Received: 28 January 2022 | Accepted: 23 August 2022 | Published online: 11 January 2023

DOI: 10.1002/agj2.21207

Agronomy Journal

ORIGINAL ARTICLE

Soil Tillage, Conservation, and Management

Remote sensing evaluation of winter cover crop springtime performance and the impact of delayed termination

Alison Thieme[1] | **W. Dean Hively**[2] | **Feng Gao**[3] | **Jyoti Jennewein**[4] | **Steven Mirsky**[4] | **Alexander Soroka**[5] | **Jason Keppler**[6] | **Dawn Bradley**[6] | **Sergii Skakun**[1] | **Gregory W. McCarty**[3]

[1]Univ. of Maryland, Dep. of Geographical Sciences, College Park, MD 20740, USA

[2]USGS, Lower Mississippi-Gulf Water Science Center

[3]USDA-ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA

[4]USDA-ARS, Sustainable Agricultural Systems Laboratory, Beltsville, MD 20705, USA

[5]USGS, Maryland-Delaware-District of Columbia Water Science Center, Baltimore, MD 21228, USA

[6]Maryland Dep. of Agriculture, Annapolis, MD 21401, USA

Correspondence
Alison Thieme, Dep. of Geographical Sciences, Univ. of Maryland, College Park, MD 20740, USA.
Email: thieme@terpmail.umd.edu

Assigned to Associate Editor Arun Jani.

Funding information
U.S. Geological Survey, Grant/Award Number: Land Change Science program; Agricultural Research Service, Grant/Award Number: Precision Sustainable Agriculture Network; U.S. Department of Agriculture, Grant/Award Number: Conservation Effects Assessment Project; National Fish and Wildlife Foundation Innovative Nutrient and Sediment Reduction Grant

Abstract

In 2019, the Maryland Department of Agriculture's Winter Cover Crop Program introduced a delayed termination incentive (after May 1) to promote springtime biomass accumulation. We used satellite imagery calibrated with springtime in situ measurements collected from 2006–2021 (n = 722) to derive biomass estimates for Maryland fields planted to cereal cover crop species (286,200 ha total over two seasons). Cover crop C content remained steady throughout the cover crop growing season (42.6% of biomass), whereas N concentration had an inverse relationship with biomass and ranged from 1.7 to 2.9%. Throughout Maryland, delayed termination fields (n = 19,120; average termination of May 18) were, on average, estimated to accumulate an additional 789 kg of biomass, 15 kg of N, and 336 kg of C per hectare when compared to fields associated with standard termination dates (n = 28,811; average termination of April 16). Over two cover crop seasons (2019–2021), the delayed termination incentive yielded an extra 75,660,000 kg biomass, 1,526,000 kg N, and 32,230,000 kg C across 96,040 hectares. Regularly terminated field incentives cost an average of US$0.10 per kg of biomass and $4.09 per kg of N, with variability associated with agronomic management (species, planting method). Delayed termination fields cost of $0.08 per kg of biomass and $3.51 per kg of N. Late-planted cover crops that were terminated early had minimal environmental benefit,

Abbreviations: BARC, Beltsville Agricultural Research Center; HLS, Harmonized Landsat Sentinel-2; MACS, Maryland Agricultural Water Quality Cost-Share; MDA, Maryland Department of Agriculture; NDVI, normalized difference vegetation index.

and wheat, which comprised 68% of cover crop area, performed poorly compared with other cereal species. Our findings demonstrate that substantial additional springtime biomass, C, and N accumulation were achieved through the delayed termination incentive.

1 | INTRODUCTION

Winter cover crops serve as conservation tools to reduce erosion and take up excess N, and as such are strongly promoted by the Chesapeake Bay Program partnership (Dabney et al., 2001; Maryland Department of Natural Resources, 2012; Staver & Brinsfield, 1998). They can also improve soil health, increase infiltration, and can be used as a form of C sequestration (Dabney et al., 2001; Hartwig & Ammon, 2002; Poeplau & Don, 2015). Winter cover crops comprise a variety of species that are planted in the fall following cash crop harvest to provide green biomass and ground cover in the winter–spring season. The cover crops can take up residual N from annual fertilizer applications and from deeper layers of the soil (Staver & Brinsfield, 1998). Upon termination, the cover crop biomass is usually left to decompose in the field and N is released back into the soil for use by summer crops (Jahanzad et al., 2016; Ranells & Wagger, 1996). Whereas successful winter cover crops emerge and begin growing in the fall in the window between cash crop harvest and winter, in northern temperate climates, their growth typically plateaus in the winter and then increases again in the spring as the temperatures increase (Gao, Anderson, & Hively, 2020).

The Maryland Department of Agriculture (MDA) started the Maryland Agricultural Water Quality Cost-Share (MACS) cover crop program on the Eastern Shore in 1984 and expanded statewide in 2003 (Bradley, 2022). The cost-share program pays Maryland farmers to plant winter cover crops with variable payment rates based on factors such as species, planting date, and planting method (Bradley, 2022; Maryland Department of Agriculture, 2019). These payments average the highest per acre of any state program and are associated with the highest cover crop adoption rates of any state (Bowman & Lynch, 2019; Wallander et al., 2021). Since 2005, program enrollment has grown 10-fold, and with it, the number of fields requiring in-person verification of program adherence by the soil conservation districts (Bradley, 2022). With nearly 230,000 hectares (ha) enrolled in 2021, the task of monitoring program performance (cover crop biomass, C, and N accumulation) of all enrolled fields through field visits becomes infeasible.

Satellite remote sensing is a tool that can be used to identify cover crop adoption, identify field boundaries, monitor phenology, measure yields, and estimate planting and termination dates (Beeson et al., 2020; Gao, Anderson, & Hively, 2020; Gao, Anderson, & Daughtry, 2020; Hagen et al., 2020). Within known field boundaries, remote sensing also allows for the estimation of cover crop biomass, biomass N, and biomass C across large areas within days of clear imagery collection (Hively et al., 2009; 2020; Thieme et al., 2020). Maryland collects geospatial boundary data for all fields enrolled in their cover crop incentive program. By combining MACS geospatial enrollment data, remote sensing data, and the Soil and Water Assessment Tool (USDA-ARS, Grassland Soil, and Water Research Laboratory; Texas A&M AgriLife Research, 2018), the increased adoption of cover crops from 2008 to 2017 was estimated to result in a 25% reduction in nitrate (NO_3^-) leaching from croplands in the Upper Tuckahoe Watershed on Maryland's Eastern Shore (Hively et al., 2020). Another study combined remote sensing data, MACS geospatial enrollment data, and in-field measurements to identify wintertime and springtime performance in four Maryland counties (Thieme et al., 2020). These assessments suggested that shifting agronomic management of cover crops to promote early planting and drill seeding as opposed to late planting and broadcast seeding could increase environmental benefits associated with cover crop performance (Hively et al., 2020; Thieme et al., 2020).

The adoption of effective agronomic methods for cover crop management can be encouraged by varying incentives in the MACS Winter Cover Crop Program, and payment rates change from year to year based upon program objectives, expert knowledge, and availability of funding (Bradley, 2022; Maryland Department of Agriculture, 2019). Early planted cover crops (planted at least 2 wk prior to the first frost) take up N more effectively and reduce fall NO_3^- leaching (Sedghi & Weil, 2022; Staver & Brinsfield, 1998; Thapa et al., 2018). Whereas delaying termination in the springtime increases biomass production and N uptake, the timing of N uptake by cover crops is important as NO_3^- leaching potential is highest in the fall–winter (Di & Cameron, 2002; Otte et al., 2019). The MDA has encouraged early planting of cover crops to reduce fall–winter NO_3^- leaching through various early planting incentives. Additionally, cereal rye (*Secale cereale* L.) has been shown in small-plot studies to take up more N than other cover crop species and was, therefore, incentivized from 2008 to 2020 (Bradley, 2022; Shipley et al., 1992).

In 2019, in response to poor fall growing conditions, the MACS Winter Cover Crop Program introduced a delayed termination incentive to encourage spring growth. The incentive paid US\$37.07 ha^{-1}(\$15 ac^{-1}) for fields terminated after May 1, in contrast to the regular termination minimum of March 1, and the incentive was continued in 2020 at a rate of \$24.71 ha^{-1}(\$10 ac^{-1}) (Maryland Department of Agriculture, 2018). This incentive encourages later termination of winter cover crops to maximize springtime accumulation of biomass, N, and C. Farmers apply for delayed termination at the time of program enrollment (fall) and can withdraw from the incentive if they terminate fields prior to May 1.

The objectives of this research were the following:

1. Use satellite remote sensing and in situ measurements to correlate normalized difference vegetation index (NDVI) values to springtime cover crop biomass.
2. Estimate springtime cover crop biomass on MACS-enrolled cover crop fields using satellite NDVI values just prior to the time of farmer-reported termination for 2019–2020 and 2020–2021.
3. Estimate biomass N and biomass C on MACS-enrolled cover crop fields for 2019–2020 and 2020–2021, relative to agronomic management methods (species, planting date, planting method).
4. Compare the springtime performance (biomass, biomass N, biomass C) of cover crop fields enrolled in delayed termination incentives with fields not enrolled in the incentive.
5. Estimate the cost effectiveness (using a cost per mass basis) of cover crop performance by variable incentive agronomic groupings.

Core Ideas

- Remote sensing, combined with destructive sampling, can enable the estimation of winter cover crop biomass at scale.
- Winter cover crop fields that delay termination showed higher biomass, N, and C accumulation.
- Fields that received an incentive to delay termination had, on average, lower cost per unit performance.
- Performance varied by species, planting date, planting method, and termination date.

2 | MATERIALS AND METHODS

2.1 | Study area and time period

This research evaluated MDA MACS-enrolled fields for the 2019–2020 and 2020–2021 winter cover crop growing seasons. We limited the analysis to four monoculture grass species for which we had previously obtained in situ measurements for remote sensing calibration: wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), cereal rye, and triticale (× *Triticosecale* Wittmack). These four monoculture cereal grain species make up 84.9% of the enrolled hectarage of MDA cover crops (156,900 ha across 26,393 fields in 2019–2020, and 129,300 ha across 21,538 fields in 2020–2021) (Table 1). Planting began as early as August and termination was completed by June each year. Approximately 40% (19,120 out of 47,931) of enrolled fields from 2019 to 2021 participated in the delayed termination incentive (Table 2).

