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Fall cover crop nitrogen uptake drives reductions in winter-spring leaching

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Abstract

Cover crops can reduce nitrate leaching after cash crop harvest. Despite widespread cover crop implementation, there has been a limited effect on water quality in the Chesapeake Bay watershed. We hypothesize that typical timing for Maryland cover crop planting after cash crop harvest is too late to allow roots to take up substantial nitrate from the soil profile before it is leached by winter drainage water. Across four site-years (including sandy and silty soils), we compared various planting dates for a radish (*Raphanus sativus* L.)–crimson clover (*Trifolium incarnatum* L.)–triticale (*Triticosecale*) cover crop mixture. Also, across two site-years we compared early-planted pure rye, radish, and a three-species mixture with no cover. We measured cover crop biomass and N content and used tension lysimeters to measure deep soil porewater nitrate concentrations. Cumulative nitrate leaching was calculated from these concentrations and weather-based drainage estimates. Cover crops were planted on four dates over a 6-wk period. Overall, cover crops planted first, second, third, fourth, and no cover crop (just weeds) resulted in 3,340, 3,160, 1,600, 303, and 164 kg ha^{-1} of biomass; biomass N accumulation of 65.5, 68.6, 44.0, 9.88, and 4.79 kg N ha^{-1}; and mean porewater concentrations of 2.71, 2.57, 4.72, 10.0, 17.1 mg L^{-1} of nitrate-N, respectively. Over two site-years, the three-species mix performed as well or better than pure rye or radish. Early planting altered cover crop species proportions, increased cover crop productivity, and reduced nitrate leaching from agricultural fields.

1 | INTRODUCTION

Cover crops offer many agroecosystem benefits, including capture of nitrogen (N) that might otherwise be lost by leaching (Daryanto et al., 2018; Doran & Smith, 1991; Snapp et al., 2005). Actively growing cover crops reduce N leaching by removing soluble N from the soil profile before the leaching season and by temporarily reducing drainage water volume during the leaching season (Meisinger et al., 1991). Cover crop N can be remineralized after termination. The N from winter-killed cover crops may be susceptible to leaching (Dean & Weil, 2009), but N released from cover crops terminated at the end of the leaching season can increase surface soil mineral N concentrations (Hirsh et al., 2021) and may be available to the following cash crop (Snapp et al., 2005; White et al., 2017). Nonleguminous cover crops are especially effective for reducing nitrate leaching (Constantin et al., 2010;

Abbreviations: ET, evapotranspiration; GDD, growing degree days; MACS, Maryland Agricultural Water Quality and Cost Share program.

Quemada et al., 2013; Thapa et al., 2018; Valkama et al., 2015).

Agricultural land contributes approximately 42% of the eutrophication-stimulating N in the Chesapeake Bay (Chesapeake Bay Program, 2017; Testa et al., 2014). The Eastern Shore of Maryland watersheds annually contribute approximately 7 kg fertilizer or fixed N and 2 kg manure N ha^{-1} (Ator & Denver, 2015). The Maryland Agricultural Water Quality and Cost Share program (MACS) pays farmers US$100–US$200 ha^{-1} for planting cover crops, with higher incentives for practices thought to enhance N capture (MACS, 2020), resulting in the highest level of cover crop adoption in the United States (USDA, 2017). Although MACS prevented an estimated 544 Mg N loading in 2009–2010 (MACS, 2010) and 1,600 Mg N loading in 2019–2020 (MACS, 2020), greater N load reductions are required to restore the health of the Chesapeake Bay.

Currently MACS allows winter cereals to be planted up to 5 November and other species up to 1 October, limiting potential cover crop N accumulation prior to the winter leaching season. When rainy weather delays harvests and cover crop planting, these deadlines are typically extended (Kess, 2020). Planting cover crops earlier in fall provides more growing degree days (GDD) before winter dormancy, which can increase fall cover crop biomass (Lawson et al., 2015; Mirsky et al., 2011) and N uptake (Hashemi et al., 2013; Lawson et al., 2015). Trials on mid-Atlantic region farms demonstrated that brassica–legume–grass cover crops planted in early fall or late summer can remove most NO_3–N present in the soil profile to 2 m (Hirsh et al., 2021).

Fast-growing deep-rooted cover crops may most effectively reduce nitrate leaching (Kristensen & Thorup-Kristensen, 2004; Hirsh & Weil, 2019). Sainju et al. (1998) reported that soil profiles under mid-Atlantic fields at corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] maturity averaged 115 kg NO_3–N ha^{-1}, regardless of soil texture (loamy sand to silty clay loam) or parent material (coastal sediments or igneous and sedimentary rocks). Furthermore, 55% of this large pool of residual nitrate was found between 90 and 210 cm deep. If not captured by cover crops, this deep soil nitrate will likely leach to groundwater. Brassica cover crops can reduce soil N to at least 180 cm depth (Dean & Weil, 2009). Forage radish can be exceptionally effective at N capture, but the N it accumulates may become susceptible to leaching during winter because temperatures below −7 ˚C usually release N from damaged tissues (Rutan & Steinke, 2019; Weil & Kremen, 2007). When planted with radish, a winter-hardy grass may capture N released by radish frost-kill before it can be lost by leaching. Thus, an early-planted forage radish–grass cover crop mixture may more effectively capture N than either species separately as well as avoid the post-termination N immobilization associated with single-species grass cover crops (Hirsh et al., 2021).

Core Ideas

- Earlier-planted cover crops took up more nitrogen in fall than later-planted cover crops.
- Earlier planting of radish–clover–grass cover mix increased radish proportion in fall biomass.
- The mass of nitrate leached from plots planted in early October was 2–4 times greater than earlier planted covers.
- Fall cover crop nitrogen uptake was closely and negatively related to mass of nitrate leached during winter and spring.

Many studies compare biomass accumulation by single-species cover crops (Coombs et al., 2017; Dean & Weil, 2009; Fisher et al., 2011; Guldan et al., 1997; Odhiambo & Bomke, 2001), including some that evaluate planting date effects (Komainda et al., 2016; Mirsky et al., 2011). Fewer reports focus on mixed-species cover crops (Finney & Kaye, 2017; Hirsh et al., 2021), and few of these evaluate planting date effects (Murrell et al., 2017; Ruis et al., 2020).

