% cereal, and 3% legume. Weed biomass was lowest for Standard and greatest for No Cover. Averaged across all three years, fall brassica biomass was greater for Extended than for Standard; there was no effect of year on brassica biomass. Other researchers studying diverse cover crop mixtures have found that winter cereal species perform well when temperatures are low (Hayden et al. 2015; Baraibar et al. 2020), and brassicas dominate fall cover crop mixtures if planted early under warm conditions (Murrell et al. 2017; Farney et al. 2018; Baraibar et al. 2020).

Fall Cover Crop Nitrogen Content. Fall cover crop tissue N concentration and N content varied by treatment (table 2). Averaged across the 18 site-years, fall cover crop N content was significantly highest for Extended (48.8 kg N ha^{-1}), followed by Standard (28.2 kg N ha^{-1}), and lowest for No Cover (6.44 kg N ha^{-1}), despite No Cover having the highest tissue N concentration (37.3 g N kg^{-1}). However, this statistical difference in treatments was controlled by the 2018 season. In 2018 cover crop N content for Standard was only 9.62 kg N ha^{-1}, which was not significantly different than No Cover (8.35 kg N ha^{-1}), but was significantly lower than Extended (65.3 kg N ha^{-1}) where biomass was ~3 times higher than in the other treatments. In the dry falls of 2017 and 2019, there was no difference between Standard and Extended. Sowing date and the resulting availability of GDD had no effect on cover crop N content in fall of 2017 or 2019, but in the wet fall of 2018 cover N content increased exponentially with additional GDD (figure 2b). The late planted 2018 Standard was comprised of 72% cereals (table 2), which tend to have lower tissue N concentrations than brassicas or legumes (Snapp et al. 2005; Jahanzad et al. 2016; Rutan and Steinke 2019). Thus, the GDD available before December 1 accounted for 94% of all variation in fall cover crop N content in 2018 (figure 2b). Early aerial interseeding (Extended) produced fall biomass and N content that was greater than the more common practice of drilling after harvest (Standard) under wet fall conditions in 2018. However, no difference was observed if fall precipitation was below average. This evidence partially supports our hypothesis in that Extended captured as much or more N than standard in all three years of this study.

Nitrate Concentrations and Estimated Leaching. Averaged across all 18 site-years porewater NO_3-N concentration was greatest for No Cover (11.8 mg NO_3-N L^{-1}), and lower for Standard (2.68 mg NO_3-N L^{-1}) and Extended (1.95 mg NO_3-N L^{-1}; data not shown). In 2017 to 2018, the cover crop stands for Standard and Extended both produced successful cover crop stands (table 2), and porewater NO_3-N concentrations were very low (1.3 to 1.4 mg NO_3-N L^{-1} average for season; figure 3a), but did not differ between treatments. In 2018 to 2019 with a wet fall (figure 1b), mean porewater NO_3-N concentration was significantly lower for Extended (1.29 mg NO_3-N L^{-1}) than for Standard (4.45 mg NO_3-N L^{-1}), and both were significantly lower than for No Cover (7.66 mg NO_3-N L^{-1}; figure 3b). In the driest year, 2019 to 2020, porewater NO_3-N concentrations and variability were both high; however concentrations were significantly lower in Extended (1.6 mg L^{-1}) and Standard (0.8 mg L^{-1}) as compared to No Cover (13.05 mg L^{-1}; figure 3c), but there was no difference between Extended and Standard. There was no interaction between cover management and time on porewater

Figure 2

Relationship between cumulative growing degree days (GDD) available (cover crop planting to December 1) and (a) total fall cover crop biomass or (b) fall cover nitrogen (N) content. Each data point is the mean for one treatment at one site-year. Trendlines include Standard and Extended for each year. No Cover was excluded. ***significant at $p < 0.001$; ns indicates not significant at $p < 0.05$.