Each year the MACS program collects geospatial and agronomic data for all fields enrolled in the Winter Cover Crop Program (Figure 1). A polygon is mapped for each field and the corresponding database stores information about the cover crop species, planting date, planting method, previous crop, termination date, and termination method. Additionally, the dollar amount of cost-share funding spent per field is calculated based on agronomic management using the payment tables for that specific year (Table 1). This field-specific dataset is privacy protected and was accessed under a research partnership with MDA. Each fall, 20% of all enrolled hectares are checked by MDA staff for program compliance, and each spring, at least 10% of hectares per county are checked for termination compliance.

2.2 | Calibration: cover crop sampling and satellite imagery acquisition

To understand the relationship between winter cover crop biomass and satellite imagery, in situ samples were paired with closely timed, clear satellite images. The in situ cover crop samples were collected from 2006 to 2012 and 2019 to 2021 from MDA-enrolled fields on the Eastern Shore of Maryland (with farmer permission), and from 2019 to 2021 at the USDA Beltsville Agricultural Research Center (BARC), Beltsville, MD (Prabhakara et al., 2015; Thieme et al., 2020). Because we were focused on cover crop biomass, N, and C at the time of termination, analysis focused on a springtime dataset collected in March, April, and May for a total of 1,025 plant samples. There were 3–5 destructive plant samples collected from each field and sampling date. Each sample was paired with reflectance values from satellite remote sensing collected at a spatial resolution of 20–30 m based upon recorded geospatial coordinates. Whereas the number of samples per field does not fully capture within-field variability due to topographic position and other factors, at this spatial resolution, the effects of within-field variability are dulled. Each sample was collected from a different location spaced at least 30 m from other sampling locations to represent a

TABLE 1 Maryland Department of Agriculture Maryland Agricultural Water Quality Cost-Share base payment and incentive options for cover crops, 2019–2020 and 2020–2021 (Maryland Department of Agriculture, 2019

	Planting method					
Cover crop payment options	No till	Drilled with light tillage	Broadcast with light, minimum, or vertical tillage	Aerial	Aerial ground seeding	Broadcast stalk chop and broadcast cultipacker
	$ ha^{-1}					
2019–2020						
Base payment	45	45	45	50	45	45
Plant by 1 Oct.	20	10	10	0	0	0
Plant 2–15 Oct.	10	5	5	0	0	0
Aerial seeding in corn by 1 Sept.	0	0	0	10	0	0
Plant cereal rye	10	10	10	10	10	10
Delayed termination after 1 May	15	15	15	15	15	15
Maximum payment	90	80	80	85	70	70
2020–2021						
Base payment	40	40	40	45	45	40
Plant by 10 Oct.	10	10	10	0	0	0
Aerial seeding in corn by 10 Sept.	0	0	0	10	10	0
Delayed termination after 1 May	10	10	10	10	10	10
Maximum payment	60	60	60	65	65	50

TABLE 2 Area, number of enrolled fields, and average termination date associated with Maryland winter cover crop program enrollment, categorized by regular (after 1 March) and delayed (after 1 May) termination for 2019–2020 and 2020–2021

	2019–2020			2020–2021		
Termination category	Area	Enrolled fields	Termination date average	Area	Enrolled fields	Termination date average
	ha	*n*		ha	*n*	
Regular termination	104,100	16,020	12 Apr.	86,000	12,791	17 Apr.
Delayed termination	52,800	10,373	14 May	43,300	8,747	11 May
Total	156,900	26,393	25 Apr.	129,300	21,538	27 Apr.

different pixel within the satellite imagery, and at least 30 m from field edges to prevent mixed pixels with adjacent land cover. At each location, aboveground destructive biomass samples were cut at ground height within a 0.5-m^2 quadrat, cleaned for any residual soil and crop residue, dried at 60 ˚C for 2–5 d, weighed, and extrapolated to kg ha^{-1} (Prabhakara et al., 2015). Dried samples were ground to 2 mm using a Wiley hammermill (Thomas Scientific) and analyzed for C and N content using a TruSpec C/N Analyzer (Leco Corp).

The NDVI uses a normalized difference between the red and near-infrared and red reflectance to estimate plant health and productivity, as healthy plants absorb red light and cell walls reflect near-infrared light (Labus et al., 2002; Tucker, 1979). NDVI is calculated using the following equation:

$$\mathrm{NDVI} = \frac{R_{\mathrm{NIR}} - R_{\mathrm{Red}}}{R_{\mathrm{NIR}} + R_{\mathrm{Red}}}$$

where R_{NIR} is near-infrared reflectance and R_{Red} is red reflectance. In cover crops, NDVI correlates well with percent ground cover and biomass (until saturation at ∼80% ground cover and 1,500 kg ha^{-1} biomass, beyond which additional growth may not be detected) (Prabhakara et al., 2015; Thieme et al., 2020; Xia et al., 2021). Numerous vegetation indices can be used to evaluate plant growth over time; NDVI was selected as it uses sections of the electromagnetic spectrum that are common to many satellite sensors and is normalized, which reduces variability between different images collected under differing light conditions. It also performs well; Prabhakara et al. (2015) evaluated 11 multispectral indices for measurement of cover crop biomass and found NDVI to be the top performer. Normalized difference vegetation index was also selected based on availability within historical satellite imagery to match with biomass samples collected since 2006.

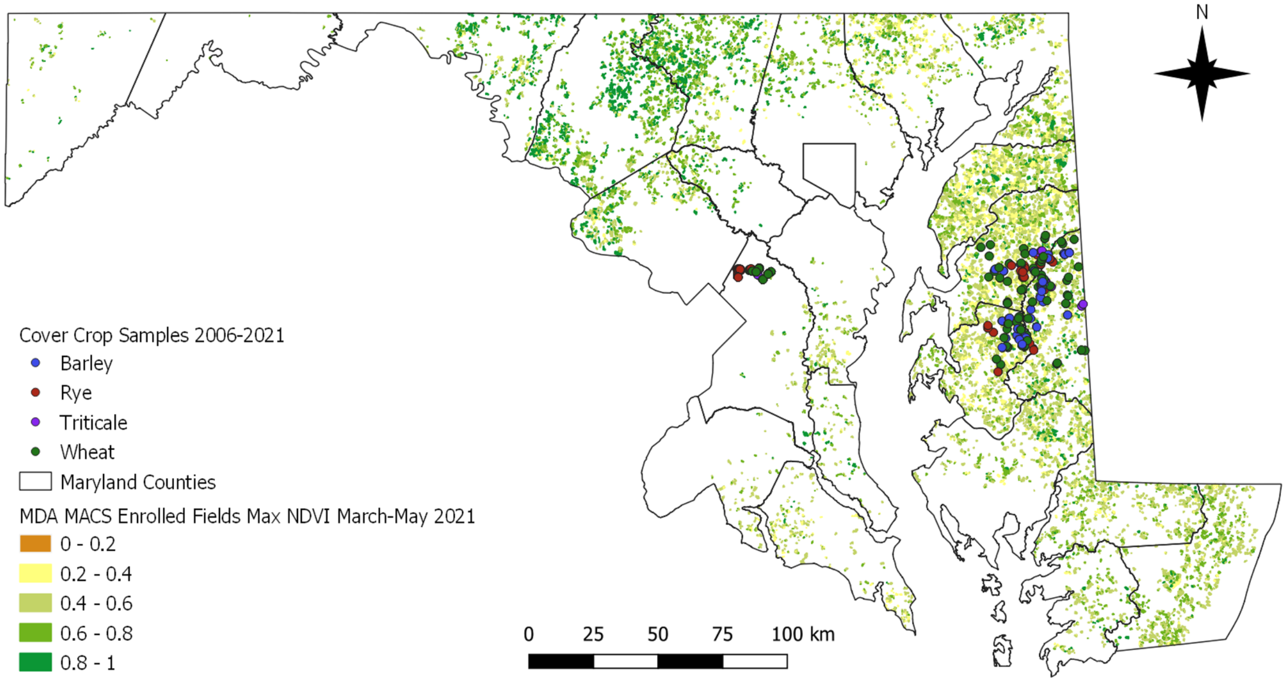

FIGURE 1 Map of Maryland with Maryland Department of Agriculture (MDA) Maryland Agricultural Water Quality Cost-Share (MACS) winter cover crop program enrolled fields depicted using Normalized Difference Vegetation Index (NDVI) values from Harmonized Landsat Sentinel-2 Surface Reflectance Product (Claverie et al., 2018) observed prior to termination for 1 Mar.–31 May 2021, and cover crop samples collected from 2006–2021 colored by species. County and state boundaries provided by United States Census Bureau (2021)

We used imagery from several satellites to maximize the number of cloud-free NDVI values. For 2006–2012, NDVI values were extracted from *Satellite Pour l'Observation de la Terre* (lit. "Satellite for observation of Earth") SPOT 4(20 m) and SPOT 5(10 m) surface reflectance or Landsat 5 Thematic Mapper (TM, 30 m) or Landsat 7 Enhanced Thematic Mapper Plus (ETM+, 30 m) surface reflectance, relying on the closest imagery to the sampling date (SPOT 4 and SPOT 5 imagery available through Spot Image; Landsat 5 TM and Landsat 7 ETM+ imagery available courtesy of the USGS). The SPOT imagery was acquired through the USGS SPOT Data Buy, downloaded through the USGS Earth Explorer website (https://earthexplorer.usgs.gov/) and converted to surface reflectance using MODTRAN (Berk et al., 2014). Fine scale georegistration of SPOT imagery was achieved by shifting the x,y datum coordinates such that image features matched National Agricultural Imagery Program Digital Ortho Quarter Quadrangle imagery in order to correct georegistration errors known to SPOT imagery (Weber et al., 2008). Finally, the SPOT NDVI values were smoothed to 30-m resolution using ENVI 4.8 software (Exelis Visual Information Solutions) to reduce outlier pixels and to improve comparability with Landsat pixels (Hively et al., 2015). Landsat 5 TM and Landsat 7 ETM+ imagery collected within ±15 d of biomass sampling were downloaded from the USGS Earth Explorer website as a Level 2 Surface Reflectance Product (Earth Resources Observation and Science (EROS) Center, 2012, 2020; Hively et al., 2022; Masek et al., 2006).