This study aimed to determine (a) how radish–clover–triticale cover crop planting date affects N leaching losses in a grain production agroecosystem and (b) whether a radish–clover–rye cover crop can reduce N leaching as effectively as single-species rye or radish cover crops. We hypothesized (a) that earlier planting would increase cover crop biomass and N accumulation in fall and reduce the amount of nitrate in the soil profile available to be dissolved in drainage waters during winter and early spring and (b) that a three-species mixture would equal the N capture capacity of rye or radish cover crops.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

Two replicated experiments were conducted at the Central Maryland Research and Education Center in Beltsville, MD (39˚0′42.91″ N, 76˚49′54.20″ W). Typical annual precipitation and temperature are 1,100 mm and 12.8 ˚C, respectively (PRISM, 2004), and updated Köppen–Geiger climate is temperate–without dry season–with hot summers (Peel et al., 2007).

The first experiment (Planting Date Experiment) was repeated for 2 yr (2016–2017 and 2017–2018) on two fields (one with silty soils and one with sandy soils) from which winter wheat (*Triticum aestivum* L.) was harvested in early July

TABLE 1 Site characteristics and cover crop planting treatments for four experimental site-years

Year	Soil texture	Site GPS coordinates	Mapped unit name	Cover crop treatments				
Planting date experiment								
				Planting date treatments				
2016–2017	sandy loam to loamy sand	39˚0′38.91″ N, 76˚49′53.79″ W	Downer–Hammonton complex	15 Aug. 2016	30 Aug. 2016	15 Sept. 2016	30 Sept. 2016	no cover
2016–2017	silt loam to silty clay loam	39˚1′5.90″ N, 76˚49′23.85″ W	Russett–Christiana complex	15 Aug. 2016	30 Aug. 2016	15 Sept. 2016	30 Sept. 2016	no cover
2017–2018	sandy loam to loamy sand	39˚0′42.91″ N, 76˚49′54.20″ W	Downer–Hammonton complex	12 Sept. 2017[a]	21 Sept. 2017	3 Oct. 2017	17 Oct. 2017	no cover
2017–2018	silt loam to silty clay loam	39˚1′35.13″ N, 76˚50′10.95″ W	Christiana–Downer complex	12 Sept. 2017[a]	21 Sept. 2017	3 Oct. 2017	17 Oct. 2017	no cover
Species experiment								
				Cover crop species treatments				
2019–2020	sandy loam to loamy sand	39˚00′39.79″ N, 76˚49′58.93″ W	Downer–Hammonton complex	rye	radish	mix	no cover	–
2019–20	silt loam to silty clay loam	39˚01′01.00″ N, 76˚49′38.90″ W	Christiana–Downer complex	rye	radish	mix	no cover	–

[a]Equipment breakdown delayed cover crop plantings in fall 2017.

(Table 1). The fields all had grown no-till corn, soybean, and wheat with a variety of winter cover crops for over 10 yr. On the day before the first cover crop planting, 46,800 L ha^{-1} of liquid dairy manure (67 kg plant available N ha^{-1}) was applied to the entire experiment. Fall application of dairy manure is a common local practice when cover crops are grown (MDA, 2021), and we wanted to ensure a relatively high N environment for the study.

The Planting Date Experiment was a randomized complete block with three replicates. The plot dimensions were 9.1 m by 42.6 m. Measurements were made >1 m from plot edges. Treatments (Table 1) were a no–cover crop control and a mix of 3.4 kg ha^{-1} forage radish, 67 kg ha^{-1} triticale (*Triticosecale*), and 9 kg ha^{-1} crimson clover seeds (hereafter termed radish, triticale, and clover) no-till drilled on four planting dates approximately 2 wk apart, beginning in late summer (hereafter First planting, Second Planting, Third Planting, Fourth Planting, and No Cover).

A second experiment (Species Experiment) was conducted in 2019–2020 on two fields (one sandy and one silty). To estimate the cover crop potential to reduce NO_3 leaching under conditions with substantial available N, soybean was planted after wheat harvest in July and terminated with herbicides at stage R1-3 prior to no-till drilling cover crops on 26 Aug. 2019. The treatments were forage radish (8.9 kg ha^{-1}), cereal rye (112 kg ha^{-1}), a three-species mixture (6.7 kg ha^{-1} forage radish + 84 kg ha^{-1} cereal rye kg ha^{-1} + 13.5 kg ha^{-1} crimson clover), and a no–cover crop control, hereafter referred to as Radish, Rye, Mix, and No-cover (Table 1). The experimental design was a randomized complete block with three replicates using 3.1 m by 30.5 m plots.

2.2 | Cover crop biomass

In both experiments, fall biomass was measured in early December before radish winter-killed. All vegetation within a 0.5-m by 0.5-m quadrat was clipped 1 cm above the soil surface, except for aboveground and belowground portions of fleshy radish taproots, which were collected and rinsed thoroughly with tap water to remove any adhering soil. Biomass was collected at three random locations within each plot, consolidated into one paper bag for each component (radish taproots, radish shoots, clover, grass, and weeds), and dried at 60–70 ˚C to constant weight. Radish biomass reported includes shoot and fleshy taproot.

2.3 | Nitrate leaching

For both experiments, clean tension lysimeters made of butyrate tubes (22-mm outer diameter) with 100-kPa air entry ceramic tips (Irrometer) were installed to 100 cm deep (70 cm at silty sites of Planting Date Experiment) at two representative locations in each plot as soon as possible after cover crop planting to obtain soil macro-porewater samples from the bottom of the crop root zone. Before installing each lysimeter, a pilot hole of the same diameter was made, and 200 ml of water–subsoil slurry (using soil material from 80–110 cm in the same field) was poured down the hole to ensure good contact between the ceramic tip and the soil. The upper 5–10 cm of soil around each lysimeter was sealed with bentonite to prevent preferential flow. A 75-to-85-kPa vacuum was applied for ∼24 h to collect porewater samples every 2 wk throughout the cover crop growing season. Porewater samples were kept cold during transport and frozen until analyzed.