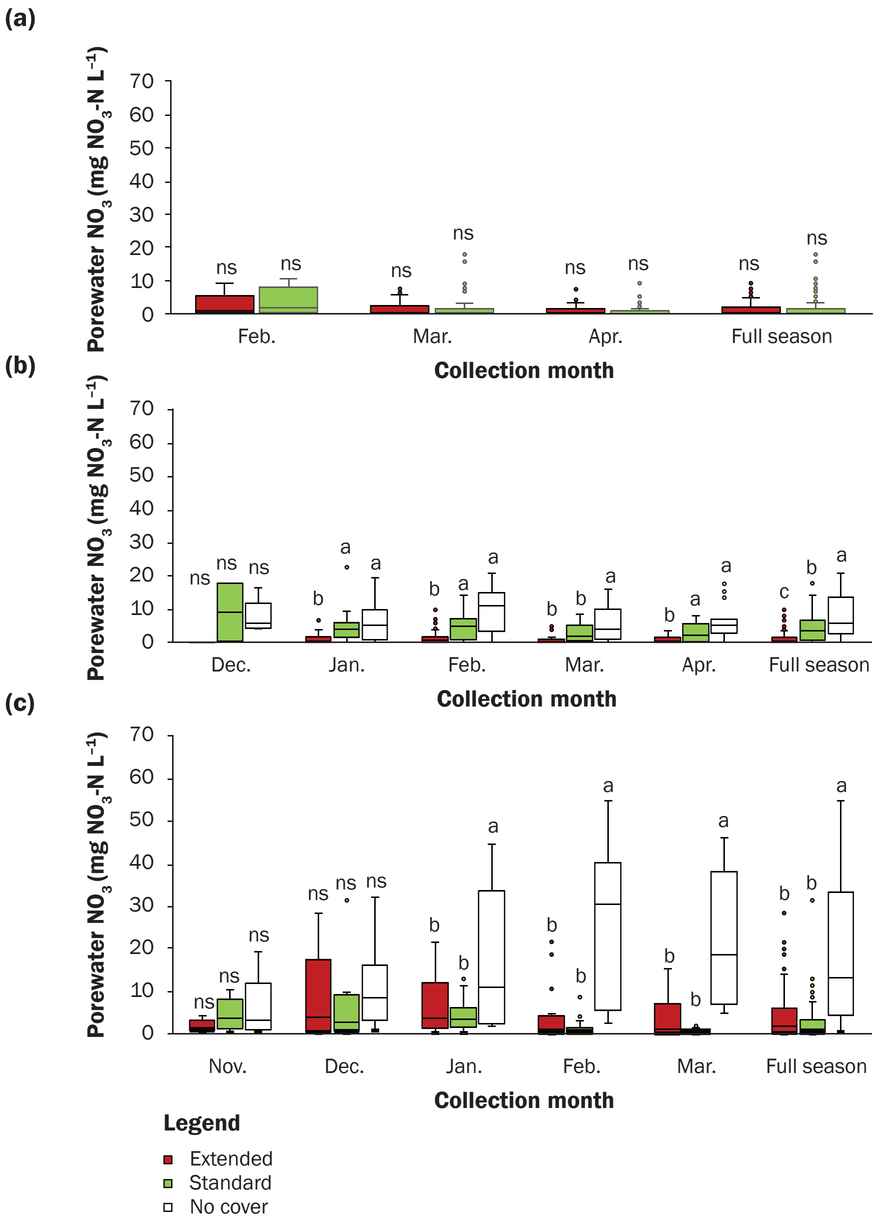
NO_3-N concentrations overall or in any of the three years of this study (figure 3). This is in contrast to studies in Delaware (Ritter et al. 1991, 1993) where higher soil porewater NO_3-N concentrations were measured in fall and winter than in spring. The dry conditions in fall of 2017 and fall of 2019 were not favorable for aerial seeding early germination, resulting in no statistical difference in winter-spring NO_3-N concentrations between Standard and Extended (figures 3a and 3c).

Cumulative estimated NO_3-N leached (equation 4) was significantly affected by cover management treatments, and those effects varied by year (figure 4). Extended resulted in significantly less NO_3-N leached than Standard in 2018, but statistically indistinguishable leaching in comparison to Standard in the dry falls of 2017 and 2019. This was likely due to the early germination of the flown cover crop seed in the Extended treatment under the wet September of 2018 conditions and the late planting and germination of the drilled Standard cover crop. In 2018, Standard reduced NO_3-N leached by 45% relative to No Cover, whereas Extended reduced NO_3-N leached by 84%. In contrast, in the dry year of 2019, Standard and Extended reduced NO_3-N leached by 78% to 82%, relative to No Cover (figure 4). This cover crop effect on NO_3-N leaching is nearly identical to the 78% to 85% reduction estimated by Hively et al. (2020) for fields in Maryland planted early to cereal cover crops. However, it is likely that our measurements underestimated the reduction in NO_3-N leached by Extended every year because the early established cover crop likely began affecting porewater NO_3-N for several weeks before the Standard cover crop was established and the lysimeters were installed. Future cover crop timing research should measure ET and porewater NO_3-N concentrations immediately after cover crops emerge to determine how early the cover crop effect is detectable.

The early planting for Extended resulted in additional GDD, which resulted in greater cover crop N content in a wet year (2018; figure 2b), and therefore reduced NO_3-N leached. Among all 46 experimental units, across 18 site-years, fall cover crop N content accounted for 91.6% of the variation in NO_3-N leached (figure 5). This relationship was nonlinear with an apparent threshold such that all cover crop treatments with fall cover crop N content of 22.5 kg N ha^{-1} or greater had estimated cumulative NO_3-N leaching losses <10.3 kg NO_3-N ha^{-1}. Previous research in Maryland (Staver et al. 1991; Meisinger and Ricigliano 2017) and Delaware (Ritter et al. 1998) also found low NO_3-N leaching losses under cover crop treatments with high cover crop N content. A similar relationship was established between spring cover crop N content and the cover crop effect on NO_3-N leached in the meta-analysis by Thapa et al. (2018a). Of these studies, only Ritter et al. (1998) measured fall cover crop biomass, but none of these studies used regression analyses to describe the relationship between fall cover crop N content and cumulative mass of NO_3-N leached. Our regression analysis (figure 5) supports the concept that reductions in NO_3-N leached over

Figure 3

Box plots showing monthly and full season porewater nitrate-nitrogen (NO_3-N) concentrations for each treatment between fall and spring in (a) 2017 to 2018, (b) 2018 to 2019, and (c) 2019 to 2020. Boxes with the same lowercase letters within each month indicate that NO_3-N concentrations do not differ significantly at $p < 0.05$. Horizontal lines indicate median NO_3-N concentrations. Treatment differences were analyzed within each month and no treatment by time interactions were significant. Ns indicates not significant at $p < 0.05$.



winter are driven by removal of soluble N from the profile by the cover crop before cover crop winter dormancy. Our hypothesis that early interseeded cover crops would reduce NO_3-N leached more than late Standard cover crops was supported only in years when sufficient rainfall was received soon after aerially broadcasting seed.