For 2019–2021, the cloud masked NDVI values were extracted from Sentinel-2 (20 m) Level 2A surface reflectance imagery (collected within ±15 d of biomass sampling) downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home) operated by the European Space Agency (Drusch et al., 2012; Hively et al., 2022). The resulting dataset of clear (non-cloudy) NDVI in situ samples (n = 1,025) was subset by the number of days between biomass and available imagery, a factor that contributed to outliers in the dataset, and analysis was limited to samples (n = 757) that had clear imagery acquisition within ±6 d of biomass collection (Table 3). Cereal rye data collected at BARC (n = 35) were excluded as fields were known to have substantial amounts of weeds. The remaining samples (n = 722) were used to create biomass estimation equations.

2.3 | Calibration: biomass equations

The relationship between NDVI and biomass was not normally distributed, thus we explored the use of log linear, second-order polynomial, third-order polynomial, and bilinear models evaluated based on the adjusted R^2 values. Next, we evaluated the relationships between species (cereal rye, barley, wheat, triticale), sampling location (BARC vs. Eastern

TABLE 3 Count of destructive winter cover crop samples by species and year

Species	2006	2007	2008	2009	2010	2019	2020	2021	Total
Barley	6	32	27	18	6	NA	NA	12	101
Cereal rye	30	21	18	21	NA	NA	NA	6	96
Triticale	3	3	NA	NA	NA	NA	20	69	95
Wheat	31	35	45	21	18	45	124	111	430

Note. NA, no applicable samples collected that year. Samples were collected on the eastern shore, MD (2006–2010, 2021) and at Beltsville Agricultural Research Center, MD (2019–2021)

Shore), season (winter vs. spring), sampling period (2006–2012 vs. 2019–2021), NDVI, and natural log biomass using ANOVA and Bonferroni post hoc tests (Bonferroni, 1936; Scheffe, 1999). Bonferroni post hoc tests were selected to detect statistically significant differences in a small number of means in the calibration dataset (n = 722) for significant effects of species, sampling location, or sampling period. Because we were primarily focused on evaluating the effects of the delayed termination in the springtime, once season was found to have a significant effect, we subset the data by season and applied calibration equations for the spring season. We calculated uncertainty using the following equation:

$$\text{Uncertainty} = y_{\text{est}}\sqrt{(x\,\text{SE slope})^2 + (\text{SE intercept})^2}$$

where SE represents the standard error, y is the estimated dry aboveground biomass, and x is NDVI. Uncertainty increases linearly with biomass, a disadvantage of using exponential models that saturate at high NDVI.

2.4 | Calibration: N, and C equations

The in situ cover crop biomass samples (n = 1,094) were analyzed using dry combustion on a TruSpec C/N Analyzer (Leco Corp) to quantify the N and C content of the biomass. Whereas C content (kg ha^{-1}) increased as plants matured, C concentration (% biomass) remained stable throughout all growth stages, and thus one value was multiplied by the average biomass grouped by agronomic variables (i.e., planting date, species, and termination date) to estimate total biomass C (Hively et al., 2022). Plant N concentration (%) has been shown to have an inverse relationship with biomass, particularly in the later growth stages of grasses (Odhiambo & Bomke, 2001; Wagger, 1989). Measured average N concentration of cover crop samples were, therefore, grouped by the measured biomass (500 kg ha^{-1} bins). Species were not equally represented in each bin and were, therefore, not analyzed separately. Once average biomass values were estimated based on NDVI measurement of Maryland enrolled fields and grouped by agronomic variables, mean N concentration for each biomass class were used to calculate predicted N content of cover crop fields based on remotely sensed biomass estimations.

2.5 | Application: Flexfit NDVI data for estimating springtime performance

To estimate cover crop springtime performance on MDA MACS-enrolled fields, we used NDVI values from Harmonized Landsat Sentinel-2 (HLS), a multi-sensor data product that combines both NASA–USGS Landsat 8 and European Space Agency Sentinel-2 imagery at the same spatial resolution (30 m) (Claverie et al., 2018). The Landsat 8 mission began collecting data in 2013, whereas the Sentinel-2 missions began collecting data in 2015. Because our plant sampling began prior to the launch of Sentinel-2 and Landsat 8, we used satellite imagery from several other sensors to obtain NDVI values from 2006 to 2012. There is no temporal overlap between SPOT 4, SPOT 5, and HLS, so it is not possible to compare them. We compared SPOT 4 and SPOT 5 NDVI values with Landsat 5 and Landsat 7 NDVI values on matching overpass dates and the differences in the values were minimal (Supplemental Table S1). Sentinel-2 and HLS were compared across locations on the Eastern Shore and at BARC for 5 Apr. 2021. Normalized difference vegetation index differences between the two were minimal and likely attributable to differing spatial resolutions (Supplemental Table S1).

For 2019–2021 MACS-enrolled fields, we calculated daily NDVI values that were estimated using a Flexfit interpolation (a modified Savitzky–Golay filter) of HLS 1.4 imagery available from the NASA Goddard Space Flight Center and HLS 1.5 imagery formerly available through the Land Processes Distributed Active Archive Center (Gao, Anderson, & Hively, 2020; Gao, Anderson, & Daughtry, 2020; Sun et al., 2021). Daily NDVI values were extracted (spatial median of each field after a −30-m buffer was applied to remove edge effects) prior to the reported crop termination date, and then the springtime temporal maximums of these NDVI values for each of the 2019–2020 and 2020–2021 MDA-enrolled cover crop fields were calculated. These values were then linked back to the agronomic data collected from farmers by the MDA using a GIS.

2.6 | Application: biomass, N, and C estimation in enrolled fields

We applied the biomass calibration equations detailed in Section 3.1 to the maximum spring NDVI values. Enrollment NDVI values were capped to the in situ sampled range per species to avoid extrapolation. Next, the biomass estimation equations were applied to each field, by species. Carbon pools in the cover crop were estimated as a consistent percentage of biomass per field. Biomass and C estimates (kg ha^{-1}) were multiplied by the total area of each field (ha) for an estimated total biomass and biomass C (kg) per field. These were summed and divided by the sum of total field areas to produce overall program performance estimates that weren't biased by large or small field sizes. The cover crop biomass N pool (kg ha^{-1}) was estimated by multiplying N concentration (%) with estimated biomass (kg ha^{-1}). Nitrogen concentrations (%) were binned by the measured biomass (500 kg ha^{-1} bins). Analysis of variance was applied to the resulting data to determine if there were differences in fields grouped by species, planting date, planting method, termination date, or termination method. If there were statistically significant differences found among groups, a post hoc Tukey's Least Significant Difference test (well suited for comparing significant differences in larger numbers of means) was used to determine the relationship between groups including termination date, species, and planting date (Abdi & Williams, 2010). Payment calculations for groups were based on incentives for species, planting method, and planting date, with an additional delayed termination incentive of \$15 ac^{-1}(\$37.07 ha^{-1}) 2019–2020 and \$10 ac^{-1}(\$24.71 ha^{-1}) in 2020–2021(Table 2). Cost per unit performance (\$ kg^{-1}) equals the total payment (\$ ha^{-1}) calculated using the parameters in Table 2 divided by the performance metric (kg biomass ha^{-1}, kg N ha^{-1}). Cost per kg C can be calculated by multiplying cost per kg biomass by the C concentration (%), and cost per Mg C by multiplying the product by 1,000. Finally, to calculate Mg C sequestered, we estimated that root C is 50% of aboveground dry C and that 15% of aboveground dry C and 35% of root C convert to soil organic matter (Magdoff & Weil, 2004).

2.7 | Data processing

Normalized difference vegetation index values were averaged for each field from daily HLS NDVI images using the R language for statistical computing and the following packages: raster, sf, rgeos, extractextractr, rgdal. Statistical analyses were performed using R and the following packages: car, dplyr, emmeans, lsmeans, Metrics, MuMIn, plyr, polynom, reshape2, segmented, AICcmodavg, olsrr (R Core Team, 2021). Tables and figures were created using QGIS, Excel, Adobe Illustrator, and R along with the following packages: ggplot2, viridisLite (R Core Team, 2021).

TABLE 4 Spring correlation equations between in situ cover crop aboveground biomass and satellite-derived normalized difference vegetation index (NDVI) by species, including goodness of fit (R^2) and number of samples (n)

Species	Formula	Adjusted R^2	n
Barley	ln(biomass) ~ 7.29 * NDVI + 3.00	.57	101
Cereal rye	ln(biomass) ~ 5.01 * NDVI + 3.99	.60	96
Triticale	ln(biomass) ~ 6.46 * NDVI + 2.58	.77	95
Wheat	ln(biomass) ~ 5.10 * NDVI + 4.00	.62	430

3 | RESULTS

3.1 | Biomass calibration models

In situ biomass samples ranged from 12 to 11,651 kg ha^{-1} and corresponding NDVI values ranged from 0.27 to 0.91 (Figures 2 and 3). Analysis of variance tests showed that NDVI accounted for the most explained variance in biomass followed by season and species. Because the relationship between biomass and NDVI was significantly different by season ($p < .001$), different calibration equations were developed for winter (November–February) and spring (March–May), and the springtime model was used for the late termination analysis. Of the models applied, a natural log linear equation was selected for ease of use, high performance, and because model residuals best met normality assumptions (Figure 3; Table 4). A segmented regression model marginally outperformed the natural log linear model, and the second and third order polynomial models performed worse than the natural log linear model (Supplemental Table S2). An issue with logarithmic equations based on NDVI is that uncertainty increases linearly with biomass. Bonferroni post hoc tests demonstrated significant (p adj $< .01$) NDVI and springtime aboveground biomass differences between some species, so different equations were applied for each species (Table 4). Of the sampled species, wheat and rye had the most similar relationship between NDVI and biomass (Figure 3). The largest difference in slopes can be seen in comparing barley (7.3) and rye (5.0) (Figure 3; Table 4). Because NDVI saturates, we limited the biomass estimation to HLS NDVI values within the in situ sampled range (NDVI = 0.27–0.91), capping values that exceeded the sampled range (2).