2.4 | Weather

Weather data were obtained from an Ag DTN weather station (www.dtn.com) located within 1 km of the study site, and weather anomalies were identified using 30-yr local weather averages (PRISM, 2004). Cumulative growing degree days (GDD_{cum}) with 4 ˚C base mean daily temperature (Brennan & Boyd, 2012; De Notaris et al., 2018) were calculated using Equation(1.

$$GDD_{cum} = \sum (\text{daily mean air temp} - 4) \quad (1)$$

2.5 | Plant N analysis

Dried tissue for each species was ground separately (<1 mm), and a subsample (0.2 ± 0.001 g) was analyzed for total N by high-temperature combustion (LECO CN628 Elemental Analyzer, LECO Corp.) for samples representing >50 kg dry matter ha^{-1}. Cover crop N content for each species was calculated as dry matter (kg ha^{-1}) × N concentration (mg kg^{-1}). The N content for each plot was calculated as the sum of N in grass + clover + weeds + radish + radish taproot.

2.6 | Nitrate in soil porewater

After thawing, porewater samples were filtered through 2.5-μm filter paper (Whatman 42) and analyzed for nitrate-N + nitrite-N (hereafter NO_3^--N) via cadmium reduction and colorimetric determination at 520 nm using QuikChem method 12-107-04-1-H with a deionized water matrix (LaChat Flow Injection Analyzer, Hach). Concentrations lower than the lowest standard (0.05 mg L^{-1} NO_3–N) were reported as 0.025 mg L^{-1}. For the Species Experiment, porewater NH_4^+–N was also determined and summed with NO_3–N.

Soil series and associated textural and hydrologic soil groups were determined using soil survey data (USDA-NRCS, 2020) and field observations (Table 2). Composite soil samples (0–30 cm) taken in June from each site were analyzed for organic matter, pH, texture, and Mehlich 3 extractable nutrients (Waypoint Analytical Laboratory) (Table 2).

2.7 | Estimation of field drainage water volume

Tension lysimeters sample porewater from variable, imprecisely known soil volumes. Therefore, to determine mass of N leached, the volume of water drained through the soil profile was estimated using a daily water balance equation provided by Allen (1998) (Equation 2).

$$DP_i = D_i - D_{i-1} - ET_i + P_i - Q_i \quad (2)$$

where DP is deep percolation, D is moisture deficit relative to field capacity, P is precipitation, Q is runoff, i represents the ith calculated day, and ET is evapotranspiration (Penman, 1948). This water balance approach has been used to estimate cumulative nitrate leaching losses (Heinrich et al., 2014; Tosti et al., 2014) and has been validated by comparisons with ET measurements (Cai et al., 2007; Mutziger et al., 2005). An initial field capacity value from Allen et al. (2005) was assumed for each soil textural class. Runoff was estimated using the curve number method (Hawkins et al., 1985), which can accurately predict runoff volume with curve numbers calibrated to rain events (Jin et al., 2015; Zema et al., 2017) or without calibration (Ficklin & Zhang, 2013). We had no rooting depth or leaf area measurements to justify different drainage calculations among cover crop treatments, so a single estimate was calculated for each site-year.

Because not every lysimeter produced a porewater sample on every sampling date, NO_3–N concentrations were aggregated by month. On each day for which the water balance predicted drainage, mean monthly NO_3–N concentration was multiplied by calculated drainage to estimate daily NO_3–N leached, which was summed to estimate cumulative NO_3–N leaching losses (Equation 3).

$$\begin{aligned}&\text{Cum } NO_3 - \text{N leached } \left(\text{kg } NO_3 - \text{N ha}^{-1}\right)\\&= \sum DP_i\,(\text{cm}) \times NO_3 - N_{\text{month}}\left(\text{mg L}^{-1}\right)\\&\times \frac{1\ \text{L}}{1\times10^{3}\ \text{cm}^{3}} \times \frac{1\times10^{8}\ \text{cm}^{2}}{1\ \text{ha}} \times \frac{1\ \text{kg}}{1\times10^{6}\ \text{mg}}\end{aligned}$$

2.8 | Statistical analyses

Data were analyzed using R Studio version 1.2.5042 and Microsoft Excel (Office 365, Microsoft Corporation).

TABLE 2 Characteristics of the upper 30 cm of soil determined from USDA-NRCS (2020) and standard soil test analyses for both experiments

Site	Soil characteristics: Hydrologic group	pH	P[a]	K[a]	Mg[a]	Ca[a]	CEC[b]	OM	Sand[c]	Silt[c]	Clay[c]
			mg kg^{-1}					g kg^{-1}	g kg^{-1}		
Planting date experiment											
2016–2017 sandy	A	4.9	86	37	57	564	6.1	15	772	144	82
2016–2017 silty	C	6	78	29	44	521	3.6	10	461	427	112
2017–2018 sandy	A	5.6	106	60	44	447	3.6	10	812	164	22
2017–2018 silty	C	6	19	50	84	965	6.7	19	452	404	142
Species experiment											
2019–2020 sandy	A	5.7	46	45	45	413	3.3	12	792	184	24
2019–2020 Silty	C	6	52	51	65	447	3.4	11	220	606	174

[a]Mehlich3 extraction.
[b]Cation exchange capacity.
[c]Hydrometer particle size analysis.

Whenever there were multiple samples per experimental unit (plot), the mean was used for statistical analyses. All ANOVAs were performed using the aov command in R. If ANOVA indicated a significant main treatment or interaction effect, Tukey's honestly significant difference test was used to differentiate among treatment levels. Power transformations (Planting Date Experiment) or log transformations (Species Experiment) were used to satisfy assumptions of normality (Shapiro–Wilk test) and homogeneity of variances. Any variables that could not be transformed to achieve normality were analyzed via permutational multivariate ANOVA (Anderson, 2001) using the 'Vegan' package (Dixon, 2003) followed by a nonparametric paired contrast (Jan, 2004) using the package 'nparcomp' (Konietschke et al., 2015). The Microsoft Excel data analysis add-in was used to perform all regression analyses.

Regressions were used separately for sandy and silty sites to analyze the relationships between GDD and cover crop biomass or cover crop tissue N concentration and between cover crop N content and cumulative NO_3–N leached in the Planting Date Experiment. In R, NO_3–N concentrations were analyzed for each site-year in repeated-measures ANOVA to test for effects of cover crop plant timing, collection month, and monthly differences among treatments. Fall cover crop biomass, N concentration, and N content were analyzed by species across all four site-years using a three-factor nested hierarchical ANOVA to test for differences due to fixed factors of year, soil texture, planting treatment, and their interactions, with each replicate used as a random factor nested within its soil by year combination.