Our calculations also likely underestimated the cover crop effect on NO_3-N leaching losses due to our assumption that drainage volume was the same for all treatments. An actively growing cover crop is likely to increase ET and reduce drainage water volume (Meisinger et al. 1991; McCracken et al. 1993; Unger and Vigil 1998; Meisinger and Delgado 2002; Meyer et al. 2018). The groundwater recharge season in the mid-Atlantic region begins in mid-November and ends in late April (Staver and Brinsfield 1998; Meisinger and Delgado 2002), with leaching to groundwater mostly occurring in December to April (Meisinger et al. 1990). During late spring and summer (May to June), high ET results in little to no drainage and a dropping water table (Meisinger and Delgado 2002), barring extreme rainfall events. During the early fall, before the Standard cover crops were planted (September to October), relatively high ET by cover crops would be expected to dry the soil profile and reduce drainage water volume generated by rain events. Thus, the true effect of successfully established early planted cover crops on NO_3-N leaching is likely greater than our estimates.

Late Cover Crop Termination Affects Spring Biomass and Species Balance. Averaged across all 18 site-years, spring biomass for Extended (2,610 kg ha^{-1}) was more than twice that for Standard (1,240 kg ha^{-1}), and almost four times the biomass in No Cover (702 kg ha^{-1}; table 3). Averaged across the three years of the study, Standard cover crop was terminated and sampled 23 days earlier than Extended. Extended spring cover crop biomass was significantly greater than both Standard and No Cover (table 3) in all three years, and at both the sandy and silty sites (table S4), regardless of fall precipitation. However, Standard and No Cover accumulated statistically similar biomass amount in 2019, but a different amount in 2020. This supports our hypothesis that extending the cover crop season will increase spring cover crop biomass.

Extended, with increased GDD available, significantly increased spring biomass in all three years (figure 6); however the rate of biomass accumulation in spring varied among years (figure 6a). Between December 1 and spring cover crop termination, cover crop biomass increased in the 2017 to 2018 and 2018 to 2019 seasons at a rate of 6.4 to 6.9 kg ha^{-1} GDD^{-1}, and available spring GDD accounted for 44% to 48% of variation in spring biomass (figure 6a). Because of the unusually warm winter of 2019 to 2020 (figure 1c), radish did not winter-kill and contributed to the much higher rate (15.0 kg ha^{-1} GDD^{-1}) of dry matter accumulation in spring 2020. In 2020, the available spring GDD accounted for 65% of variation in spring biomass (figure 6a). Mirsky

Figure 4
Estimated cumulative nitrate-nitrogen (NO_3-N) leached for the entire field season differentiated by cover crop treatment and year. All letters on graph indicate significant differences at $p < 0.05$ as assessed by Tukey HSD.

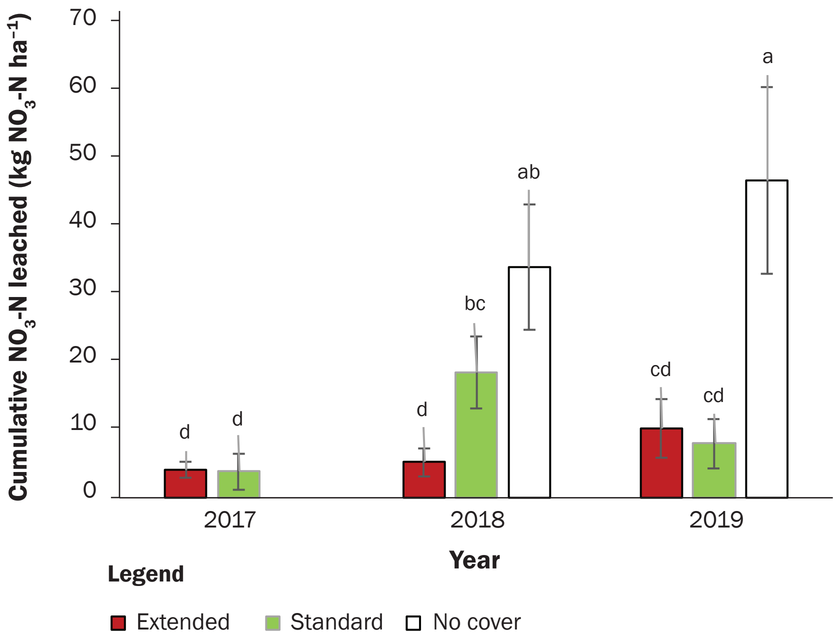
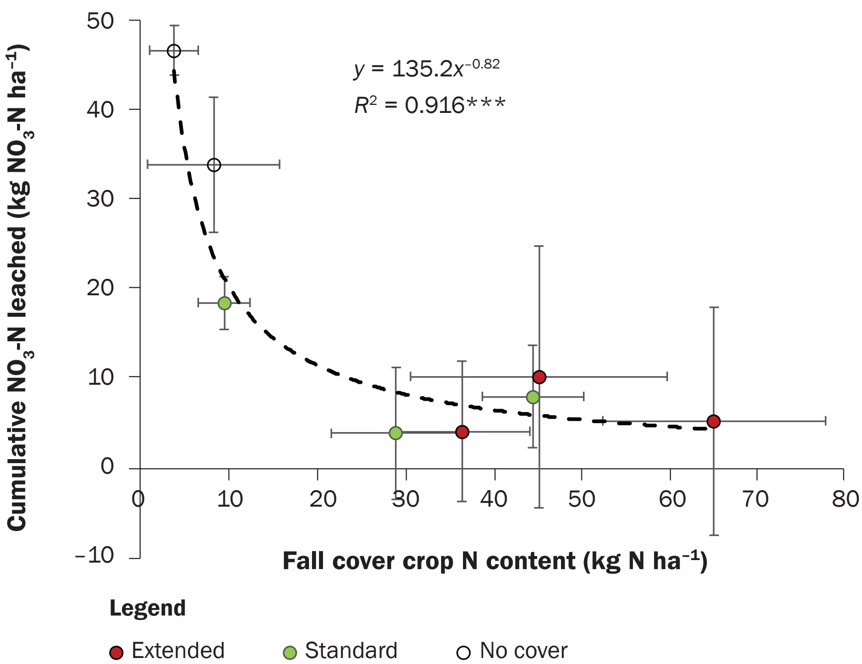