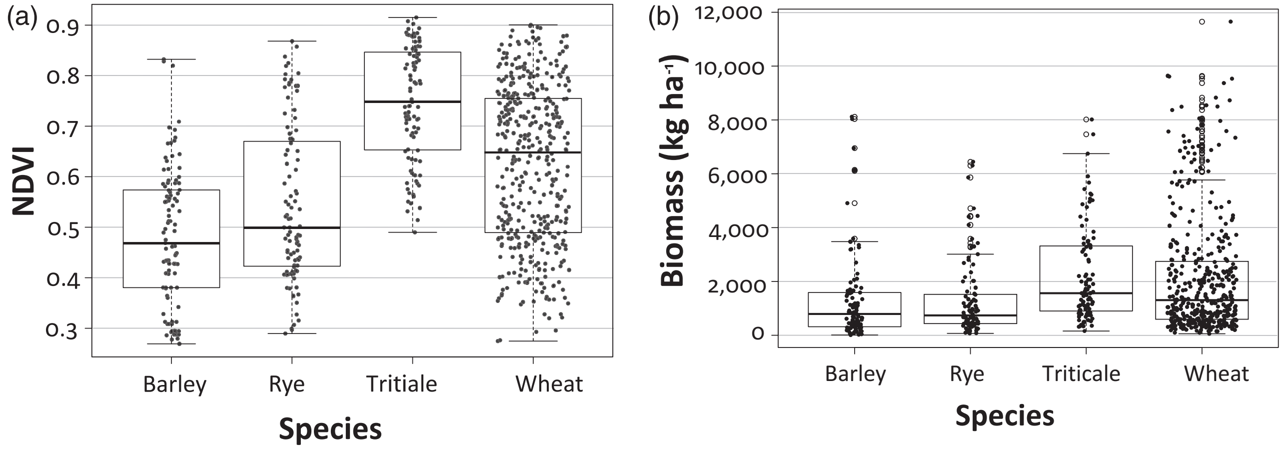

FIGURE 2 In situ cover crop samples ($n = 722$) depicting (a) species-level differences in the normalized difference vegetation index (NDVI) and (b) aboveground biomass measurements kg ha^{-1}. Boxplots represent the interquartile range, tails represent the minimum and maximum values, and the thick black line represents the median value. Points falling outside of the boxplot range are potential outliers. Plots are represented per species: barley ($n = 101$), cereal rye ($n = 96$), triticale ($n = 95$), and wheat ($n = 430$)

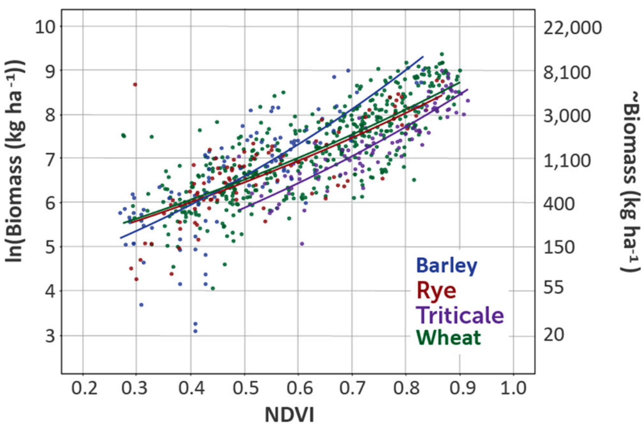

FIGURE 3 Spring correlation equations for in situ cover crop samples ($n = 722$) depicting satellite-derived normalized difference vegetation index (NDVI), the natural logarithm of aboveground biomass [ln(kg ha^{-1})], and the approximate aboveground biomass by species (~kg ha^{-1}). The corresponding equations are listed in Table 4

3.2 | Nitrogen and C estimation

The C concentration in cereal winter cover crops remained constant around 42.6%. The N concentration decreased as the cover crops grew, showing lower concentrations at higher levels of biomass. No significant differences in N concentration were correlated with cereal cover crop species. The N concentrations from the calibration dataset were, therefore, analyzed across species, binned into groups of 500 kg ha^{-1} biomass (Figure 4). Low biomass (0–500 kg ha^{-1}) samples largely represented young vegetation with higher concentrations of N. The N concentration decreased slowly during growth until 3,000 kg ha^{-1} followed by sharper declines at very high biomass levels (greater than 3,500 kg ha^{-1}) as the plants exhibited stem elongation and reproductive growth.

3.3 | Enrolled field performance

A comparison of MDA enrollment data between the two enrollment years with the delayed termination incentive (2019–2020, 2020–2021) and the two prior enrollment years (2017–2018, 2018–2019) shows a clear increase in length of farmer reported cover crop growth span (days between planting and termination), indicating that the delayed termination incentive did, in fact, shift farmer behavior (Figure 5).

Fields with delayed termination showed an average delay of 32 d in 2019–2020 and 24 d in 2020–2021 for an average 29-d delay relative to fields enrolled in the regular termination category (Table 2). In those 29 d, they accumulated an estimated 63% more biomass than regularly terminated winter cover crops. Delayed termination fields comprised 33% of the total winter cover crop hectarage in Maryland (96,100 ha of a total 286,200 ha), while accounting for 45% (196,805,000 kg of a total 436,579,000 kg) of the total biomass. Across all species and planting dates, delayed termination fields outperformed regular termination fields in terms of biomass, as would be expected from the longer springtime growth period (Tables 5 and 6; Figures 6 and 7). This corresponded to substantial increases in cover crop N uptake associated with delayed termination (Tables 5 and 6) even though tissue N concentrations decreased with higher springtime biomass.

In 2019–2020, all species of early planted cover crops (by 1 October) outperformed late-planted cover crops (after 15 October) in terms of biomass production under regular termination conditions (Figure 6), because there are more growing degree days available to support growth in the early

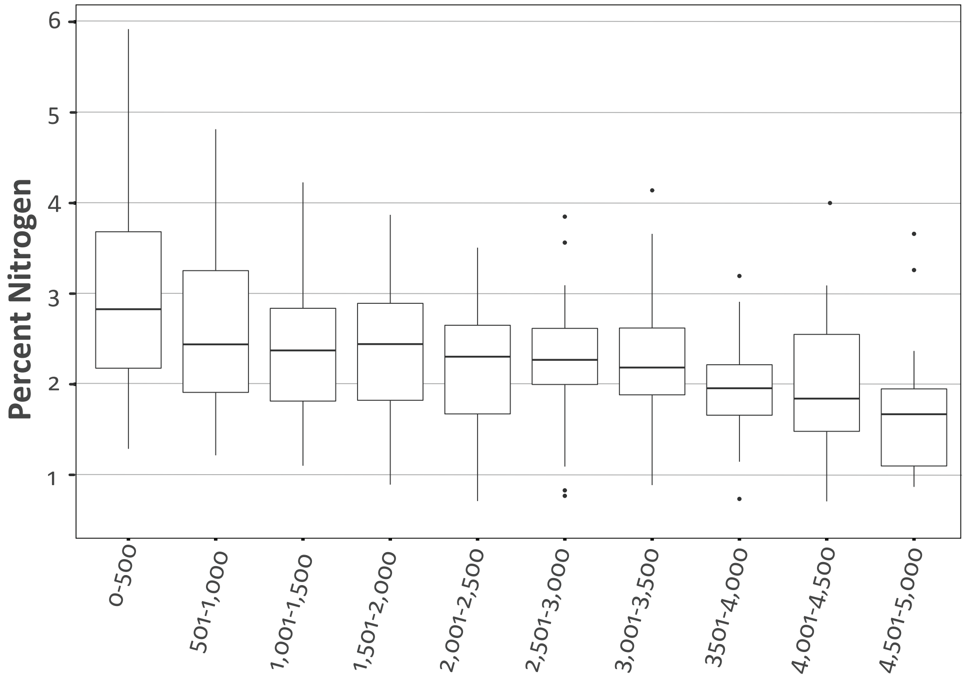

FIGURE 4 Cereal cover crop N concentration (%) binned by above-ground dry biomass (500 kg ha^{-1} bins) from 1,094 in situ cover crop destructive samples collected from 2006–2021). Boxplots represent the interquartile range, tails represent the minimum and maximum values, and the thick black line represents the median value

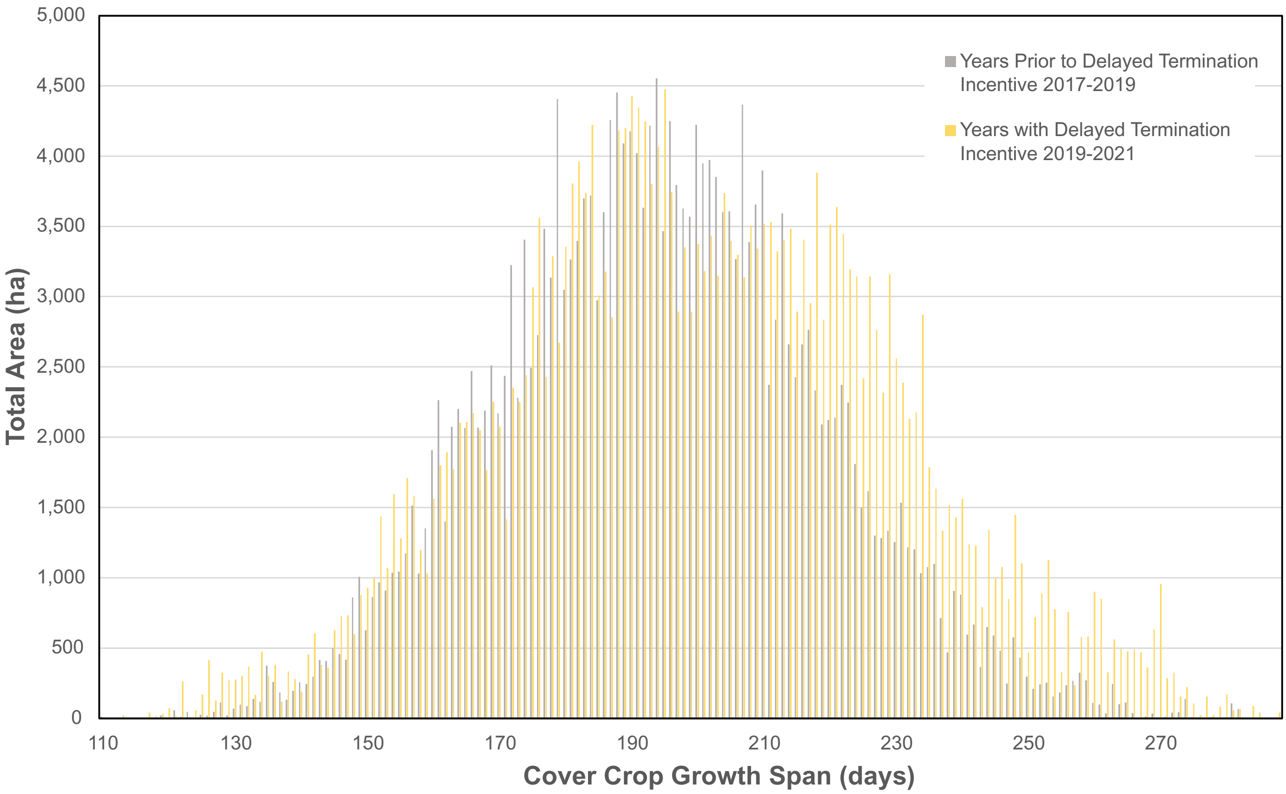

FIGURE 5 Enrolled winter cover crop area by cover crop growth span (days from planting to termination) for years with the delayed termination incentive (2019–2021) in yellow and prior to the incentive (2017–2019) in grey

