Research Reports

Winter-killed Cereal Rye Cover Crop Influence on Nitrate Leaching in Intensive Vegetable Production Systems

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Summary. High levels of residual soil nitrate are typically present in cool-season vegetable fields in coastal regions of California in the fall, after the production of multiple crops over the course of the growing season. This nitrate is subject to leaching with winter rains when fields are left fallow. Although the benefits of growing nitrate scavenging cover crops on soil and water quality are well documented, the portion of vegetable production fields planted to winter cover crops in this region is low. Most growers leave their fields unplanted in bare-fallow beds because the risk of having too much cover crop residue to incorporate may delay late winter and early spring planting schedules. A possible strategy to derive benefits of a cover crop yet minimize the amount of residue is to kill the cover crop with an herbicide when biomass of the cover crop is still relatively low. To evaluate whether this strategy would be effective at reducing nitrate leaching, we conducted field studies in Winter 2010–11 (Year 1) and Winter 2011–12 (Year 2) with cereal rye (*Secale cereale*). Each trial consisted of three treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide 8 to 9 weeks after emergence). In Year 1, which received 35% more rainfall than the historical average during the trial, the Full-season cover crop reduced nitrate leaching by 64% relative to Fallow, but the Partial-season had no effect relative to Fallow. In Year 2, which received 47% less rainfall than the historical average during the trial, the Full- and Partial-season cover crops reduced nitrate leaching by 75% and 52%, respectively, relative to Fallow. The Full-season cover crop was able to reduce nitrate leaching regardless of yearly variations in the timing and amount of precipitation. Although the Partial-season cover crop was able to reduce leaching in Year 2, the value of this winter-kill strategy to reduce nitrate leaching is limited by the need to kill the crop when relatively young, resulting in the release of nitrogen (N) from decaying residues back into the soil where it is subject to leaching.

Concern over nitrate contamination in drinking water has led to increased regulatory scrutiny of N fertilizer use by regional water quality agencies. A recent assessment of nitrate in groundwater for two of the most intensive agricultural production regions in California (the Salinas Valley and Tulare Basin) found that 51% of all N applied to cropland is leached to groundwater (Harter and Lund, 2012). As a result, many wells in these areas exceed the U.S. Environmental Protection Agency (EPA) drinking water standard for nitrate-N of 10 mg·L^{-1}.

The high N requirement of cool-season vegetables produced in the coastal valleys of California results in a high nitrate leaching hazard. The mild year-round climate allows for the cultivation of two to three cool-season vegetable crops per year, with lettuce (*Lactuca sativa*) being the dominant crop in both value and acreage (Monterey County Agricultural Commission, 2012). Vegetable production fields often receive N fertilizer applications in excess of crop uptake or the amount of N needed for maximum yield and product quality (Bottoms et al., 2012; Breschini and Hartz, 2002; Hartz et al., 2000; Heinrich et al., 2013). This tendency for overfertilization occurs because N fertilizer is a small part of the overall production budget for the high-value vegetable crops grown in the region (e.g., Tourte and Smith, 2010) and growers do not want to risk an economic loss for these crops that have exacting market standards for size, color, and quality. Another factor leading to high postharvest nitrate levels is the fact that less than 50% of the crop biomass may be removed during harvest for some crops (Bottoms et al., 2012; Heinrich et al., 2013). The remaining crop residues typically have a high N content and rapidly breakdown after incorporation into the soil and release nitrate. As a result of these factors, high concentrations of residual nitrate may be present in the soil at the end of the vegetable cropping cycle and before the onset of the winter rainy season. Unless a winter vegetable or cover crop is planted, much of this end of season nitrate can be leached by winter rains (Wyland et al., 1996).

In the vegetable producing regions on the central coast of California, farmers almost exclusively grow cereal rye as a winter cover crop because of the low seed cost and it does not set seed too early in the growth cycle, eliminating the potential for it to become a weed hazard. In this region, a full-season cereal rye cover crop has been shown to effectively reduce nitrate leaching during the winter by 65% to 70% relative to land left bare fallow (Jackson et al., 1993; Wyland et al., 1996). Nitrogen scavenging cover crops reduce nitrate leaching through increased evapotranspiration (i.e., reducing soil moisture thus increasing water storage between rain events) and nitrate scavenging (Brennan et al., 2013; Jackson et al., 1993; Wyland et al., 1996). After incorporation into soil, decomposing cover crop can increase soil N available for subsequent crops (Jackson, 2000; Lundquist et al., 1999; Wyland et al., 1996), and over time may increase soil organic matter (Kong et al., 2005), and improve long-term nutrient cycling as well as many soil chemical and physical properties. An additional benefit is that winter cover crops have been shown to increase infiltration (Joyce et al., 2002) thereby reducing runoff, nutrient, and sediment losses (Smuckler et al., 2012).

Despite the benefits of an N scavenging winter cover crop, the proportion of vegetable acreage in cover crops in the coastal valleys of California is low (we estimate between 5% and 7%). During the winter, most of the vegetable acreage is left in listed (peaked/unshaped), bare-fallow beds. This simplifies soil preparation operations and allows for timely access to fields to meet late winter and early spring planting schedules. A Full-season cover crop requires additional tractor operations (i.e., mowing, multiple disking passes, listing, and bed shaping), and there is the risk that rain will prevent access to fields and delay plantings. Furthermore, by allowing a cover crop to grow to full-season, this may reduce the number of cash crops that can be planted in a year, which is difficult to do in the region because of the high land value resulting in high rental costs. A Full-season cover crop is therefore not compatible with much of the vegetable producing acreage in this region.