In the Species Experiment, porewater mineral-N concentrations were analyzed over time in repeated-measures ANOVA to test for differences among cover crop treatments and the change in mineral-N concentrations over time.

3 | RESULTS

3.1 | Cover crop biomass in planting date experiment

Cover crop biomass (Table 3) was greater for earlier compared with later plantings, at silty compared with sandy sites, and in 2016 compared with 2017. Cover crop N content was greatest for First and Second plantings. Tissue N concentration was lower for early-planted cover crops and at sandy sites. First and Second plantings produced more than twice the radish biomass of Third planting and ∼2,500 kg ha^{-1} more than Fourth planting. Radish comprised a larger percentage of total biomass (77–81%) for First and Second plantings than for Third (63.5%) and Fourth (36.9%) plantings. Triticale biomass was increased by planting early. Clover biomass was greater at silty than sandy sites ($p = .061$) and was greatest for First and Second plantings.

Mean air temperatures for 2016–2017 (Figure 1a) and 2017–2018 (Figure 1b) were similar to 30-yr averages. Precipitation was greater in 2016–2017, but both years had 11–19.5 cm less precipitation than the 30-yr average. The earlier First planting in 2016 (15 August) resulted in 500 more GDD than for First planting (12 September) in 2017. Additional GDD available before 1 December increased cover crop biomass linearly up to ∼800 GDD (Figure 2). After accumulating 800 GDD, the rate of biomass increase per GDD declined. Tissue N concentrations decreased linearly with additional GDD available with earlier plantings.

TABLE 3 Effect of soil texture, year, and cover crop planting date on fall cover crop biomass, tissue N concentration, and N content at four site-years

Source of variability	Clover	Triticale	Weeds	Radish	Cover crop biomass	Radish	Cover N content	Cover tissue N concentra-tion
	——kg dry matter ha^{-1}——					% of total biomass	kg N ha^{-1}	g N kg^{-1}
Soil (S)								
Sandy	91.6b[a]	202b	114	1,390b[a]	1,450b	64.6	35.7b	24.6b
Silty	125a[a]	293a	112	1,910a[a]	1,970a	64.5	53.8a	27.3a
Year (Y)								
2016	107	202b	177a	2,480a	2,400a	74.5a	59.5a	24.8b
2017	110	292a	49.6b	816b	1,020b	54.7b	27.6b	27.1a
S × Y								
2016								
Sandy	108	181	1,67b[a]	1,990	1,990b[a]	75.3	48.0	24.1c
Silty	106	223	186a[a]	2,960	2,810a[a]	73.6	71.4	25.4b
2017								
Sandy	76.7	223	60.2c[a]	778	922c[a]	54.0	23.1	25.1b
Silty	143	362	38.9c[a]	854	1,130c[a]	55.4	33.0	29.2a
Planting treatment (T)								
First planting	252a	318a	73.8ab	2,700a	3,340a	77.1a	65.5a	19.6e
Second planting	98.9b	316a	80.0ab	2,670a	3,160a	80.7a	68.6a	21.7d
Third planting	60.6b	253a	204a	1,080b	1,600b	63.5b	44b	27.5c
Fourth planting	22.3c	101b	43.4b	135c	303c	36.9c	9.88c	32.6a
No Cover	–	–	164a	–	164c	–	4.79c	29.2b
S × T								
Sandy								
First planting	200	238	68.1b	2,270	2,780	81.2a	54.2	19.5g
Second planting	94.1	257	127ab	2,320	2,780	80.1a[a]	58.9	21.2f
Third planting	61.9	240	243a	834	1,380	58.4c[a]	36.3	26.3d
Fourth planting	11.1	71.1	12.7b	125	220	38.8d[a]	6.75	30.7b
No Cover	–	–	118ab	–	118	–	3.07	26.0d
Silty								
First planting	303	398	79.5b	3,120	3,900	73.1ab[a]	76.8	19.7g
Second planting	103	376	32.9b	3,020	3,530	81.4a[a]	78.4	22.2e
Third planting	59.3	266	165ab	1,340	1,830	68.6b[a]	52.7	28.8c
Fourth planting	33.6	132	74.1b	146	386	35.0d[a]	13.3	34.5a
No Cover	–	–	211a	–	211	–	6.60	31.3b
Y × T								
2016								
First planting	216a	150b	127b	3,840a	4,330a	87.3	77.9ab	18.0g
Second planting	111b	270b	148b	4,110a	4,620a	88.8	96.1a	20.8f
Third planting	59.4bc	243b	382a	1,710b	2,390b	71.1	63.8b	26.7d
Fourth planting	42.4c	144b	79.7b	250c	517c	50.7	15.3d	29.5c
No Cover	–	–	146b	–	146d	–	4.57e	31.3b

(Continues)

TABLE 3 (Continued)

Source of variability			Clover	Triticale	Weeds	Radish	Cover crop biomass	Radish	Cover N content	Cover tissue N concentration
2017										
First planting			287a	486a	20.3c	1,550b	2,350b	67.0	49.8c	21.2f
Second planting			89.2b	372ab	12.3c	1,230b	1,690b	72.7	38.4c	22.7e
Third planting			61.8bc	263b	25.4c	463c	813c	55.9	23.1d	28.4c
Fourth planting			2.18d	58.6c	7.11c	20.3d	88.2d	23.1	3.15e	35.7a
No Cover			–	–	183b	–	183d	–	5.09e	27.8c
Source of variation	**df[b] cover species**	**df[c] other**	***P > F***							
Rep (S)	1	1	.069	*.040*	.557	.051	*.010*	0.735	*.002*	*<.001*
Rep (Y)	1	1	.360	*.017*	*.004*	*<.001*	*<.001*	*<0.001*	*<.001*	*<.001*
Rep (S × Y)	1	1	.192	.212	.059	.229	.072	0.683	.306	*<.001*
Error (rep)	8	8								
T	3	4	*<.001*[d]	*<.001*	*.009*	*.001*	*<.001*	*<.001*	*<.001*	*<.001*
S × T	3	4	.450	.893	*.015*	.587	.913	.057	.869	*<.001*
Y × T	3	4	*.017*	*<.001*	*.004*	*.006*	*<.001*	.775	*<.001*	*<.001*
S × Y × T	3	4	.072	*.037*	*.003*	.140	.314	*.002*	.075	*<.001*
Error	25	33								

Note. Means within an effect followed by the same letter do not differ significantly.