TABLE 5 Overview of 2019–2020 performance of delayed termination fields (after 1 May) vs regular termination fields (after 1 March) displaying the mean estimated biomass and related uncertainty, carbon accumulation, nitrogen uptake, total area and cost.

	Biomass, mean ± uncertainty		C, mean		N, mean		Area, sum		Total cost, sum	
Species and planting date	**Regular term.**	**Delayed term.**	**Regular term.**	**Delayed term.**	**Regular term.**	**Delayed term.**	**Regular term.**	**Delayed term.**	**Regular term.**	**Delayed term.**
	——kg ha^{-1}——		——kg C ha^{-1}——		——kg N ha^{-1}——		——ha——		——$ ha^{-1}——	
Barley										
Early planting	3,080 ± 1,760	4,080 ± 2,360	1,310	1,740	69	78	4,700	2,900	673,000	534,000
Standard planting	2,940 ± 1,670	4,350 ± 2,510	1,250	1,850	66	84	2,200	1,200	279,000	200,000
Rye										
Early planting	1,490 ± 570	2,060 ± 820	630	880	36	45	10,300	7,000	1,703,000	1,462,000
Standard planting	1,600 ± 610	2,160 ± 870	680	920	38	47	4,000	3,900	607,000	746,000
Late planting	1,190 ± 440	2,180 ± 870	510	930	29	48	4,900	4,300	669,000	749,000
Triticale										
Early planting	3,840 ± 1,640	4,150 ± 1,780	1,640	1,770	74	80	1,100	1,500	164,000	277,000
Standard planting	2,780 ± 1,170	3,900 ± 1,670	1,180	1,660	62	76	300	500	47,000	94,000
Late planting	980 ± 380	3,800 ± 1,630	420	1,620	25	74	400	500	43,000	71,000
Wheat										
Early planting	1,140 ± 200	1,600 ± 300	490	680	28	38	43,200	15,600	5,854,000	2,729,000
Standard planting	1,410 ± 260	2,140 ± 410	600	910	34	47	17,600	8,100	2,205,000	1,332,000
Late planting	1,280 ± 230	1,960 ± 380	540	840	31	46	15,500	7,200	1,734,000	1,091,000
Total										
All planting dates	1,420 ± 400	2,200 ± 720	600	940	34	48	104,100	52,800	13,978,000	9,285,000

Note. term., termination. Estimates are based on normalized difference vegetation index (NDVI) values from Harmonized Landsat Sentinel-2 using per-species estimation equations. Early planting was before 1 October standard planting was 2 October to 15 October, and late planting was 16 October onward. The delayed termination incentive was $37.07 ha^{-1} ($15 ac^{-1}) and maximum payments ranged from $172.97 to $$222.39 ha^{-1} ($70–90 ac^{-1}) agronomy, calculated using Table 1.

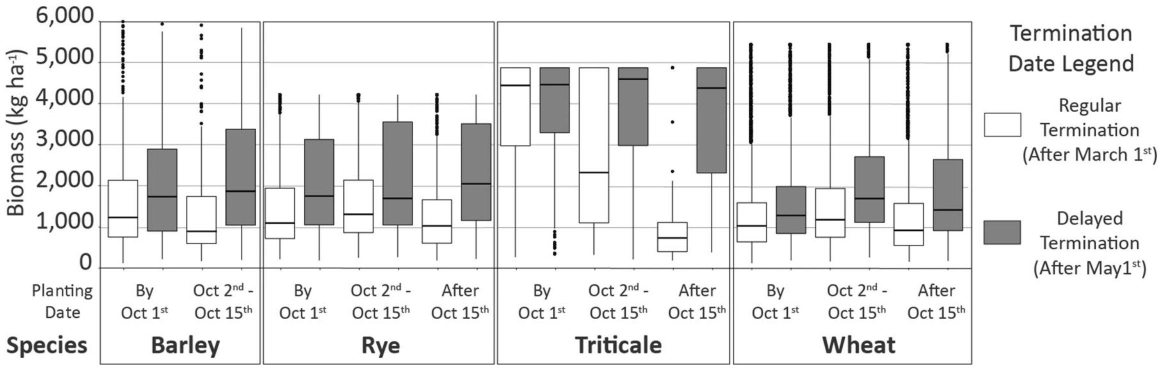

FIGURE 6 Aboveground biomass estimates (kg ha^{-1}) calculated from satellite-derived normalized difference vegetation index (NDVI) and grouped based on species, planting date, and termination date for Maryland Agricultural Water Quality Cost-Share enrolled fields in 2019–2020. Planting dates are grouped as early (by 1 October), standard (2–15 October), and late (after 15 October) following the 2019–2020 program planting deadlines. Boxplots represent the interquartile range, tails represent the minimum and maximum values, and the thick black line represents the median value

fall when soil temperatures remain warm. In the following year, using updated planting date cutoffs, early planted cover crops (by 10 October) outperformed standard-planted cover crops (after 10 October; Figure 7). These findings are similar to performance calculated for four Maryland counties in previous years (Thieme et al., 2020). Under delayed termination conditions, plants that failed to accumulate substantial biomass in the fall often exhibited abundant growth

TABLE 6 Overview of 2020–2021 performance of delayed termination fields (after 1 May) vs regular termination fields (after 1 March) displaying the mean estimated biomass and related uncertainty, carbon accumulation, nitrogen uptake, total area, and cost.

Species and planting date	Biomass, mean ± uncertainty		C, mean		N, mean		Area, sum		Total cost, sum	
	Regular term.	Delayed term.	Regular term.	Delayed term.	Regular term.	Delayed term.	Regular term.	Delayed term.	Regular term.	Delayed term.
	kg ha^{-1}		kg C ha^{-1}		kg N ha^{-1}		ha		$	
Barley										
Early planting	1,600 ± 840	4,160 ± 2,140	680	1,770	36	80	6,700	2,500	823,000	367,000
Standard planting	1,890 ± 1,000	3,570 ± 2,030	810	1,520	43	69	700	600	70,000	71,000
Rye										
Early planting	1,340 ± 500	1,910 ± 750	570	810	32	43	5,700	5,100	687,000	746,000
Standard planting	1,030 ± 370	1,650 ± 640	440	700	25	40	7,700	5,300	757,000	650,000
Triticale										
Early planting	2,610 ± 1,100	3,880 ± 1,660	1,110	1,650	59	75	2,200	2,100	271,000	308,000
Standard planting	2,010 ± 820	2,720 ± 1,140	860	1,160	45	61	700	600	67,000	69,000
Wheat										
Early planting	970 ± 170	1,510 ± 280	410	640	25	34	36,858	14,100	4,450,000	2,039,000
Standard planting	850 ± 140	1,460 ± 270	360	620	22	35	25,572	13,100	2,540,000	1,618,000
Total										
All planting dates	1,070 ± 290	1,870 ± 600	450	800	26	42	86,077	43,300	9,665,000	5,868,000

Note. term., termination. Estimates are based on normalized difference vegetation index (NDVI) values from Harmonized Landsat Sentinel-2 using per-species estimation equations. Early planting was before 10 October and standard planting was 11 October onward. The delayed termination incentive \$24.71 ha^{-1} (\$10 ac^{-1}) and maximum payments ranged from \$123.55 to \$160.62 ha^{-1} (\$50–65 ac^{-1}) based on agronomy, calculated using Table 1.

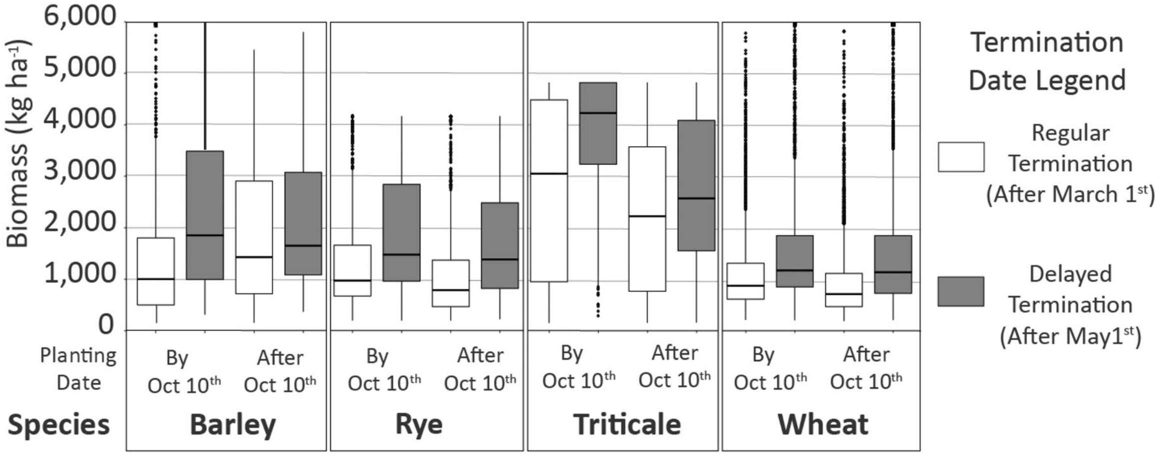

FIGURE 7 Aboveground biomass estimates (kg ha^{-1}) calculated from satellite-derived normalized difference vegetation index (NDVI) and grouped based on species, planting date, and termination date for Maryland Agricultural Water Quality Cost-Share enrolled fields in 2020–2021. Planting dates are grouped as early (by 10 October) and standard (after 10 October) following the 2020–2021 program planting deadlines. Boxplots represent the interquartile range, tails represent the minimum and maximum values, and the thick black line represents the median value

in the spring and achieved similar biomass by termination as early planted crops, due to growth compensation in the warm spring period (Figures 6 and 7).