One possible strategy to derive some of the benefits of a winter cover crop yet have minimal residue to impede ground preparation operations for subsequent vegetable crops is to kill the cover crop with a herbicide when it is young [i.e., low carbon (C) to N ratio and low lignin content] so that it rapidly decomposes. For this strategy to most effectively reduce nitrate leaching, the cover crop should grow long enough to reduce soil nitrate concentrations through crop uptake and also deplete soil moisture (i.e., reduce soil moisture between rain events) before it is killed. But, it should not be allowed to grow too long and produce too much residue that could impede early spring land preparation operations. By killing when young, the cover crop will have a low C:N and low lignin content, and break down rapidly after killing. The objective of this study was to evaluate if an early killed cover crop management strategy could reduce nitrate leaching relative to vegetable production fields left bare fallow during the winter.

Materials and methods

The 2010–11 trial (Year 1) was conducted at the Hartnell East Campus Research Facility in Salinas, CA. The soil is a Chualar loam (Typic Argixerolls) and had the following properties: 1.27% total C, 0.10% total N, 41 ppm Olsen phosphorus (P), and pH 7.6. Before the trial, two back-to-back lettuce crops were grown. The second lettuce crop was disked on 12 Nov. 2010. On 18 Nov., the field was chiseled, rototilled, and fertilized with granular urea at the rate of 117 lb/acre N. We fertilized the field to create a worst-case scenario: high nitrate at the beginning of winter. On 19 Nov., ‘AGS 104’ cereal rye was seeded with a grain drill at a rate of 225 lb/acre. Rainfall, which occurred the day after seeding, germinated the crop.

The 2011–12 trial (Year 2) was conducted on a commercial farm in the Salinas Valley. Although the soil is mapped as a Placentia sandy loam (Typic Natrixeralfs), the soil texture to a depth of 90 cm was measured as a clay loam using the hydrometer method (Bouyoucos, 1962). The soil had the following properties: 1.20% total C, 0.11% total N, 68 ppm Olsen P, 135 ppm potassium (K), and pH 7.5. The previous crop was lettuce. ‘Merced’ cereal rye was seeded by the grower with a grain drill at a rate of 90 lb/acre on 26 Oct. 2011. Because of no rain and low soil moisture, the cover crop was irrigated on 31 Oct. Because of working on a commercial farm, we did not have control over the cereal rye variety or seeding rate in Year 2.

Each trial consisted of three treatments planted on flat ground: 1) Fallow (winter fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season [cover crop killed with herbicide ≈62 d after emergence (DAE)]. In Year 1, each experimental plot was 25 × 80 ft, and 25 × 40 ft in Year 2. Each treatment was replicated four times in a randomized complete block design. Fallow plots were established by applying a 2% glyphosate and 1% oxyfluorfen spray mixture 16 DAE in both years. The Partial-season plots were established by applying the same

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
100	bar	kPa	0.01
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
0.0283	ft^3	m^3	35.3147
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1.1209	lb/acre	kg·ha^{-1}	0.8922
1	micron(s)	μm	1
1.7300	oz/inch^3	g·cm^{-3}	0.5780
1	ppm	mg·kg^{-1}	1
1	ppm	mg·L^{-1}	1
6.8948	psi	kPa	0.1450
2.2417	ton(s)/acre	Mg·ha^{-1}	0.4461
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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spray mix used to establish the Fallow plots 62 DAE (25 Jan. 2011) and 60 DAE (5 Jan. 2012) in Year 1 and 2, respectively. The trial was ended on 11 Mar. and 16 Feb. in Year 1 and 2, respectively. The Year 2 trial was ended earlier than anticipated so that the Full-season treatment would not interfere with the grower's spring soil tillage operations. In both years, the trial was ended shortly before the Full-season cover crop was mowed and incorporated.

Aboveground cover crop biomass was collected (five to six times) from a 1-m^2 area, dried at 60 °C, and ground to pass a 40 mesh screen (420 μm). The plant samples were sent to the University of California Davis Analytical Laboratory (UCDAL, Davis, CA) for total C and N analysis by combustion (AOAC International, 2006). Soil samples were collected every 2 weeks or less from the top 30 cm. Soil was also collected at 30-cm intervals to a depth of 90 cm at the beginning, middle, and end of each trial. The soil was extracted with a 2 M potassium chloride (KCl) solution and analyzed by the UCDAL for nitrate (Knepel, 2003) and ammonium (Hofer, 2003). Soil nitrate concentration (in milligrams per kilogram of soil) was converted to pounds per acre assuming a bulk density of 1.4 $g \cdot cm^{-3}$.

To monitor nitrate in the soil solution during leaching events, suction lysimeters with a 1-bar ceramic tip (Soil Solution Access Tubes; Irrometer Co., Riverside, CA) were installed vertically at a depth of 60 cm according to manufacturer specifications; two lysimeters per plot were installed in Year 1, and three per plot in Year 2. For fields left fallow in winter, nitrate moved beyond this depth is considered leached and unusable by most subsequent cool season vegetable crops, which tend to have shallow root systems and receive large preemergent irrigations (Heinrich et al., 2013). In Year 1, a constant vacuum was maintained at ≈–20 kPa using diaphragm pumps (model SP-8000; Smart Products, Morgan Hill, CA). In Year 2, peristaltic pumps (FPU122; Omega Engineering, Stamford, CT) were used to maintain a constant suction of –20 kPa using a data logger (model CR1000; Campbell Scientific, Logan, UT) as a controller, electronic vacuum gauges (1008-E, Irrometer Co.) to monitor vacuum pressure, and solid-state relay switches (CMX60D10; Crydom, San Diego, CA) to actuate the pumps. Each lysimeter was connected to its own 250-mL collection vessel. The pumps were turned on before or during a rain event and typically ran for ≥24 h before we collected the extract. Nitrate in lysimeter extracts was analyzed by UCDAL as previously described.