[a]Significant at $p < 0.1$; all other letter differences are significant at $p < .05$.

[b]Degrees of freedom for triticale, radish, crimson clover biomass, and radish percentage of total biomass.

[c]Degrees of freedom for total biomass, weed biomass, cover N content, and N concentration.

[d]Numbers in italics indicates F values in ANOVA table are significant at $p < .05$.

3.2 | Cover crop biomass in species experiment

Fall cover crop biomass and total N content in the Species Experiment were greatest for Radish, followed by Mix, Rye, and No Cover (Table 4). Tissue N concentration was lowest for Radish and lower at the silty site than the sandy site. Total precipitation was near the 30-yr average, but mean air temperatures in 2019–2020 were higher than average (Figure 1c).

3.3 | Porewater nitrate

3.3.1 | Planting date experiment

Planting cover crops early reduced porewater NO_3–N concentrations at all four site-years (Figure 3). Porewater NO_3–N concentrations were greater in 2016–2017 than in 2017–2018 and greater at sandy than silty sites. Porewater NO_3–N concentrations decreased over time at the 2016–2017 sandy site and the 2017–2018 silty site. Although porewater NO_3–N concentrations were usually greatest for No Cover (Figure 3), the cover crop treatments were not significantly different during several months. At the sandy site in 2016–2017, mean NO_3–N concentrations for No Cover and Fourth planting (23.6 and 15.1 mg NO_3–N L^{-1}, respectively) did not differ, but mean NO_3–N concentrations were much lower for First, Second, and Third plantings (1.7–2.2 mg NO_3–N L^{-1}) (Figure 3a). At the silty site in 2016–2017, NO_3–N concentrations were greater for No Cover and Third and Fourth plantings (7.8–13.2 mg NO_3–N L^{-1}) than for First and Second plantings (1.6–2.9 mg NO_3–N L^{-1}) (Figure 3c). At the sandy site in 2017–2018, NO_3–N concentrations for First and Second plantings (4.3–5.6 mg NO_3–N L^{-1}) were lower than NO_3–N concentrations for Third (6.5 mg NO_3–N L^{-1}) and Fourth plantings (13.6 mg NO_3–N L^{-1}), and NO_3–N concentrations were greatest for No Cover (19.3 mg NO_3–N L^{-1}) (Figure 3b). At the silty site in 2017–2018, NO_3–N concentrations among all treatments with cover crops did not differ (1.3–3.0 mg NO_3–N L^{-1}) but were lower than No Cover (11.4 mg NO_3–N L^{-1}; Figure 3D).

Averaged across all four site-years, the greatest estimated NO_3–N leaching losses were for No Cover (43.8 kg NO_3–N ha^{-1}) (Figure 3) and Fourth planting (29.9 kg

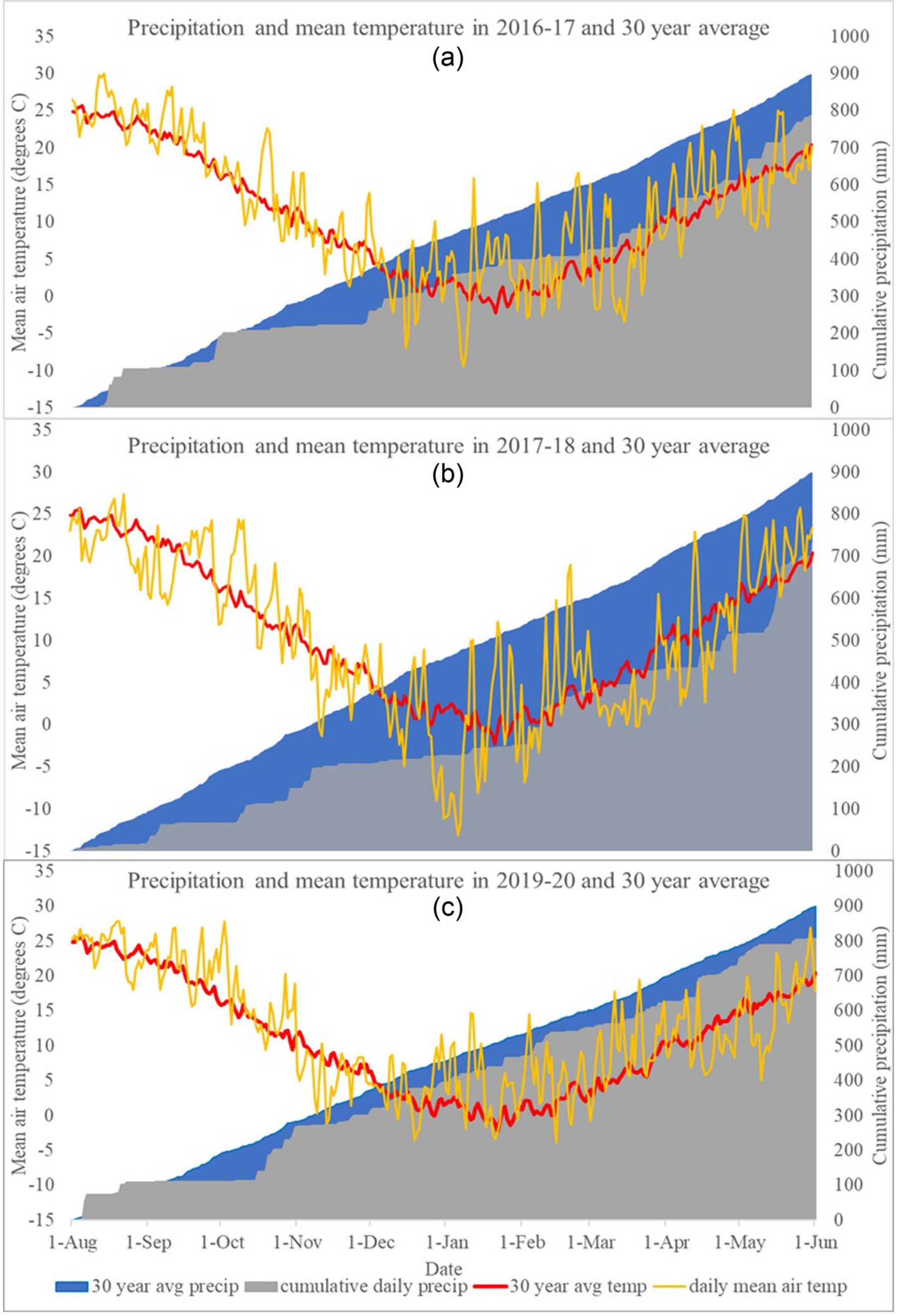

FIGURE 1 Daily mean air temperature and cumulative daily precipitation for (a) 2016–2017, (b) 2017–2018, and (c) 2019–2020. The 30-yr local averages are included for comparison