Performance varied significantly ($p < .01$; 95% family-wise confidence level) by species, with triticale estimated to have the highest average biomass and wheat having the lowest average biomass in both time periods (Figures 6 and 7). Barley and triticale were the least common species planted but consistently exhibited high biomass when termination was delayed. Many triticale fields were reaching the point of NDVI saturation (Prabhakara et al., 2015; Thieme et al., 2020) and may have had biomass higher than our range of prediction

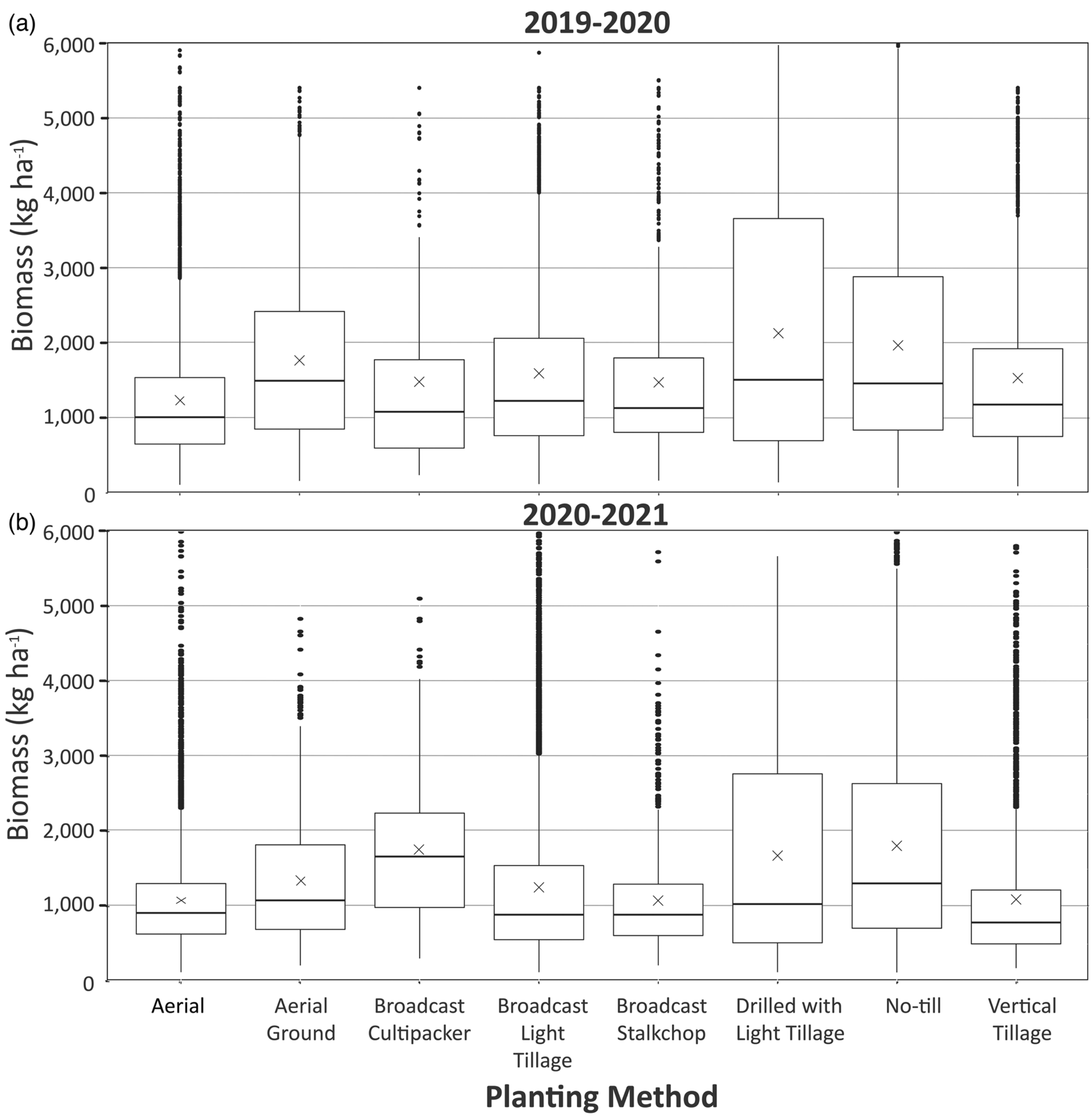

FIGURE 8 Winter cover crop biomass (kg ha^{-1}) for the Maryland Agricultural Cost Share summarized by planting method for (a) 2019–2020 and (b) 2020–2021. Boxplots represent the interquartile range, tails represent the minimum and maximum values, and the thick black line represents the median value. Points falling outside of the boxplot range are potential outliers

of ~1,500 kg ha^{-1}. Barley and triticale were the two most cost-effective species, with biomass costing an average of \$.04 kg^{-1}. When planted early, barley and triticale had higher average biomass at both regular and delayed termination than wheat (Figures 6 and 7). Wheat was by far the most commonly planted cover crop (68.7% of enrolled grasses and 58.5% of all cover crops by area in 2019–2020 and 2020–2021) but had significantly ($p < .01$; 95% family-wise confidence level) lower than other species, even under late-termination and early planting conditions (Figures 6 and 7).

Planting method also affected the performance of winter cover crops (Figure 8). The most common planting method was early aerial seeding (26% of enrolled area, 75,100 of 286,200 ha in 2019–2021) even though it was the worst performing (average 1,100 kg ha^{-1} in 2019–2021). No till (average 2,100 kg ha^{-1} in 2019–2021) and drilling with light tillage (average 2,240 kg ha^{-1} in 2019–2021) consistently yielded higher biomass than planting methods with less seed-to-soil contact (average 1,300 kg ha^{-1} in 2019–2021) but represented only 24–27% of cover crop area.

TABLE 7 Cost per unit performance in capturing biomass and nitrogen cost per kilogram of biomass and nitrogen estimated using remote sensing under regular and delayed termination conditions (before and after 1 May) for the Maryland Agricultural Cost Share (MACS) winter cover crop program.

Species and planting date	2019–2020				2020–2021			
	Regular term.	Delayed term.	Regular term.	Delayed term.	Regular term.	Delayed term.	Regular term.	Delayed term.
	biomass $ kg^{-1}		N $ kg^{-1}		biomass $ kg^{-1}		N $ kg^{-1}	
Barley								
Early planting	0.05	0.04	2.07	2.31	0.09	0.04	3.71	2.25
Standard planting	0.04	0.04	1.90	2.00	0.07	0.05	3.08	2.34
Rye								
Early planting	0.11	0.10	4.63	4.62	0.11	0.10	4.49	4.45
Standard planting	0.10	0.09	4.05	4.07	0.12	0.11	5.04	4.57
Late planting	0.11	0.08	4.73	3.62	0.14	0.11	5.30	4.49
Triticale								
Early planting	0.04	0.04	2.01	2.34	0.05	0.05	2.06	2.49
Standard planting	0.05	0.04	2.24	2.30	0.08	0.05	3.39	2.17
Late planting	0.11	0.04	4.42	2.01	0.06	0.05	2.70	2.44
Wheat								
Early planting	0.12	0.11	4.92	4.63	0.14	0.11	5.40	4.69
Standard planting	0.09	0.08	3.70	3.50	0.12	0.10	5.06	4.25
Late planting	0.09	0.08	3.63	3.26	0.13	0.10	5.18	4.35
Total								
All planting dates	0.09	0.08	3.92	3.65	0.12	0.09	4.89	3.77

Note. term., termination. Costs are derived from the total MACS payment divided by total estimated biomass and nitrogen accumulation on fields within each management category. Returns on investments were calculated using the 2019–2020 MACS payment structure (Table 2) applied to both years. Early planting was before 1 October, standard planting was 2 October to 15 October, and late planting was 16 October onward. The delayed termination incentive was $37.07 ha^{-1} ($15 ac^{-1}) and maximum payments ranged from $172.97 to $222.39 ha^{-1} ($70–90 ac^{-1}) based on agronomy.

Cost per unit mass ($ kg^{-1}) for cover crop biomass and N accumulation were calculated using the incentive payment per unit area ($ ha^{-1}) divided by the biomass (kg ha^{-1}) or N content (kg ha^{-1}) per management class. Regular termination biomass gave a lower return on investment (higher cost per unit performance) than delayed termination biomass (Tables 7 and 8). Aboveground C was similarly more cost effective in fields with delayed termination ($188 Mg^{-1} C in 2019–2020; $171 Mg^{-1} C in 2020–2021) than in regularly terminated fields ($222 Mg^{-1} C in 2019–2020; $247 Mg^{-1} C in 2020–2021). Cost per Mg C sequestered ranged from $525 to $759. Within termination categories, a comparison of cost per unit biomass demonstrates that triticale and barley provided a particularly high return on investment (Tables 7 and 8). For N uptake, the return on investment was more varied, because N concentration decreased with increased biomass. However, delayed termination still generally resulted in lower cost per unit N uptake, and certainly resulted in larger amounts of N uptake, regardless of cost. Cost per kg N in 2019–2020 ranged from $4.05 to $5.30 for rye, due to the $24 ha^{-1} incentive payment for planting that species (discontinued in 2020–2021), and varied from $1.90 to $5.40 for the remaining species, with the highest costs associated with early-planted, late-terminated wheat (Table 7). Costs per kg N were lower across the board in 2020–2021 due to simplification of planting date incentives, no incentive for planting rye, and reduced payments for late termination (Table 8).