Precipitation and soil moisture were measured onsite using a high-resolution (0.25 mm) tipping bucket rain gauge (ECRN 100; Decagon Devices, Pullman, WA) and soil moisture probes (Echo 10HS, Decagon Devices), respectively, both of which were connected to data logger (Em50, Decagon Devices). In each plot, moisture probes were placed horizontally at 30 and 60 cm, and vertically 3 cm below the soil surface, which measured soil moisture from 3 to 15 cm. This was done because fluctuations in moisture in the surface layer (3 to 15 cm) were much greater than at 30 and 60 cm.

Because of the low rainfall in Year 2, 25 mm of well water was applied to simulate rainfall using overhead sprinklers (model 20JH; Rainbird Corp., Azusa, CA) on 9 Feb. To account for nonuniform distribution by the sprinklers, buckets were placed in each plot adjacent to the lysimeters. The volume collected in each bucket was used to estimate irrigation volumes for each plot. Based on the nitrate-N concentration in the well water of 11 $mg \cdot kg^{-1}$, ≈2.4 lb/acre N was applied.

For most lysimeter collection intervals (when the lysimeter tubes were under vacuum), crop evapotranspiration (ETc) was assumed to be zero because reference evapotranspiration (ETo) was very low (<1 mm) during rain events. For lysimeter collection intervals >24 h and when the cover crop had full canopy cover, we assumed that ETc = ETo. ETo was obtained from the nearest California Irrigation Management Information System weather station. Water drainage below 60 cm was calculated by the following one-dimensional water balance equation:

$$D = P - \Delta SM - ETc \qquad [1]$$

where D is drainage (inches), P is precipitation or irrigation water applied (inches), ΔSM (inches) is the change in soil moisture in the 0 to 60 cm soil layer calculated by subtracting the water content before the storm event from the water content 24 h after the storm event (as measured by the soil moisture probes), and ETc (inches) is crop evapotranspiration over the collection interval. Both fields were flat and no surface flow was observed to move beyond plot boundaries. For each storm event, the load of N leached below 60 cm (in pounds per acre) was then calculated with the following equation:

$$N_{leached} = 0.23 \times D \times L \qquad [2]$$

where D is drainage (inches) as calculated by Eq. [1], and L (milligrams per liter) is the nitrate-N concentration in the lysimeter extract (i.e., soil pore water), and $N_{leached}$ (pounds per acre) is the amount of N leached below 60 cm.

For each year, soil and lysimeter nitrate concentrations, drainage, and N leaching were subjected to analysis of variance in SAS (version 9.2; SAS Institute, Cary, NC) using the general linear model procedure. Mean separation was determined using Fisher's least significant difference test ($P < 0.05$).

Results

RAINFALL. Rainfall amounts and patterns differed greatly over the study period, with Year 1 being wetter and Year 2 drier than normal. Historically, the city of Salinas, CA, receives 83% of its yearly precipitation between November and March, with the rainiest months being January through March (Table 1). In Year 1, the experimental site located in the city of Salinas received 35% more precipitation than the historical mean, with more rainfall in all months except January. In Year 2, the experimental site located 6 miles southwest of Salinas received 47% less precipitation than the historical mean with only trace amounts of rainfall recorded in December and most of January (Fig. 1E).

In Year 1, 9.6 inches of precipitation was recorded during the study period compared with 2.9 inches in Year 2, a 70% reduction. In Year 2, because of an 8-week period of negligible precipitation, 1 inch of water was applied by sprinkler irrigation on 9 Feb. 2012 to simulate a rainfall event (Fig. 1E).

Table 1. Monthly historical precipitation for the city of Salinas, CA, and precipitation at experimental field sites. In Year 1, the experiment field site was in the city of Salinas. In Year 2, the site was $\approx$6 miles (9.7 km) southeast of Salinas.

Month	Historical (1981–2010)^z	Yr 1 (2010–11)	Yr 2 (2011–12)
	Monthly precipitation (inches)^y		
November	1.4	2.3	1.3
December	1.9	3.4	0.1
January	2.5	1.9	0.0
February	2.5	3.7	0.8
March	2.3	3.0	3.3
Total	10.5	14.3	5.6

^{z}National Oceanic and Atmospheric Administration (2013).

^{y}1 inch = 2.54 cm.

Cover crop biomass. Aboveground dry biomass and biomass nitrogen are given in Fig. 2. In Year 1, 3 d after the Partial-season cover crop was sprayed with an herbicide, the cover crops had accumulated 0.76 ton/acre dry matter (DM) and 71 lb/acre N (Fig. 2A and B). When the cover crop was sprayed in the Partial-season treatment, it had an N content of 5.0%. At the end of the trial (44 d after spraying), there was only 0.55 ton/acre DM and 31 lb/acre N remaining in the dead cover crop residue of the Partial-season treatment. This change is equal to a 54% decrease in biomass N that was released back to the environment after killing the cover crop. The Full-season cover crop continued to grow until the end of the trial and accumulated 3.54 tons/acre DM and 142 lb/acre N.