NO_3–N ha^{-1}), followed by Third planting (11.5 kg NO_3–N ha^{-1}) and then First and Second plantings (7.4–7.6 kg NO_3–N ha^{-1}). Cumulative leaching season N loss was closely predicted by late fall cover crop N accumulation (Figure 4). Higher N accumulation by earlier-planted cover crops correlated with decreased NO_3–N leached. Nitrate-N leached per kilogram of fall biomass N accumulation was greater for weeds in No Cover than for cover crops. Therefore, in each year, weeds did not fit the same regression as cover crops (Figure 4).

3.3.2 | Species experiment

Average porewater mineral (NO_3 + NH_4) N concentrations (mg N L^{-1}) were 24.2 for No Cover, which was

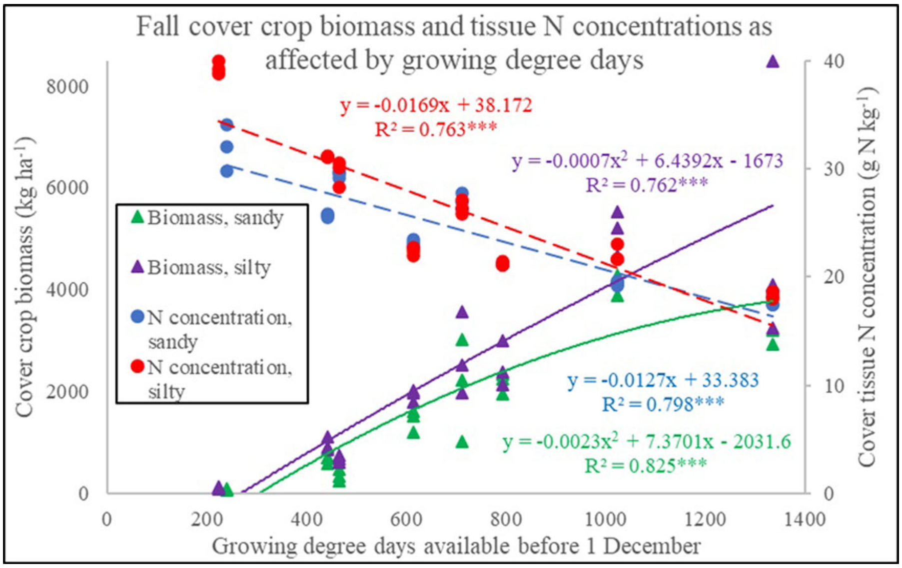

FIGURE 2 Relationships between cumulative growing degree days between planting and 1 December and the total accumulated fall cover crop biomass in 2016 and 2017 or the cover crop tissue N concentration. The two years were combined with the regressions separated by soil texture. Each data point represents the average of the subsamples within one plot. ***$p < .001$

TABLE 4 Effect of soil texture and cover crop treatment on total cover crop biomass, radish biomass, tissue N concentrations, and N content in the species experiment in fall 2019

Source of variability	Soil	Species	Radish biomass	Total biomass	Cover N content	Cover tissue N concentration
			kg ha^{-1}		kg N ha^{-1}	g N kg^{-1} tissue
Soil (S)	sandy		1,820	2,110	51.5	24.4a
	silty		1,930	2,270	45.9	20.2b
Treatment (T)		rye	–	997c	22.3c	22.4a
		radish	3,320a	3,350a	69.2a	20.7b
		mix	1,510b	2,170b	49.7b	22.9a
		no cover	–	188d	4.41d	23.5a
S × T	sandy	rye	–	831	16.6	20.0c
		radish	3,010b[a]	3,020	63.4	21.0bc
		mix	1,550c[a]	2,220	49.2	22.2b
		no cover	–	80.2	2.84	35.4a
	silty	rye	–	1,110	26.3	23.7b
		radish	3,640a[a]	3,680	74.7	20.3c
		mix	1,480c[a]	2,130	50.1	23.5b
		no cover	–	274	3.83	14.0d
Source of variation	**df**		*P > F*			
Rep (S)	1		.264	.229	.245	*<.001*[b]
Error (rep)	2		–	–	–	–
T	3		*<.001*	*<.001*	*<.001*	*<.001*
S × T	3		.080	.288	.435	*<.001*
Error	15					

Note. Means within an effect followed by the same letter do not differ significantly.

[a]Significant at p < .1; all other letter differences are significant at $p < .05$.

[b]Numbers in italics indicates F values in ANOVA table are significant at $p < .05$.