4 | DISCUSSION

Delayed termination incentives accounted for only 8% of the total winter cover crop payments ($3,025,0000 out of $38,000,000 total over the two time periods) but resulted in an estimated 21% increase in cover crop biomass (75,660,000 kg out of 436,600,000 kg total over the two time periods) and C (32,230,000 kg out of 186,000,000 kg total over the two time periods). Whereas sequestered C costs through MACS were significantly higher than current C trading market prices, MACS MDA's incentives are focused on improving water quality in the Chesapeake Bay, primarily by N uptake (Santikarn et al., 2021). The delayed termination incentives were estimated to increase N uptake by 17% (1,526,000 kg out of 10,390,000 kg total over the two time periods). In the average 29 d of extra springtime growth, delayed termi-

TABLE 8 Cost per unit performance in capturing biomass and nitrogen cost per kilogram of biomass and nitrogen estimated using remote sensing under regular and delayed termination conditions (before and after 1 May) for the Maryland Agricultural Cost Share (MACS) winter cover crop program.

Species and planting date	2019–2020 Biomass Regular term.	2019–2020 Biomass Delayed term.	2019–2020 Nitrogen Regular term.	2019–2020 Nitrogen Delayed term.	2020–2021 Biomass Regular term.	2020–2021 Biomass Delayed term.	2020–2021 Nitrogen Regular term.	2020–2021 Nitrogen Delayed term.
	$ kg^{-1}							
Barley								
Early planting	0.04	0.04	1.73	1.89	0.08	0.04	3.42	1.87
Standard planting	0.05	0.03	2.06	1.44	0.05	0.04	2.38	1.83
Rye								
Early planting	0.08	0.07	3.47	3.30	0.09	0.08	3.73	3.37
Standard planting	0.08	0.06	3.16	2.59	0.10	0.07	4.00	3.11
Triticale								
Early planting	0.03	0.04	1.71	1.87	0.05	0.04	2.11	1.97
Standard planting	0.07	0.03	2.98	1.78	0.05	0.05	2.19	2.02
Wheat								
Early planting	0.10	0.09	4.30	3.72	0.12	0.10	4.38	4.25
Standard planting	0.07	0.06	3.09	2.75	0.12	0.08	4.56	3.51
Total								
All planting dates	0.08	0.06	3.38	2.91	0.11	0.07	4.36	3.08

Note. Costs are derived from the total MACS payment divided by total estimated biomass and nitrogen accumulation on fields within each management category. Returns on investments were calculated using the 2020–2021 MACS payment structure (Table 2) applied to both years. Early planting was before 10 October and standard planting was 11 October onward. The delayed termination incentive was \$24.71 ha^{-1} (\$10 ac^{-1}) and maximum payments ranged from \$123.55 to \$160.62 ha^{-1} (\$50–65 ac^{-1}) based on agronomy.

nation cover crops added an extra 63% biomass (2,049 kg ha^{-1} delayed termination; 1,261 kg ha^{-1} regular termination) and 48% N (44.9 kg ha^{-1} delayed termination; 30.4 kg ha^{-1} regular termination) due to increased springtime growth. This finding is in accord with previous studies that show that delayed termination increases cover crop quantity, N content, and C/N ratio (Clark et al., 1997). As with past studies on wheat, rye, and triticale, cereal grain samples in this study showed an inverse relationship between N concentration and biomass (Clark et al., 1997; Engel & Zubriski, 1982; Odhiambo & Bomke, 2001; Schwarte et al., 2005; Wagger, 1989). Whereas fields with high biomass have larger cover crop N pools than lower biomass fields, they also have higher C/N ratios, which have positive implications for reducing NO_3^- leaching but can immobilize N and affect future crop yields (Finney et al., 2016). These findings highlight the importance of balancing the benefits of springtime cover crop growth with the potential N immobilization that can occur with high biomass, late-terminated cover crops.

Links between early planting dates and drilled with light tillage planting methods may partially account for species performance differences. Triticale was often planted using drilling with light tillage or no-till methods (70% hectarage in 2019–2021), whereas barley and wheat were often aerially seeded (44 and 32% hectarage, respectively). Early planted triticale experienced the bulk of growth in the fall and experienced less spring growth relative to other species and planting date combinations. However, when planting date and method were controlled for, triticale and barley still exhibited higher biomass than wheat and rye. Triticale fields were commonly terminated using green chopping (72% in 2019–2020), a termination method common on dairy farms that typically have high levels of N in the soil resulting from manure applications. The variation of biomass accumulation among species was also reflected in the cost per unit biomass to MACS, with triticale being the best economic value for the MACS program. In the 2019–2020 season, with an incentive specifically for planting cereal rye (+\$24.71 per hectare), the average cost of biomass and N was highest in cereal rye. In 2020–2021, when that incentive was removed, regular termination wheat was, on average, the most expensive on a cost per mass basis.

Early planted cover crops reduce fall NO_3^- leaching (Sedghi & Weil, 2022; Staver & Brinsfield, 1998; Thapa et al., 2018). Although delaying termination increases biomass and N uptake in the springtime, the timing of N uptake by cover crops is also important as NO_3^- leaching potential is highest in the fall–winter (Di & Cameron, 2002; Otte et al., 2019). The

MDA has encouraged early planting of cover crops to reduce fall–winter NO_3^- leaching through various early planting incentives, and their efficacy is supported in these findings. The combination of early planting and delayed termination cover crops had the highest average biomass in 2020–2021. In 2019–2020, there was little precipitation in late September and early planted cover crops were outperformed by those planted October 2–15. Fields planted later (after 15 Oct. 2019 and 10 Oct. 2020) had cover crops that were relatively unproductive if terminated before spring growth, but developed similar biomass to earlier planted cover crops if terminated after May 1, implying that cost-share programs could increase their environmental benefit by requiring late termination for late-planted cover crops. Rye tended to have later planting dates (36% hectares planted after October 15 in 2019–2021) than other species (28% of wheat hectarage and 19% triticale hectarage planted after October 15 in 2019–2021; MDA does not allow late planting of barley). Late-planted, regularly terminated cover crops consistently cost more per kg than other combinations because they established poorly in the fall and were terminated before considerable spring growth occurred. This may indicate an area for potential improvement in the incentive structure either by requiring delayed termination in late-planted fields or by reducing incentives for late-planted, regularly terminated fields.

5 | CONCLUSIONS

The MDA has recently incentivized delayed cover crop termination in springtime, which is shown to increase N uptake and biomass accumulation. Because fields with delayed termination outperformed regular termination fields, the delayed termination incentive appears to be a good investment by the state. Late-planted cover crops are unlikely to accumulate much N in the fall but can achieve substantial N and biomass accumulation in the spring if termination is delayed. Current incentives focus on planting date and termination date, but an alternative approach could incentivize lengthening the winter cover crop growth span with higher payments for longer growth periods. The addition of incentives for well-performing species like triticale could also increase biomass accumulation in the state. Incentivizing farmers to use planting methods with better seed contact, like drilling with light tillage or no till, may also yield higher average biomass.

Future research could include improved N estimation using remote sensing, root studies to determine below ground biomass and C contribution, soil C studies, and denitrification–decomposition modeling to estimate when the cover crop C and N will become available for the next season of summer crops. Current and future efforts could also make site-specific cover crop performance data available to farmers on a timely basis to inform field management decisions. Additionally, analysis of the impacts of grazing cover crops would be valuable, particularly in states with larger cattle and dairy cow populations.

This research was affected by linearly increasing uncertainty with biomass. This uncertainty could be reduced by using a polynomial equation to estimate biomass, and estimates could be improved by incorporating red-edge bands widely available in Sentinel-2 imagery. Additionally, species differences in NDVI–biomass relationships may be caused by structural differences in species-specific leaf angle distribution and should be studied further.

AUTHOR CONTRIBUTIONS

Alison Thieme: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing. W. Dean Hively: Conceptualization; Methodology; Supervision; Writing – review & editing. Feng Gao: Methodology; Software; Writing – review & editing. Jyoti Jennewein: Investigation; Software; Writing – review & editing. Steven Mirsky: Supervision; Writing – review & editing. Alexander Soroka: Data curation; Software. Jason Keppler: Writing – review & editing. Dawn Bradley: Writing – review & editing. Sergii Skakun: Formal analysis; Writing – review & editing. Gregory W. McCarty: Data curation; Writing – review & editing.

ACKNOWLEDGMENTS & DISCLAIMER

This project was supported by the USGS Land Change Science Program within the Core Science Systems Mission Area, the USDA-ARS, National Program 211, and the USDA Lower Chesapeake Long Term Agricultural Research (LTAR) program. Initial field data collection was supported by an Innovative Nutrient and Sediment Reduction Grant administered by the National Fish and Wildlife Foundation. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government. We would like to thank the farms and the soil conservation districts of the Maryland Department of Agriculture that supported our field sampling efforts—your support makes this research possible.

CONFLICT OF INTEREST

Authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data supporting this analysis are published as a USGS data release in Hively et al. (2022).

ORCID

Alison Thieme https://orcid.org/0000-0001-5458-7554
W. Dean Hively https://orcid.org/0000-0002-5383-8064

REFERENCES

Abdi, H., & Williams, L. (2010). Tukey's honestly significant difference (HSD) test. In N. J. Salkind (Ed.), *Encyclopedia of research design* (pp. 1–5). Sage Publications.

Beeson, P. C., Daughtry, C. S. T., & Wallander, S. A. (2020). Estimates of conservation tillage practices using Landsat archive. *Remote Sensing*, *12*(16), 2665. https://doi.org/10.3390/rs12162665

Berk, A., Conforti, P., Kennett, R., Perkins, T., Hawes, F., & van den Bosch, J. (2014). MODTRAN® 6: A major upgrade of the MODTRAN® radiative transfer code. *2014 6th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)* (pp. 1–4). IEEE. https://doi.org/10.1109/WHISPERS.2014.8077573

Bonferroni, C. (1936). Teoria statistica delle classi e calcolo delle probabilita. *Pubblicazioni Del R Istituto Superiore Di Scienze Economiche e Commericiali Di Firenze*, *8*, 3–62.

Bowman, M., & Lynch, L. (2019). Government programs that support farmer adoption of soil health practices. *Choices*, *34*(2), 1–8.

Bradley, D. (2022). *Brief history of our cover crop program*. Maryland Department of Agriculture.