In Year 2, 1 d before the Partial-season cover crop was sprayed with an herbicide, the cover crops had accumulated 0.66 ton/acre DM and 73 lb/acre N (Fig. 2C and D). Despite different planting dates, varieties, rainfall, and seeding densities, early season growth was very similar in both years. But, because of a severe rust (*Puccinia graminis* f. sp. *secalis*) infestation as well as moisture stress, later season biomass accumulation for the Full-season cover crop was reduced in Year 2 (Fig. 2C). Although the Full-season had a lower DM accumulation in Year 2, N uptake was similar for both years (Fig. 2B and D), the result of higher tissue N concentrations in Year 2 (data not shown). For example, at harvest in Year 2, the Full-season had half the DM accumulation as in Year 1, but had twice the N concentration in the tissue, resulting in almost the same N uptake in both years. Due to soil nitrate levels remaining high in Year 2—the result of less rainfall and leaching—the plants may have luxury consumed nitrate, resulting in a higher N concentration in the plant tissue (Fig. 3).

At the end of the trial in Year 2 (42 d after spraying), only 0.21 ton/acre DM and 14 lb/acre N was remaining in the dead cover crop residue of the Partial-season biomass. This change is equal to an 81% decrease in biomass N that was released back to the environment. The high tissue N content (5.5%) when the Partial-season cover crop was sprayed likely contributed in the rapid decomposition of the residue. The Full-season cover crop continued to grow until the end of the trial and accumulated 1.79 ton/acre DM and 142 lb/acre N.

Soil nitrate. In Year 1, nitrate concentrations 3 weeks after planting were high [>39 $mg\cdot kg^{-1}$ (equivalent to >150 lb/acre)] in the top 30 cm (Fig. 3A), but low [<6 $mg\cdot kg^{-1}$ (equivalent to >23 lb/acre)] from 30 to 90 cm (Fig. 4A). Following 5.1 inches of precipitation that fell between mid-December and early January (Fig. 1A), nitrate in the top 30 cm decreased by an average of 133 lb/acre in the top 30 cm. Nitrogen in the aboveground cover crop biomass on 5 Jan. (42 DAE) was $\approx$25 lb/acre (Fig. 2B), which does not account for the large decrease in soil nitrate concentrations observed. Therefore, much of the decrease in soil nitrate concentrations between these sampling dates was primarily the result of nitrate being transported below 30 cm.

All treatments in Year 1 initially had similar nitrate-N concentrations to a depth of 90 cm (Fig. 4A), but 2 months later (Fig. 4B), both the Partial- and Full-season treatments had lower nitrate concentrations relative to the Fallow, presumably because of crop nitrate uptake. Although deep sampling in February showed that the Partial-season cover crop had reduced nitrate levels to 90 cm relative to the Fallow (Fig. 4B), following the herbicide application, soil nitrate concentration increased at all depths presumably because of transport of nitrate that was released by decaying residues (roots and aboveground biomass) into the profile (Fig. 4C). By the time the trial was ended, soil nitrate concentrations for the Partial-season were no different from the Fallow at all depths sampled (Fig. 4C). In contrast, the Full-season treatment continued to remove nitrate from the soil until the end of the trial resulting in statistically significant lower nitrate concentrations at all depths sampled (Fig. 4C).

At the initiation of the trial in Year 2, the average soil nitrate-N concentration was 27 $mg\cdot kg^{-1}$, which is equivalent to 105 lb/acre (Fig. 3B). Because of the low rainfall in December and early January in Year 2, residual soil nitrate in the top 30 cm was not leached deeper into the profile early in the season as occurred in Year 1 and nitrate levels remained high in the surface 30 cm. With minimal leaching occurring, the decrease in soil nitrate observed for Partial- and Full-season treatments relative to Fallow is attributed to crop N uptake and not nitrate transported below 30 cm with rain (Fig. 3B). Even 1 month after the cover crop was killed, the Partial-season treatment had less nitrate-N from 0 to 60 cm (Fig. 4E). But, as in Year 1, decaying residues released N into the soil, which was transported deeper into the soil with rainfall (Fig. 4F). By the end of the trial, there was less soil nitrate below 30 cm for the Partial-season treatment relative to the Fallow, but there was no difference 0 to 30 cm because of decaying crop residues releasing N back to soil (Fig. 4F).

Nitrate leaching. In Year 1, when the cover crops were young and nitrate uptake was minimal, storm events between 12 Dec. 2010 and 3 Jan. 2011 (Fig. 1A) transported nitrate deeper into the soil profile, which was detected in lysimeter extracts (Fig. 1C). The average initial nitrate-N concentration in the