Figure 5
Relationship between fall cover crop nitrogen (N) content and estimated cumulative nitrate-nitrogen (NO_3-N) leached during winter and spring. Each data point is the average of one treatment each year. Error bars show one standard error across four to seven replications. *** $p < 0.001$.



et al. (2011), also working in the mid-Atlantic region, reported that 68% of spring cover crop biomass variation was explained by available spring GDD. Clark et al. (1997) performed small plot termination timing studies on hairy vetch + rye cover crop mixes in Maryland and reported an average rate of dry matter accumulation of 8 kg ha^{-1} GDD^{-1}. This rate is similar to what we found in the two years of this study in which radish winter-killed (2018 and 2019), but was approximately half of our 2020 value when radish survived the winter. The cover crop dry matter consistently contained approximately 40% C (data not shown), so extending the cover crop growing season by several weeks in fall and spring approximately doubled the aboveground organic C input in our study.

While seeding rates could account for differences in spring biomass, our data indicated that the difference was due to later termination of cover crop in Extended. Recommended aerially broadcast seeding rates (Extended) are typically 20% to 100% higher than drilled (Standard) seeding rates (Kearney et al. 2006; Clark 2008; Brennan and Leap 2014). For eight site-years, Extended was sown with different species and/or at a higher seeding rate than Standard (table S1). At site-years with a greater seeding rate for Extended, Extended produced 1,690 kg ha^{-1} in fall (data not shown). For site-years with the same seeding rate between Extended and Standard, Extended produced 1,220 kg ha^{-1}, whereas Standard produced 880 kg ha^{-1} in fall (data not shown). These results suggest that any effects of seeding rate on spring cover crop biomass were overshadowed by the effects of late termination. These trends are consistent with those reported by Brennan and Boyd (2012) who compared two seeding rates for mustard, rye, and rye + multiple legume mixes. They found that GDD explained 67% to 87% of cover biomass at a low seeding rate and 68% to 80% of cover biomass at high seeding rates. However, they also found that seeding rates affected fall-winter cover crop biomass, but not spring biomass. Our results indicated that fall rain and early planting were important for fall cover crop biomass and N accumulation success. Our results also suggest that longer growing time in spring was important for spring biomass, and that later termination produced greater biomass, even when early planting due to aerial seeding resulted in no difference in fall biomass.

Table 3
Spring dry matter for total cover crop and cover crop components, tissue carbon to nitrogen (C/N) ratio, tissue N concentration, and cover crop N content for cover crops just before cover crop termination at 18 site-years on commercial farms in Maryland.

Source of variability			Cereal (kg dry matter ha^{-1})	Clover (kg dry matter ha^{-1})	Brassica (kg dry matter ha^{-1})	Weeds (kg dry matter ha^{-1})	Total biomass (kg dry matter ha^{-1})	Cover crop N content (kg N ha^{-1})	Cover tissue C/N ratio	Cover tissue N conc. (g N kg^{-1})
Year (Y)	2018		1,180a	163b	148b	228ns	1,720ns	36.7ns	20.0a	21.3ns
	2019		799b	699a	224ab	458ns	2,180ns	50.4ns	—	23.1ns
	2020		925ab	413a	466a	195ns	2,000ns	45.5ns	18.6b	22.8ns
Management treatment (M)	Extended		1,130a	739a	472ns	270b	2610a	56.0a	20.9ns	21.5ns
	Standard		834b	115b	188ns	101c	1240b	29.6b	17.8ns	23.9ns
	No cover		—	—	—	702a	702c	15.3c	19.1ns	21.8ns
Y × M	2018	Extended	1,340ns	289ns	188ns	410b	2,230a	44.4b	22.8a	19.9ns
		Standard	1,040ns	54.9ns	108ns	72.1d	1,280b	28.8c	17.5b	22.6ns
		No Cover	—	—	—	—	—	—	—	—
	2019	Extended	1,050ns	1,320ns	413ns	124cd	2910a	64.5a	—	22.2ns
		Standard	546ns	80.3ns	35.7ns	174cd	835b	21.8c	—	26.1ns
		No cover	—	—	—	1,110a	1,080b	22.7c	—	21.1ns
	2020	Extended	963ns	584ns	621ns	277bc	2,440a	54.9ab	18.7b	22.5ns
		Standard	888ns	241ns	312ns	53.5d	1,490b	34.6c	18.1b	23.2ns
		No cover	—	—	—	253bc	253c	5.74d	19.1b	22.7ns

Notes: Means within an effect followed by the same letter do not differ significantly. * significant at $p < 0.1$; all other letter differences are significant at $p < 0.05$. ns is not significant at $p < 0.1$. A more detailed version of this table is available in the supplementary materials (table S4).