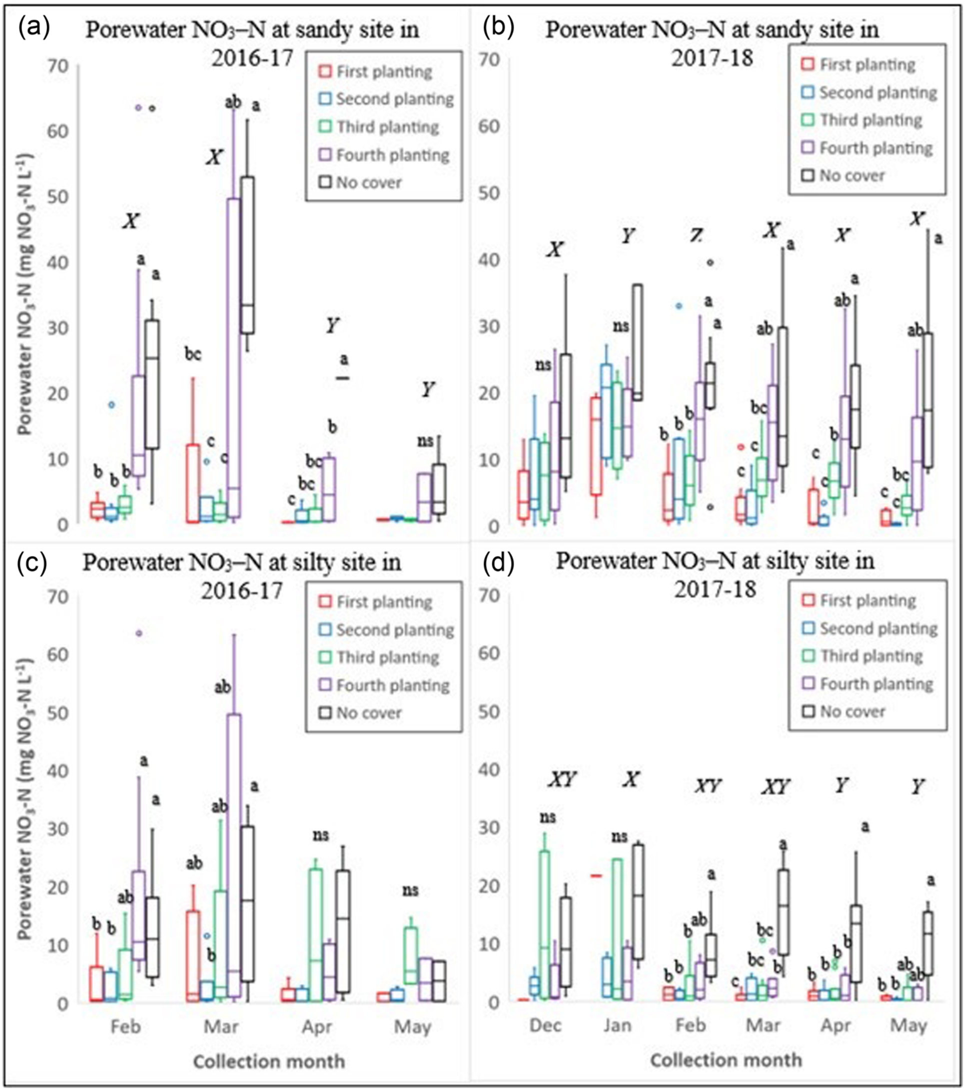

FIGURE 3 Boxplots of porewater NO_3–N concentrations of the Planting Date Experiment between fall and spring at four site-years: (a) sandy site in 2016–2017, (b) sandy site in 2017–2018, (c) silty site in 2016–2017, and (d) silty site in 2017–2018. Horizontal lines indicate monthly medians for each treatment. The NO_3–N concentrations for a treatment during each month followed by the same lowercase letter do not differ significantly at $p < .05$. Italicized uppercase letters indicate differences in NO_3–N concentrations among months of sample collection. ns, not significant at $p < .05$

significantly higher than 3.0 for Rye, 2.2 for Radish, and 1.2 for Mix (Figure 5). Porewater N concentrations were greatest in November and December and declined thereafter but were always higher under No Cover than under the cover crops. Porewater N concentrations (mg N L^{-1}) were greater for Rye than for Mix in November (10.4 vs. 1.6 mg N L^{-1}) and December (2.1 vs. 0.7 mg N L^{-1}).

4 | DISCUSSION

4.1 | Cover crop biomass

Available fall GDD in the Planting Date Experiment accounted for 76–82% of variation in cover crop biomass and N tissue concentration (Figure 2) for both soil textures. Every 2-wk planting delay in fall resulted in 160–300 fewer GDD available for growth. Cover crop biomass increased at rates of 5.4 and 6.5 kg biomass ha^{-1} GDD^{-1} at sandy and silty sites, respectively, but the additional GDD from planting before 30 August resulted in little additional biomass. Others also reported increased cover crop biomass with more GDD (Hirsh et al., 2021; Mirsky et al., 2011). Schroder et al. (1996) planted radish–grass–legume mixes between 18 August and 15 September on Pennsylvania and Maryland farms with different management practices. Those cover crops had an average of 1,412 GDD available, producing 2,651 kg ha^{-1} in fall, but the relationship between biomass and GDD was weak (R^2 = .15) due to soil N limitations and variability of management.

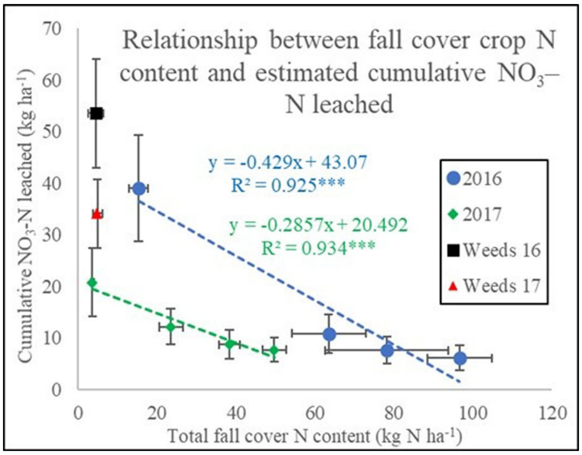

FIGURE 4 Relationship between fall cover crop N content and estimated cumulative NO_3–N leached during winter and spring of the Planting Date Experiment. Each dot represents averages from one treatment averaged between two soil textures. Weeds (no-cover treatments) were outliers from the general trend and were not included in the regressions. Error bars show 1 SE across six replications. ***$p < .001$

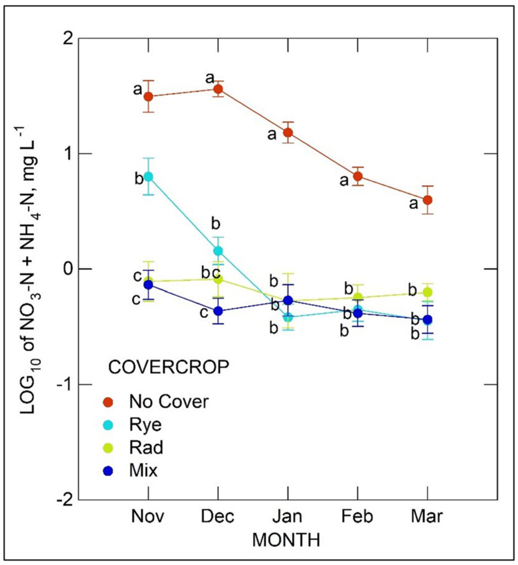

FIGURE 5 Effect of cover crop treatments on soil porewater mineral N concentrations over time in the Species Experiment. Cover crop treatments followed by the same letter do not significantly differ at $p < .05$

Because of its rapid growth in early fall and deep rooting (Kristensen & Thorup-Kristensen, 2004; Thorup-Kristensen, 2006), most of the additional biomass from planting early (Table 3) was due to greater radish growth. From early September onward, radish growth was sensitive to available GDD, and fall biomass decreased with every 2-wk delay in planting. Forage radish in the Species Experiment produced greater fall biomass and N content than Rye or Mix (Table 4). In Missouri, Sandler et al. (2015) broadcast-interseeded radish into soybeans and corn at different times in fall but measured consistently higher radish biomass with early planting in only 1 yr with sufficient rainfall. The close relationship between biomass and GDD in our study suggests we avoided growth limitations because we applied manure and because our no-till drilling is a more reliable seeding method than broadcasting (Fisher et al., 2011; Noland et al., 2018).