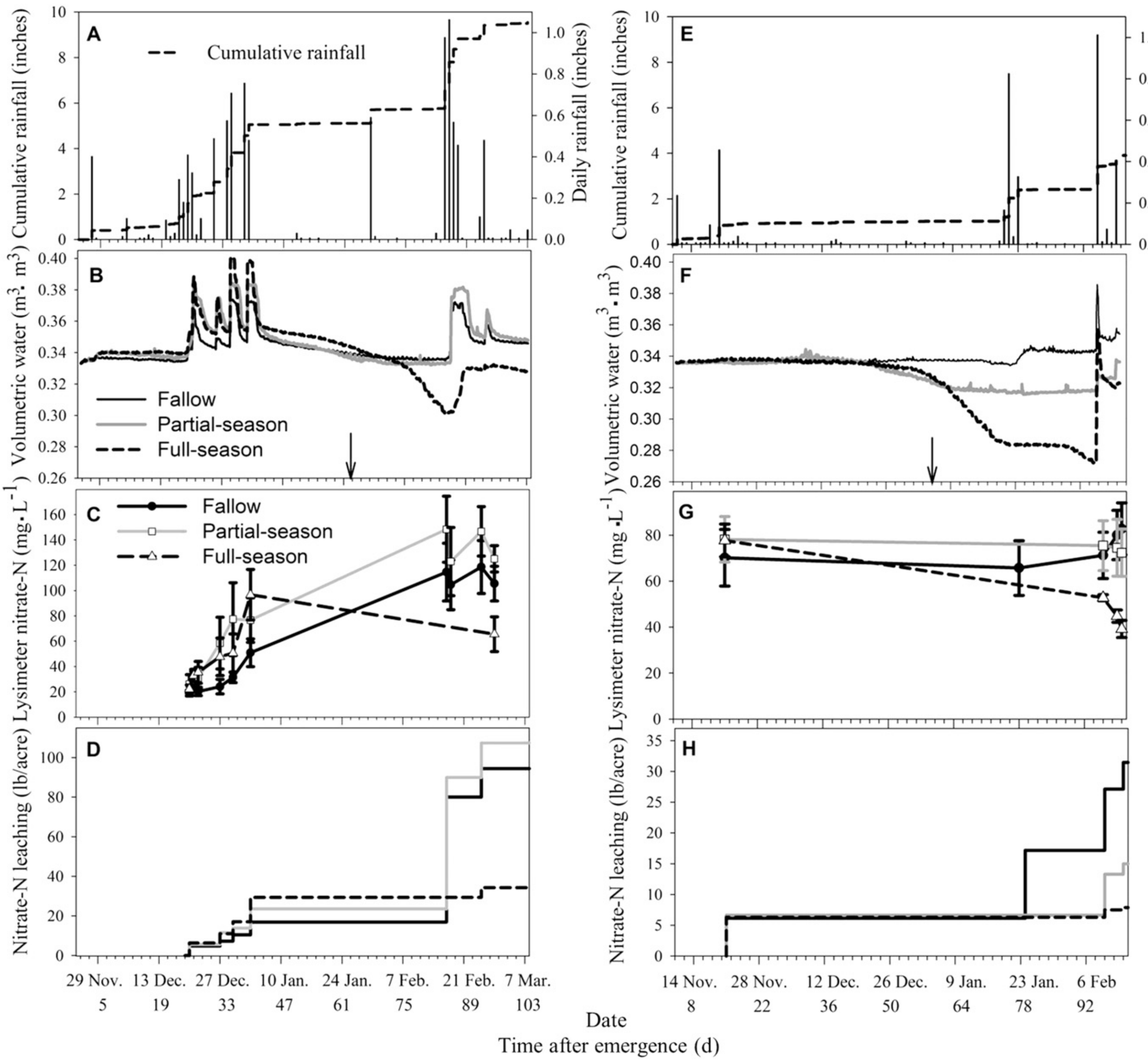

Fig. 1. Daily and cumulative rainfall (A and E), volumetric soil moisture at 60 cm [23.6 inches (B and F)], nitrate-nitrogen (N) in gravitational soil pore water extracts (from suction lysimeters placed at 60 cm) with error bars representing the SE of the mean [n = 4 (C and G)], and cumulative nitrate-N leached below 60 cm (D and H) from field trials conducted in Winter 2010–11 [Year 1 (A–D)] and Winter 2011–12 [Year 2 (E–H)] for three cover crop treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide 8 to 9 weeks after germination). The arrows indicate the date the Partial-season cover crop was sprayed with an herbicide. In Year 2, 1 inch of irrigation water was applied on 9 Feb. 2012 to simulate a rainfall event. Please note that different scales are used on some graphs; 1 inch = 2.54 cm, 1 m^3 = 35.3147 ft^3, 1 mg·L^{-1} = 1 ppm, 1 lb/acre = 1.1209 kg·ha^{-1}.

lysimeter extracts across treatments was 22 mg·L^{-1} on 20 Dec., but increased to 75 mg·L^{-1} by 3 Jan. In these early storm events, nitrate-N leaching below 60 cm was between 17 and 30 lb/acre (Fig. 1D). After the initial storm events, only 0.6 inches of precipitation fell during a 6-week dry period from early January to mid-February (Fig. 1A), which was not sufficient to cause leaching (Fig. 1D).

Over a four-day period beginning on 16 Feb. 2011 (Fig. 1A), 3.1 inches of precipitation was recorded. This resulted in the largest single leaching event of the trial in the Fallow and Partial-season treatments, but no leaching was measured for Full-season (Fig. 1D). Crop transpiration during the dry period for the Full-season had depleted the soil moisture (Fig. 1B), thus increasing the volume of water that the soil profile could store before drainage below 60 cm would occur. Only on the last lysimeter collection date was the Full-season cover crop nitrate-N concentration in the lysimeter extract statistically different from the other treatments (Fig. 1C), the result of nitrate uptake reducing soil nitrate concentrations (Fig. 4C). For the Partial-season treatment, once the crop was sprayed, transpiration had ceased. As a result, soil moisture in the profile