The species distribution differed in the spring between treatments, as it did in the fall. Averaged across all 18 site-years, the Extended season resulted in greater cereal and clover biomass in spring compared to Standard (table 3). Similar to the fall, spring weed biomass was greatest for No Cover and lowest for Standard (table 3). The spring biomass species composition for Extended was more species-balanced (43% cereal and 28% clover) than Standard (67% cereal and 9% clover; table 3). Other researchers have also reported greater spring legume biomass proportions associated with more available GDD in fall (Murrell et al. 2017; Baraibar et al. 2020) and spring (Baraibar et al. 2020). The additional clover in spring is especially important for fixing N, potentially replacing a portion of N fertilizer required by a subsequent crop.

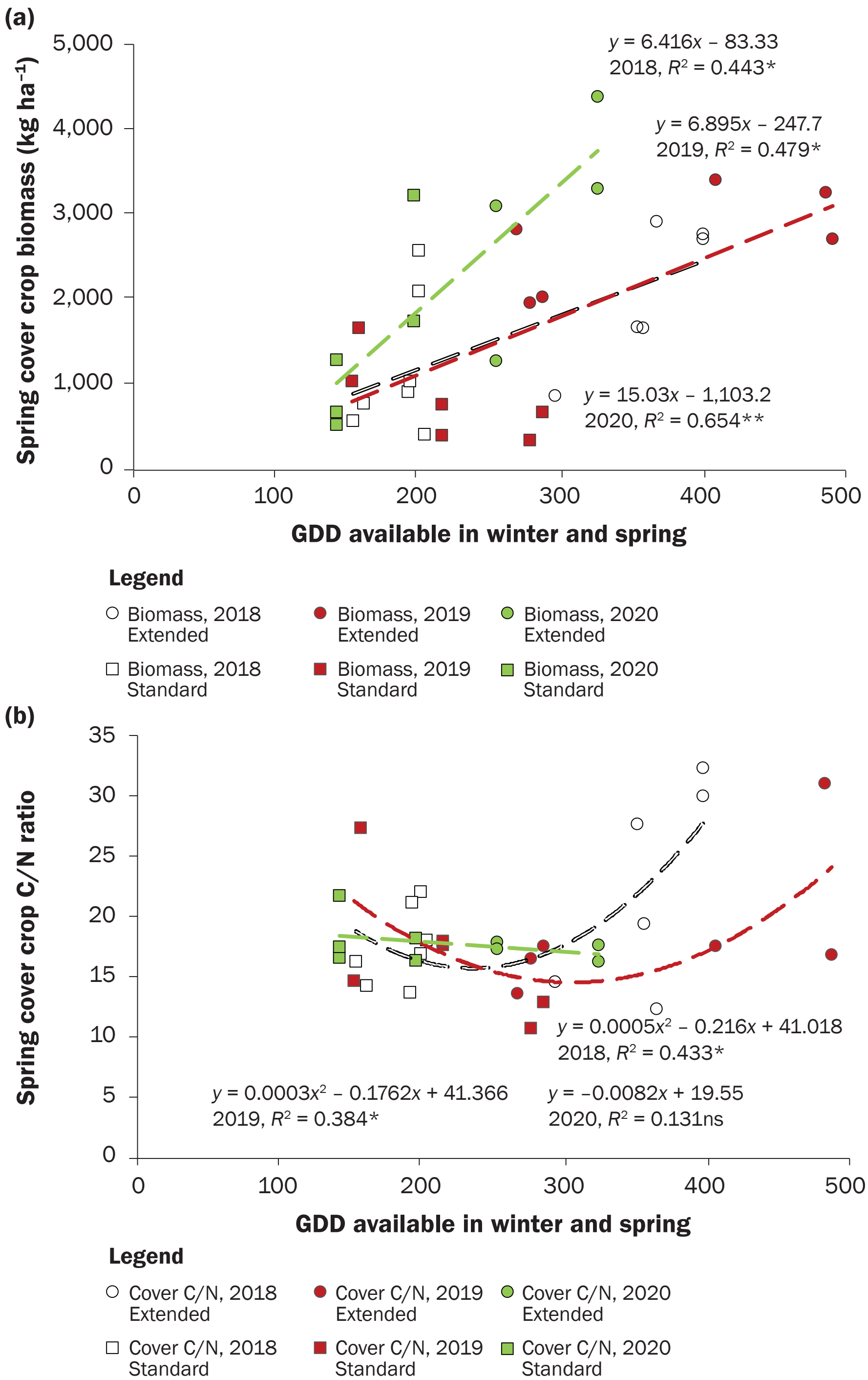
Spring Cover Crop Nitrogen Content. Across all 18 site-years spring cover crop N content was greatest for Extended (56.0 kg N ha^{-1}), followed by Standard (29.6 kg N ha^{-1}), and No Cover (15.3 kg N ha^{-1}; table 3). When comparing individual years, Extended consistently had more spring cover crop N content than Standard or No Cover, but Standard and No Cover had statistically similar N contents in 2019. Across all 18 site-years, very little cover crop total biomass (360 kg ha^{-1}) or N (1.4 kg N ha^{-1}) accumulated for Standard between fall (table 2) and early spring (typically late March) sampling (table 3). In contrast, cover crop N content increased by 7.2 kg N ha^{-1} and cover crop biomass increased by 1,110 kg ha^{-1} for Extended (tables 2 and 3). There was no significant difference in spring cover crop tissue N concentration or C/N ratio in all three years for each treatment (table 3); therefore all N content differences were due to differences in biomass. Consistent with our hypothesis, extending the cover crop growing season resulted in greater spring biomass and N content.