Earlier planting resulted in greater cover crop N content in fall despite lower N tissue concentrations in earlier-planted cover crops, which were more mature at the time of measurement (Table 3). Research in Northern Europe has documented a similar influence of available GDD on fall biomass N accumulation (e.g., Schroder et al.,1996) and N uptake (Komainda et al., 2016).

4.2 | Planting earlier reduced NO_3–N leached

Planting cover crops early reduced NO_3–N concentrations in soil porewater and N leached during winter and early spring (Figure 3) at all four site-years of the Planting Date Experiment. Compared with No Cover, NO_3–N leached was reduced by 45% in the Fourth planting but by 82–86% in First, Second, and Third plantings at sandy sites (Figure 3a,b). At silty sites, NO_3–N leaching was 46–54% lower under Third and Fourth plantings and 76–83% lower under First and Second plantings (Figure 3c,d). The data suggest that N capture effectiveness drops dramatically when fewer than 550 GGD remain before winter dormancy.

The aforementioned cover crop effects were consistent with two meta-analyses (Quemada et al., 2013; Thapa et al., 2018), which estimated that late-summer–planted cover crops reduce NO_3–N leached by 50 and 64%, respectively. Fall cover crop N content (excluding No Cover treatment) accounted for 92–93% of variability in cumulative NO_3–N leached (Figure 4). Our data, along with data in Hirsh et al. (2021) and Wang and Weil (2018), suggest that rye and radish capture N much more effectively than weeds, probably because of their deep and rapid rooting (Kristensen & Thorup-Kristensen, 2004; Thorup-Kristensen, 2001; Wahlstrom et al., 2015). As shown in Figure 4, NO_3–N leaching was much higher in both years under weeds than under cover crops, even when the aboveground biomass was similar.

The Planting Date Experiment supported the hypothesis that earlier cover crop planting reduces cumulative NO_3–N leached. However, for every kilogram of N accumulated in cover crop tissues, NO_3–N leached was reduced by only 0.29–0.43 kg NO_3–N (Figure 4). Two phenomena may account for this discrepancy. First, some of the cover crop tissue N may come from uptake of relatively immobile NH_4–N, which nearly equals NO_3–N in the soil profile after the summer crop growing season (Hirsh & Weil, 2019). Second, our data do not include NO_3–N leached during the time before our lysimeters were installed. Porewater NO_3–N concentrations tend to decline during the leaching season (Figures 3a,d and 5) (Ritter et al., 1991, 1993; Sedghi, 2019), so it is likely that they were higher in late fall before our first sampling. Therefore, we may have missed a significant portion of NO_3–N leached and therefore may have underestimated the cover crop planting date effect.

We also likely underestimated cover crop effects on NO_3–N leached due to the assumption that drainage was the same for all treatments. Growing cover crops are expected to increase ET and reduce drainage volume (McCracken et al., 1993; Meyer et al., 2018; Unger & Vigil, 1998). Groundwater recharge in the mid-Atlantic begins in mid-November and ends in late April (Meisinger & Delgado, 2002; Staver & Brinsfield, 1998), with most leaching occurring during December–April (Meisinger et al., 1990). During May–June, high ET lowers the water table and drainage is very limited (Meisinger & Delgado, 2002), barring unusual rainfall. During September–October when temperatures and ET are relatively high, cover crops may dry the soil, reducing drainage volume and in turn the amount of nitrate leached. Thus, our approach was conservative, and the true effect of early cover crop planting is likely greater than our estimates.

5 | CONCLUSIONS

Early-planted cover crops took up more N than later-planted cover crops and significantly reduced porewater NO_3–N concentrations for all site-years of this study. Planting cover crops before mid-September effectively reduced NO_3–N concentrations in deep soil porewater through spring cash crop planting time. Under the conditions of our study, a planting delay of 2 wk after mid-September substantially increased NO_3–N loss during the leaching season. We found no evidence that planting earlier than 30 August (~1,000 GDD) enhanced cover crop effect on NO_3–N leaching, but planting past late September (~600 GDD) dramatically reduced the cover crop effect. The multi-species cover crop used in the current study more effectively reduced N leaching than Rye alone and may avoid the springtime N immobilization problems that often occur with pure cereal cover crops (Hirsh et al., 2021).

Inclusion of summer-harvested small grains in the crop rotation (Mallory et al., 1998) could facilitate earlier planting of winter cover crops. This practice would be more attractive in regions north of Maryland where growing seasons do not allow a double-crop soybean after small grains. In Maryland and regions south, farmers would be unlikely to give up a soybean cash crop for a more effective cover crop. Although no-till drilling and seed costs for the mix used in the Planting Date Experiment would be approximately \$142 ha^{-1} (Dill, 2021), the Maryland cover crop program could provide more than this cost in incentives if the cover crop were planted early in fall and terminated after 1 May (MDA, 2020). Selecting earlier-maturing cash crop cultivars (Kandel et al., 2021) and interseeding cover crops into standing cash crops (Noland et al., 2018) could also facilitate earlier cover crop planting and therefore may reduce N leaching losses from agricultural fields. The importance of removing soluble N from the profile in fall makes it imperative that studies of cover crop effects on N leaching should report late fall biomass and N uptake.

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AUTHOR CONTRIBUTIONS

Nathan Sedghi: Data curation; Formal analysis; Investigation; Methodology; Supervision; Visualization; Writing – original draft; Writing – review & editing. Ray Weil: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Writing – review & editing.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

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