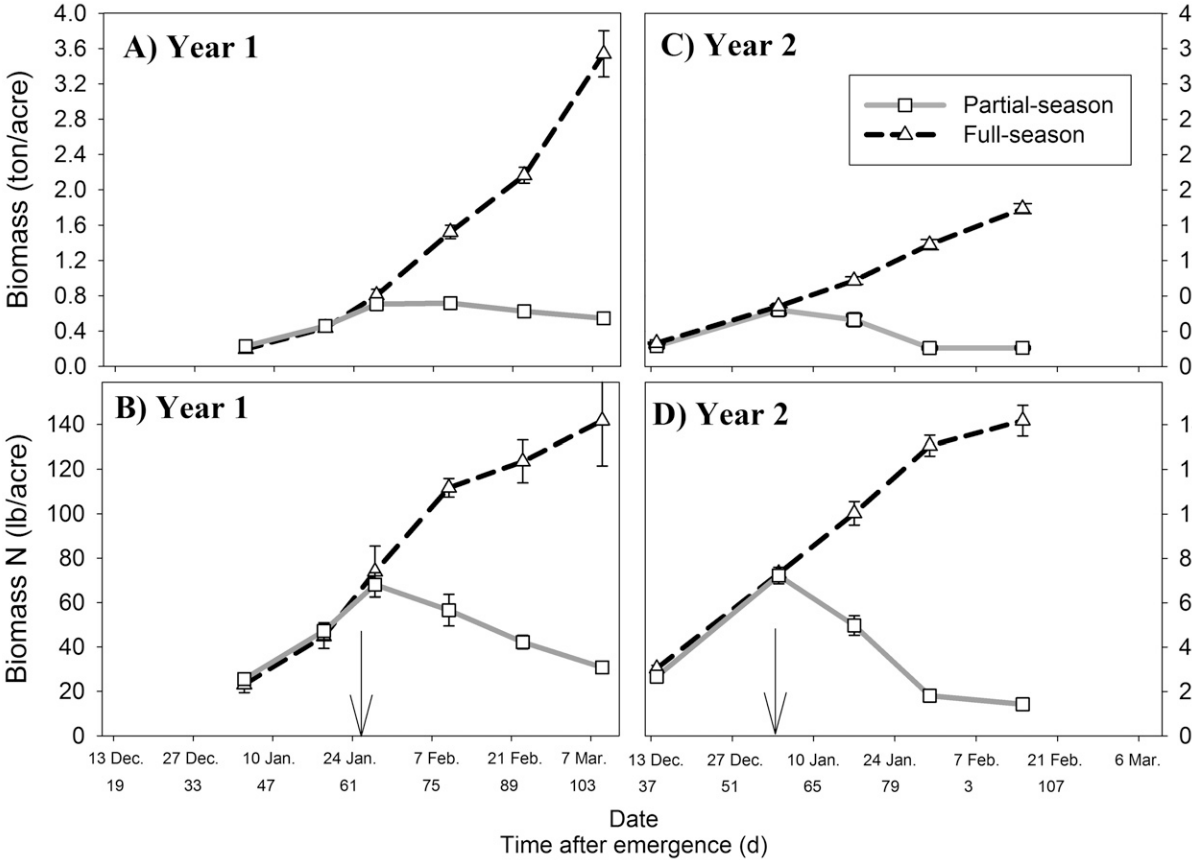

Fig. 2. Aboveground cover crop dry biomass (A and C) and biomass nitrogen [N (B and D)] for field trials conducted in Winter 2010–11 (Year 1) and Winter 2011–12 (Year 2) for three cover crop treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide ≈61 d after emergence). The arrows indicate the date the Partial-season cover crop was sprayed with an herbicide. Error bars indicate SE (n = 4); 1 ton/acre = 2.2417 Mg·ha^{-1}, 1 lb/acre = 1.1209 1 kg·ha^{-1}.

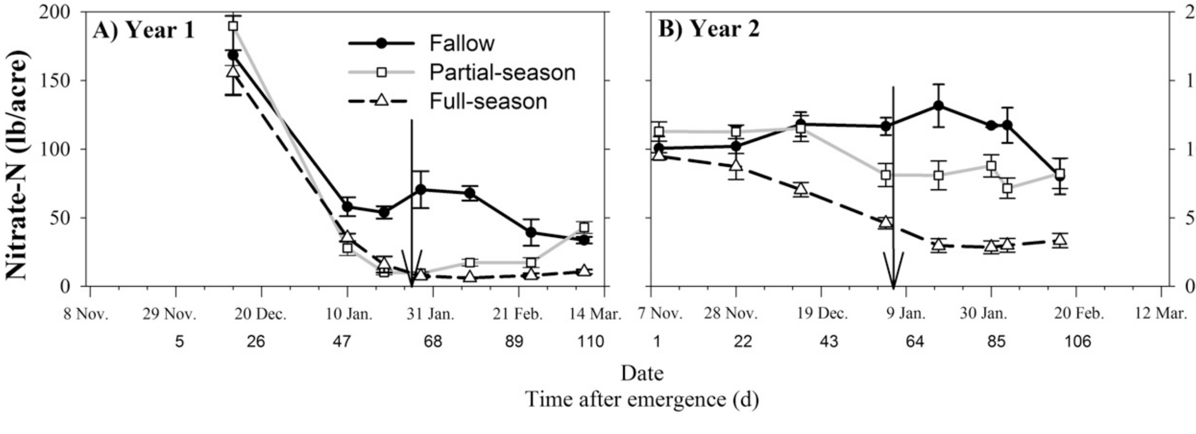

Fig. 3. Nitrate-nitrogen (N) in the top 30 cm (11.8 inches) of soil for field trials conducted in Winter 2010–11 [Year 1 (A)] and Winter 2011–12 [Year 2 (B)] for three cover crop treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide 8 to 9 weeks after germination). The arrows indicate the date the Partial-season cover crop was sprayed with an herbicide. The cover crop in Year 1 and 2 was seeded on 19 Nov. and 26 Oct., respectively. Error bars indicate SE (n = 4); 1 lb/acre = 1.1209 1 kg·ha^{-1}.

remained constant over the dry period (Fig. 1B), and the soil was not able to store additional rainfall, resulting in increased drainage.