Although a greater proportion of legumes in a cover crop mixture is expected to decrease the C/N of the biomass (Möller et al. 2008; Poffenbarger et al. 2015), our data do not exhibit this relationship (figure 6). Clover comprised a greater proportion of spring cover crop biomass for Extended (28%) than Standard (9.3%) over all 18 site-years, but we observed no differences in its C/N ratio or tissue N concentrations between treatments (table 3). Cover crop tissue N concentrations have been shown to decrease with maturity (Kladivko 2016; White et al. 2017); therefore the clover C/N ratio in this study potentially increased as it entered reproductive growth in mid to late April (figure 6b). The combination of greater legume biomass proportions for Extended and decreasing N concentrations with clover maturity resulted in a parabolic relationship between spring GDD and C/N ratio in 2018 and 2019, and no relationship in spring 2020 (figure 6b). However, due to restrictions from the COVID-19 pandemic, spring of 2020 sampling ended in March; therefore the same parabolic relationship between GDD and cover crop C/N ratio may have developed if our final samples were taken in late April.

Cover Crop Effects on Soil Properties. Cover crop management treatments had little effect on soil mineral N concentrations (NO_3-N and NH_4-N) measured in June (table 4). The PSNT revealed no difference in NO_3-N concentrations in the upper 30 cm of soil between the treatments averaged across 18 site-years (table 4), despite greater spring cover crop biomass, N content, and clover biomass proportions for Extended than Standard (table 3). On mid-Atlantic farms, Hirsh et al. (2021) also detected no differences in PSNT results between a brassica–legume–cereal mix and no cover treatments. Despite Extended having large crimson clover biomass relative to Standard (table 3), the June soil NO_3-N concentration was consistently low (table 4)—far below the 20 to 25 mg kg^{-1} level which could justify significantly reducing N fertilizer side dress application rates according to the PSNT (Meisinger et al. 1992). In this study, NH_4-N concentrations were low, with the highest treatment by year NH_4-N concentration of 13.2 mg kg^{-1}. Therefore, it is unlikely that

Figure 6

Relationship between cumulative growing degree days (GDD) available between December 1 and cover crop termination in the spring and (a) total spring cover crop biomass or (b) spring cover carbon to nitrogen (C/N) ratio. Each dot is the average of one treatment at each site-year. No Cover treatments were excluded. *significant at $p < 0.05$; **significant at $p < 0.01$; ns indicates not significant at $p < 0.05$. The field season in 2020 ended in March due to restrictions from the COVID-19 pandemic.



the cover crop treatments either supplied or immobilized significant amounts of mineral N by mid-June. While cover crop management treatments had no effect on available soil NO_3-N, cumulative rainfall between the date of cover crop termination and soil sampling accounted for ~50% of all variability in PSNT NO_3-N concentrations (figure S3). PSNT NO_3-N was lowest in the year with the wettest spring (2018) and greatest in 2019.

Our one-time measurements of soil moisture were impacted by soil texture but not treatment (table 4). We measured greater soil water at silty sites than at sandy sites, as would be expected due to higher water holding capacity. Theoretically, the treatments could impact soil moisture differently. For example, the greater surface mulch from a late terminated cover crop in a no-till system can increase surface soil water content if precipitation is limited after termination (Clark et al. 2007; Alonso-Ayuso et al. 2014). If early spring rainfall is relatively low and temperatures relatively high, growing cover crops can deplete soil profile water to the detriment of the following cash crop (Clark et al. 2007; Alonso-Ayuso et al. 2014). These moisture limiting conditions were not observed prior to June soil sampling for any of the three years of the present study. Therefore, any cover crop effects on soil moisture were not detected by our snapshot sampling regime. Cover crop management treatments had little short-term effect on soil OM (table 4). The silty sites had greater soil OM and moisture than the sandy sites. The limited post-cover crop termination soil and plant data available do not support our hypothesis that extending the cover crop growing season would increase soil mineral N and soil moisture.

Cover Crop Economics. Our economic analyses focused on private costs to the farmer or public costs to the MACS program, and compared these to the environmental benefits to society of using cover crops. The principle direct economic cost of using cover crops is the cost of purchasing and sowing the cover crop seed. Although cover crops may reduce input costs and increase yields in the long-term (Hansen and Djurhuus 1997; Campiglia et al. 2014), the principle direct short-term economic return to the farmer from the use of cover crops in Maryland is the MACS incentive payment. The return on cover crop subsidy investment from a societal viewpoint is comprised of water quality benefits from reduced N leaching, which can reduce the likelihood of algal blooms and the associated detrimental effects on local fisheries, and soil health/climate mitigation benefits from increased organic C inputs to soil. We therefore focused on these costs and

Table 4
Soil (0 to 30 cm) extractable mineral nitrogen (N) content, organic matter (OM), and gravimetric water content in June.