Clark, A. J., Decker, A. M., Meisinger, J. J., & McIntosh, M. S. (1997). Kill date of vetch, rye, and a vetch–rye mixture: I. Cover crop and corn nitrogen. *Agronomy Journal*, *89*(3), 427–434. https://doi.org/10.2134/agronj1997.00021962008900030010x

Claverie, M., Ju, J., Masek, J. G., Dungan, J. L., Vermote, E. F., Roger, J.-C., Skakun, S. V., & Justice, C. (2018). The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sensing of Environment*, *219*, 145–161.

Dabney, S. M., Delgado, J. A., & Reeves, D. W. (2001). Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis*, *32*(7–8), 1221–1250.

Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, *64*, 237–356.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., & Martimort, P. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, *120*, 25–36.

Earth Resources Observation And Science (EROS) Center. (2012). *Collection-1 Landsat ETM+ Level-2 Surface Reflectance (SR) Science Product*. USGS. https://doi.org/10.5066/F7Q52MNK

Earth Resources Observation And Science (EROS) Center. (2020). *Collection-2 Landsat 4-5 Thematic Mapper (TM) Level-2 Science Products*. USGS. https://doi.org/10.5066/P9IAXOVV

Engel, R. E., & Zubriski, J. C. (1982). Nitrogen concentrations in spring wheat at several growth stages. *Communications in Soil Science and Plant Analysis*, *13*(7), 531–544. https://doi.org/10.1080/00103628209367292

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. https://doi.org/10.2134/agronj15.0182

Gao, F., Anderson, M., Daughtry, C., Karnieli, A., Hively, D., & Kustas, W. (2020). A within-season approach for detecting early growth stages in corn and soybean using high temporal and spatial resolution imagery. *Remote Sensing of Environment*, *242*, 111752. https://doi.org/10.1016/j.rse.2020.111752

Gao, F., Anderson, M. C., & Hively, W. D. (2020). Detecting cover crop end-of-season using VENμS and Sentinel-2 Satellite imagery. *Remote Sensing*, *12*(21), 3524. https://doi.org/10.3390/rs12213524

Hagen, S. C., Delgado, G., Ingraham, P., Cooke, I., Emery, R., Fisk, J. P., Melendy, L., Olson, T., Patti, S., & Rubin, N. (2020). Mapping conservation management practices and outcomes in the Corn Belt using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. *Land*, *9*(11), 408.

Hartwig, N. L., & Ammon, H. U. (2002). Cover crops and living mulches. *Weed Science*, *50*(6), 688–699.

Hively, W. D., Duiker, S., McCarty, G., & Prabhakara, K. (2015). Remote sensing to monitor cover crop adoption in southeastern Pennsylvania. *Journal of Soil and Water Conservation*, *70*(6), 340–352. https://doi.org/10.2489/jswc.70.6.340

Hively, W. D., Jennewein, J., Soroka, A., McCarty, G. W., & Mirsky, S. (2022). Remote sensing and field data supporting the analysis of Maryland and Delaware winter cover crop performance, 2019-2021. USGS Data Release. https://doi.org/10.5066/P96L9918

Hively, W. D., Lang, M., McCarty, G. W., Keppler, J., Sadeghi, A., & McConnell, L. L. (2009). Using satellite remote sensing to estimate winter cover crop nutrient uptake efficiency. *Journal of Soil and Water Conservation*, *64*(5), 303–313. https://doi.org/10.2489/jswc.64.5.303

Hively, W. D., Lee, S., Sadeghi, A. M., McCarty, G. W., Lamb, B. T., Soroka, A., Keppler, J., Yeo, I.-Y., & Moglen, G. E. (2020). Estimating the effect of winter cover crops on nitrogen leaching using cost-share enrollment data, satellite remote sensing, and Soil and Water Assessment Tool (SWAT) modeling. *Journal of Soil and Water Conservation*, *75*(3), 362–375. https://doi.org/10.2489/jswc.75.3.362

Jahanzad, E., Barker, A. V., Hashemi, M., Eaton, T., Sadeghpour, A., & Weis, S. A. (2016). Nitrogen release dynamics and decomposition of buried and surface cover crop residues. *Agronomy Journal*, *108*(4), 1735–1741. https://doi.org/10.2134/agronj2016.01.0001

Labus, M. P., Nielsen, G. A., Lawrence, R. L., Engel, R., & Long, D. S. (2002). Wheat yield estimates using multi-temporal NDVI satellite imagery. *International Journal of Remote Sensing*, *23*(20), 4169–4180.

Magdoff, F., & Weil, R. R. (2004). *Soil organic matter in sustainable agriculture*. CRC press.

Maryland Department of Agriculture. (2018). *MACS 2018 Annual Report* (pp. 12). Maryland Department of Agriculture. https://mda.maryland.gov/resource_conservation/counties/MACS2018.pdf

Maryland Department of Agriculture. (2019). *Cover Crop Agreement 2019–2020*. https://mda.maryland.gov/resource_conservation/counties/FY20_Program%20Requirements%20and%20Agreement_website.pdf

Maryland Department of Natural Resources. (2012). *Accounting for Maryland's Ecosystem Services: Integrating the value of nature into decision making*. Maryland Department of Natural Resources. https://dnr.maryland.gov/ccs/Documents/AMESreportFinal_MDDNR.pdf

Masek, J. G., Vermote, E. F., Saleous, N. E., Wolfe, R., Hall, F. G., Huemmrich, K. F., Gao, F., Kutler, J., & Lim, T.-K. (2006). A Landsat surface reflectance dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters*, *3*(1), 68–72. https://doi.org/10.1109/LGRS.2005.857030

Odhiambo, J. J. O., & Bomke, A. A. (2001). Grass and legume cover crop effects on dry matter and nitrogen accumulation. *Agronomy Journal*, *93*(2), 299–307. https://doi.org/10.2134/agronj2001.932299x

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

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33–41.

Prabhakara, K., Hively, W. D., & McCarty, G. W. (2015). Evaluating the relationship between biomass, percent groundcover and remote sensing indices across six winter cover crop fields in Maryland, United States. *International Journal of Applied Earth Observation and Geoinformation*, *39*, 88–102. https://doi.org/10.1016/j.jag.2015.03.002

R Core Team (2021) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Ranells, N. N., & Wagger, M. G. (1996). Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agronomy Journal*, *88*(5), 777–882.

Santikarn, M., Churie Kallhauge, A. N., Bozcaga, M. O., Sattler, L., McCormick, M. S., Ferran Torres, A., & Korthuis, A. (2021). *State and trends of carbon pricing 2021*. World Bank. https://openknowledge.worldbank.org/handle/10986/35620

Scheffe, H. (1999). *The analysis of variance* (Vol. 72). John Wiley & Sons.

Schwarte, A. J., Gibson, L. R., Karlen, D. L., Liebman, M., & Jannink, J.-L. (2005). Planting date effects on winter triticale dry matter and nitrogen accumulation. *Agronomy Journal*, *97*(5), 1333–1341. https://doi.org/10.2134/agronj2005.0010

Sedghi, N., & Weil, R. (2022). Fall cover crop nitrogen uptake drives reductions in winter-spring leaching. *Journal of Environmental Quality*, *51*(3), 337–351. https://doi.org/10.1002/jeq2.20342

Shipley, P. R., Messinger, J. J., & Decker, A. M. (1992). Conserving residual corn fertilizer nitrogen with winter cover crops. *Agronomy Journal*, *84*(5), 869–876. https://doi.org/10.2134/agronj1992.00021962008400050020x

Staver, K. W., & Brinsfield, R. B. (1998). Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. *Journal of Soil and Water Conservation*, *11*, 230–240.

Sun, L., Gao, F., Xie, D., Anderson, M., Chen, R., Yang, Y., Yang, Y., & Chen, Z. (2021). Reconstructing daily 30 m NDVI over complex agricultural landscapes using a crop reference curve approach. *Remote Sensing of Environment*, *253*, 112156.

Thapa, R., Poffenbarger, H., Tully, K. L., Ackroyd, V. J., Kramer, M., & Mirsky, S. B. (2018). 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

Thieme, A., Yadav, S., Oddo, P. C., Fitz, J. M., McCartney, S., King, L., Keppler, J., McCarty, G. W., & Hively, W. D. (2020). Using NASA Earth observations and Google Earth Engine to map winter cover crop conservation performance in the Chesapeake Bay watershed. *Remote Sensing of Environment*, *248*, 111943. https://doi.org/10.1016/j.rse.2020.111943

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, *8*(2), 127–150.

United States Census Bureau. (2021). *U.S. Census Bureau TIGER, TIGER/Line and TIGER-related products electronic resource: TIGER, Topologically Integrated Geographic Encoding and Referencing system*. United States Census Bureau. https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

USDA-ARS Grassland Soil and Water Research Laboratory and Texas A&M AgriLife Research. (2018). *SWAT - Soil and Water Assessment Tool*. USDA-ARS and Texas A&M AgriLife Research. https://data.nal.usda.gov/dataset/swat-soil-and-water-assessment-tool

Wagger, M. G. (1989). Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agronomy Journal*, *81*(2), 236–241.

Wallander, S., Smith, D., Bowman, M., & Claassen, R. (2021). *Cover crop trends, programs, and practices in the United States* (Economic Information Bulletin No. 222, pp. 33). USDA Economic Research Service. https://www.ers.usda.gov/webdocs/publications/100551/eib-222.pdf?v=9246

Weber, K. T., Théau, J., & Serr, K. (2008). Effect of coregistration error on patchy target detection using high-resolution imagery. *Remote Sensing of Environment*, *112*(3), 845–850.

Xia, Y., Guan, K., Copenhaver, K., & Wander, M. (2021). Estimating cover crop biomass nitrogen credits with Sentinel-2 imagery and sites covariates. *Agronomy Journal*, *113*(2), 1084–1101. https://doi.org/10.1002/agj2.20525

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Thieme, A., Hively, W. D., Gao, F., Jennewein, J., Mirsky, S., Soroka, A., Keppler, J., Bradley, D., Skakun, S., & McCarty, G. W. (2023). Remote sensing evaluation of winter cover crop springtime performance and the impact of delayed termination. *Agronomy Journal*, *115*, 442–458. https://doi.org/10.1002/agj2.21207