At the end of the trial in Year 1, cumulative drainage below 60 cm for the Fallow, Partial-season, and Full-season treatments was 5.5, 4.7, and 3.0 inches, respectively (Table 2). Because of transpiration, only 45% of total rainfall drained past 60 cm for Full-season compared with 83% in the Fallow. Cumulative nitrate-N leached below 60 cm was 94, 107, and 34 lb/acre for the Fallow, Partial-season, and Full-season treatments, respectively (Table 2). Nitrate transported below 60 cm for the Full-

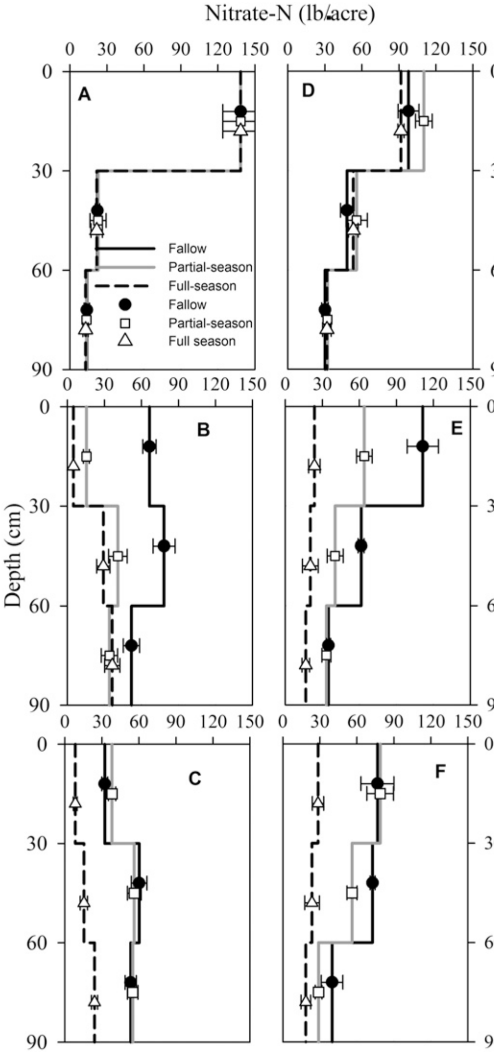

Fig. 4. Soil nitrate-nitrogen (N) concentrations at 30-cm intervals to a depth of 90 cm for field trials conducted in Winter 2010–11 [Year 1 (A–C)] and Winter 2011–12 [Year 2 (D–F)] for three cover crop treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide on 25 Jan. 2011 and 5 Jan. 2012 in Year 1 and 2, respectively). Sampling dates are (A) 2 Dec. 2010, (B) 9 Feb. 2011, (C) 9 Mar. 2011, (D) 9 Nov. 2011, (E) 3 Feb. 2012, and (F) 16 Feb. 2012. Sampling dates A and D, and C and F were taken at the beginning and termination of the trial, respectively. Symbols for each 30-cm sampling depth are offset to better be able to see treatment differences. Error bars indicate SE (n = 4); 1 lb/acre = 1.1209 1 kg·ha^{-1}, 1 cm = 0.3937 inch.

season cover crop may be an overestimation of leaching for this treatment because cover crop roots may have extended below 60 cm and may have removed nitrate that was measured to have passed 60 cm. But, there was little change in soil nitrate levels from 60 to 90 cm between 9 Feb. and 9 Mar. (Fig. 4B and C), indicating that N uptake from roots below 60 cm was likely insignificant. Because it was unlikely that significant roots of the Partial-season cover crop treatment extended below 60 cm before the crop was killed, nitrate transported below 60 cm for the Fallow and Partial-season treatments represents actually leaching.

Although the Partial-season cover crop had removed 68 lb/acre N when sprayed, this was not sufficient to reduce nitrate leaching because once the crop was killed, transpiration stopped and residues began to release N into the soil, which were then transported into the soil profile with rain later in the season (Fig. 4C). In contrast, the Full-season cover crop continued to grow, reducing both drainage below 60 cm and soil nitrate concentrations relative to the Fallow and Partial-season (Fig. 4C). This resulted in a 64% reduction in nitrate-N transported below 60 cm relative to Fallow in Year 1.

The rainfall patterns and amount in Year 2 were much different from in Year 1 (Fig. 1A and E). Rainfall on 20 Nov. (9 DAE) only resulted in nitrate leaching of ≈6 lb/acre N (Fig. 1E). Initial lysimeter extracts were higher than in Year 1 (Fig. 1G), likely due to higher soil nitrate concentrations from 30 to 60 cm early in the season (Fig. 4D). From December until mid-January, only trace amounts of precipitation were recorded. Unlike in Year 1, which was considerably wetter in December, the Partial-season cover crop reduced the soil moisture content through transpiration before it was killed (Fig. 4F). As a result, the soil moisture content remained low enough that precipitation between 20 and 21 Jan. did not cause measurable leaching (Fig. 1H). At the end of the trial in Year 2, cumulative drainage below 60 cm for the Fallow, Partial-season, and Full-season treatments was 2.0, 0.9, and 0.5 inches, respectively (Table 2). Increased soil moisture storage as the result of transpiration reduced drainage by 56% and 76% for Partial-season, and Full-season, respectively, compared with Fallow.