Source of variation			Soil NH_4-N (mg N kg soil^{-1})	Soil NO_3-N (mg N kg soil^{-1})	Soil OM (g kg^{-1})	Soil water (g g^{-1})
Year (Y)	2018		9.93ns	3.94b	20.6ns	0.192a
	2019		9.00ns	13.2a	22.1ns	0.161b
	2020		12.3ns	8.85b	—	—
Soil (S)	Sandy		11.0ns	8.88ns	19.4b*	0.142b
	Silty		10.1ns	8.39ns	23.7a*	0.205a
Management treatment (M)		Extended	9.59b	7.68ns	20.6b	0.183ns
		Standard	10.9a	7.84ns	22.6a	0.180ns
		No cover	11.1a	11.3ns	20.4b	0.154ns
Y × M	2018	Extended	9.29ab	3.78ns	19.3ns	0.191ns
		Standard	10.6ab	4.10ns	22.0ns	0.194ns
		No cover	—	—	—	—
	2019	Extended	6.67b	13.7ns	22.2ns	0.168ns
		Standard	9.96ab	13.1ns	23.4ns	0.159ns
		No cover	10.4ab	12.9ns	20.4ns	0.154ns
	2020	Extended	13.2a	7.83ns	—	—
		Standard	12.1ab	8.33ns	—	—
		No cover	11.7ab	10.1ns	—	—

Notes: Means for effects of year, soil texture, cover crop treatment and their interactions. Means within an effect followed by the same letter do not differ significantly. * significant at p <0.1; all other letter differences are significant at p < 0.05. ns is not significant at p < 0.1. A more detailed version of this table is available in the supplementary materials (table S5).

benefits in a simplified economic comparison of the cover crop treatments.

Overall, the estimated cost of planting the cover crop for Extended (US$148 ha^{-1}) was greater than for Standard (US$139 ha^{-1}; table 5). The custom rates for ground-based seeding (US$50 ha^{-1}) and aerial seeding (US$49 ha^{-1}) presented by Dill (2021) were similar, and most of the extra cost for Extended was due to some farmers using increased seeding rates. However, Extended cover crops qualified for a greater MACS incentive payment (US$176 ha^{-1}) than Standard (US$154 ha^{-1}) because of the earlier planting and later termination date (table 5). In most (11 for Extended and 13 for Standard) of the 18 site-years the MACS subsidy exceeded the combined cost of seed and sowing, and the average per hectare farmer "profit" (payment in excess of planting cost) from the MACS program was slightly greater for Extended (US$28 ha^{-1}) than for Standard (US$15 ha^{-1}).

In terms of the MACS program objectives of reducing N leaching and increasing C captured, extending the cover crop growing season with Extended represented added value compared to Standard. Due to consistently greater spring cover crop biomass, Extended added approximately twice as much organic material to soils per dollar spent either by the MACS program (14.5 kg dry matter US$$^{-1}$ spent for Extended compared to 7.7 kg dry matter US$$^{-1}$ spent for Standard; table 6) or by the farmers (17.1 kg dry matter US$$^{-1}$ spent for Extended compared to 8.6 kg dry matter US$$^{-1}$ spent for Standard; table 7). If only the delayed termination subsidy of US$24.50 ha^{-1} is considered, 54 kg of dry matter was added to the soil for every dollar spent, a consistent return on investment for delaying spring termination.

The cover crops in Extended had the same as, or greater N content than Standard in the fall for every year of this study (table 2) resulting in either similar or decreased NO_3-N leached (figure 4). This resulted in Extended accumulating significantly more N than Standard per dollar spent either on MACS subsidies (0.28 kg N US$$^{-1}$ spent for Extended, compared to 0.18 kg N US$$^{-1}$ spent for Standard; table 6) or by the farmers (0.33 kg N US$$^{-1}$ spent for Extended compared to 0.20 kg N US$$^{-1}$ spent for Standard; table 7). Extended accumulated more N per dollar spent than Standard, for either increased or at the same seeding rate. Increased cover crop N content in fall was associated with decreased winter-spring NO_3-N leaching (figure 5); therefore practices that increase fall N content should be incentivized to meet the water quality goals of programs such as MACS.

Summary and Conclusions

Despite the highly variable weather during the three years of this study, the early aerially seeded treatment with late termination (Extended) performed as well or better than late drilling after harvest and earlier termination (Standard) in all years. The three years of this study included a relatively dry fall of 2017, an extremely wet fall of 2018, and an extremely dry fall of 2019. When moisture conditions were favorable for seed germination soon after aerial seeding (fall of 2018), the extra GDD available allowed Extended to greatly outperform Standard, in terms of fall cover crop biomass, N content, and winter-spring reduction in NO_3-N leached. Across all 18 site-years, Standard and Extended both reduced winter-spring NO_3-N leached compared to No Cover. However, after a very wet fall in 2018, Standard reduced NO_3-N leached by an estimated 45.5%, whereas Extended reduced NO_3-N leached by 84%. In the two dry years of this study (2017 and 2019) there was no difference in NO_3-N leached between Standard and Extended, and in 2019 these treatments reduced NO_3-N leached by 78% to 82%. Reduction in NO_3-N leaching over the winter and early spring was driven by cover crop N content in fall, the amount of which was the greatest when planting cover crops earlier in wet conditions.

Spring cover crop biomass, N content, and proportion of crimson clover consistently increased by terminating the cover crop later in spring (Extended treatment). Importantly to farmers, a brassica-legume-cereal cover crop managed as Extended did not adversely affect June soil mineral N relative to No Cover or Standard. The estimated cover crop planting cost (planting operation plus cost of seed) for Extended (US$148 ha^{-1}) was greater than for Standard (US$139 ha^{-1}), which could disincentivize farmers from using this method. However, this difference in cost was overcome by the Maryland cover crop subsidy program (MACS). The practices employed in Extended qualified for an average of US$22 ha^{-1} more in incentive payments than Standard. Despite the greater public expenditure on subsidies, the practices of Extended produced a better

Table 5
Cost to plant Extended and Standard mix at each site-year, potential Maryland Agricultural Cost Share (MACS) program incentive payment, and the net cost of the operation (planting cost – incentive). Subsidy is sum of the MACS incentives for which the treatments qualified (MDA 2020a). Each row represents one site-year with actual seeding rates used, and planting costs estimated from median 2021 cost of drill planting, aerial seeding, and seed costs given by Dill (2021).

	Planting cost (US$ ha^{-1})		MACS incentive payment (US$ ha^{-1})		Planting cost minus incentive (US$ ha^{-1})	
Field ID	Extended	Standard	Extended	Standard	Extended	Standard
Fall of 2017 to spring of 2018						
A*	124	124	198	161	–74	–37
B	155	158	198	136	–43	22
C*	189	190	173	161	16	29
D*	178	179	148	136	30	43
E*	124	124	198	136	–74	–12
F*	129	130	198	161	–69	–31
G*	114	115	173	161	–59	–46
Fall of 2018 to spring of 2019						
A*	125	126	173	136	–48	–10
B	173	139	148	161	25	–22
D	211	183	198	161	13	22
E*	125	126	173	136	–48	–10
H	173	121	148	161	25	–40
I	173	110	148	161	25	–51
Fall of 2019 to spring of 2020						
A*	123	124	173	161	–50	–37
B	135	125	198	161	–63	–36
E*	123	124	173	161	–50	–37
H	135	125	198	161	–63	–36
J	159	181	148	161	11	20
Three-year summary						
Site-years with same Extended/ Standard mix*	135	136	178	151	–43	–15
Site-years with different Extended/ Standard mix	164	143	173	158	–9	–15

*Same cover crop mix and seeding rate used for Extended and Standard.

Table 6
Cost-effectiveness of Maryland Department of Agriculture incentive payments for Extended and Standard cover crop practices. Return on investment calculated as kilograms of nitrogen (N) taken up in fall or kilograms dry matter added to soil in spring divided by the total incentive payments for which the practices qualified in the current Maryland Agricultural Cost Share (MACS) program (MDA 2020a). Means within an effect followed by the same letter do not differ significantly.

	MACS subsidy (US$ ha^{-1})*		Fall N content (kg N US$$^{-1}$)†		Spring biomass (kg dry matter US$$^{-1}$)†	
Year	Extended	Standard	Extended	Standard	Extended	Standard
2017 to 2018	184	150	0.20ab	0.19ab	12.1ab	8.5bc
2018 to 2019	165	153	0.40a	0.06b	17.7a	5.5c
2019 to 2020	178	161	0.25ab	0.28ab	13.7ab	9.3bc
Mean	176	154	0.28a	0.18b	14.5a	7.7b

*Sum of MACS incentive payments that each practice could receive.
†Kilograms of fall N or spring dry matter / MACS incentive payment cost.

return on public investment than Standard. Extended accumulated 0.10 kg of N more than Standard in fall for every dollar spent by MACS, and in the spring, Extended accumulated 6.6 kg of dry matter more than Standard for every dollar spent by MACS. The results of this study support the current deadlines in the Maryland Cover Crop Program, which pay additional amounts for planting before September 15 and terminating after May 1. Extending the cover crop growing season with Extended was an effective method for increasing cover crop ecosystem services, even under weather conditions that were unfavorable to aerial application in comparison to cover crop establishment by drilling seed.

Table 7

Cover crop costs to farmer, before and after Maryland Agricultural Cost Share program (MACS) incentive payments, and cost-effectiveness for Extended and Standard cover crop practices for each of three years of the study. Incentive payment is the total Maryland Department of Agriculture (MDA) payment for which the practices qualify under the current program (MDA 2020a). Means within an effect followed by the same letter do not differ significantly.

	Planting cost (US$ ha^{-1})*		Planting cost minus incentive payment (US$ ha^{-1})		Fall nitrogen content (kg N US$$^{-1}$)†		Spring biomass (kg dry matter US$$^{-1}$)†	
Year	Extended	Standard	Extended	Standard	Extended	Standard	Extended	Standard
2017 to 2018	145	146	−39	−4	0.25ab	0.20ab	15.4a	8.8b
2018 to 2019	164	134	−1	−18	0.40a	0.07b	18.0a	6.2b
2019 to 2020	135	136	−43	−25	0.33a	0.33a	18.1a	11.0b
Mean	148	139	−28	−15	0.33a	0.20b	17.1a	8.6b

*Sum of seed and seeding operation costs.

†kg of fall N or spring dry matter / cover crop planting cost.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.00051.

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