At the end of the trial in Year 2, cumulative nitrate-N transported below 60 cm was 31, 15, and 8 lb/acre for Fallow, Partial-season, and Full-season, respectively (Table 2). Although Partial-season was able to reduce soil nitrate concentrations in the 30 to 60 cm depth relative to Fallow (Fig. 4E), the nitrate concentration in the lysimeter extracts for Partial-season were not different from that in the Fallow treatment (Fig. 1C). As a result, the reduction in leaching observed for the Partial-season treatment can only be attributed to crop transpiration that depleted soil moisture and reduced drainage, not N uptake. But, in a normal or wetter rainfall year (as in Year 1), rainfall may have leached N released from decaying residues below 60 cm, likely resulting in no reduction in nitrate leaching. As in Year 1, the Full-season cover crop in Year 2 reduced nitrate levels through crop uptake to a depth of 90 cm (Fig. 4F) and reduced drainage through transpiration, both of which contributed to a 75% reduction in nitrate-N transported below 60 cm relative to Fallow.

Table 2. Cumulative drainage and nitrate-nitrogen (N) leaching below 60 cm (23.6 inches) for field trials conducted in Winter 2010–11 (Year 1) and Winter 2011–12 (Year 2) for three cover crop treatments: 1) Fallow (bare fallow), 2) Full-season (cover crop allowed to grow to full term), and 3) Partial-season (cover crop killed with herbicide 8 to 9 weeks after germination). Columns with different letters are statistically significant using Fisher's least significant difference (LSD) test ($P < 0.05$).

	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
	Drainage (inches)[z]		Drainage (% of total rainfall)		Nitrate-N leached (lb/acre)[y]	
Fallow	5.5 a	2.0 a	83	62	94 a	31 a
Partial-season	4.7 b	0.9 b	71	27	107 a	15 b
Full-season	3.0 c	0.5 b	45	14	34 b	8 b
LSD ($P < 0.05$)	0.6	0.6	NA	NA	59	13

[z] Water drainage below 60 cm was calculated by the following one-dimensional water balance equation: $D = P - \Delta SM - ETc$ [1], where D is drainage (inches), P is precipitation or irrigation water applied (inches), ΔSM (inches) is the change in soil moisture in the 0–60 cm soil layer calculated by subtracting the water content before the storm event from the water content 24 h after the storm event (as measured by the soil moisture probes), and ETc (inches) is crop evapotranspiration over the collection interval; 1 inch = 2.54 cm.

[y] The load of N leached below 60 cm (in pounds per acre) was calculated with the following equation: $N_{leached} = 0.23 \times D \times L$ [2], where D is drainage (inches) as calculated by the equation above, L (milligrams per liter) is the nitrate-N concentration in the lysimeter extract (i.e., soil pore water), and $N_{leached}$ (pounds per acre) is the amount of N leached below 60 cm; 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$, 1 $mg \cdot L^{-1}$ = 1 ppm.

IMPLICATIONS FOR REDUCING NITRATE LEACHING. It is not uncommon for residual postharvest residual soil nitrate-N concentrations in vegetable production fields on the central coast valleys of California to exceed 30 $mg \cdot kg^{-1}$, which is equivalent to ≈117 lb/acre nitrate-N (Bottoms et al., 2012; Heinrich et al., 2013; Wyland et al., 1996). In our study, average soil nitrate-N concentrations close to planting were 42 and 27 $mg \cdot kg^{-1}$ in Year 1 and 2, respectively, which is consistent with other studies. Unless a winter cash crop or cover crop is planted, much of this nitrate can be lost through leaching. In this region, growers almost exclusively plant cereal rye as a cover crop because of the low cost of the seed, good growth through the winter, and late seed set, eliminating the potential for it to become a weed hazard.

Under a Mediterranean climate, a full-season cereal rye cover crop has been shown to effectively reduce nitrate leaching during the winter by 65% to 70% relative to land left bare fallow (Jackson et al., 1993; Wyland et al., 1996). This is similar to the meta-analysis results of Tonitto et al. (2006) that found that nonleguminous cover crops reduced nitrate leaching by 70% compared with bare-fallow systems in 14 studies. Although our study may overestimate nitrate leaching for the full-term cover crop treatment because of some nitrate transported below 60 cm being uptaken by the crop, our results are consistent with these studies with the Full-season cereal rye cover crop reducing nitrate leaching by 64 and 75% in Year 1 and 2, respectively, relative to Fallow.

On the central coast of California, a full-season winter cereal rye cover crop can routinely uptake 100 lb/acre N or more, though there can be significant year to year variability depending on planting date, rainfall, and temperature (Brennan and Boyd, 2012; Brennan et al., 2011; Jackson et al., 1993; Wyland et al., 1996). In both years, N uptake for the Full-season treatment at the termination of the trials was 142 lb/acre N. Through a combination of N uptake and transpiration, the Full-season treatment was able to significantly reduce nitrate leaching relative to ground left in bare fallow regardless of yearly variations in the timing and amount of precipitation. However, despite the reduction in leaching, lysimeter extract nitrate concentrations were never below the EPA drinking water standard of 10 $mg \cdot L^{-1}$ nitrate-N.

A consequence of high residual postharvest nitrate levels going into winter is that the quantity of nitrate in the profile exceeds the ability of the cover crop to remove, especially when the crop is young. There was more nitrate in the top 60 cm of soil at the beginning of the winter (≈165 and 156 lb/acre of nitrate-N in Year 1 and Year 2, respectively, assuming a bulk density of 1.4 $g \cdot cm^{-3}$) than the Full-season cover crop could remove over the entire crop cycle. Because cover crop N uptake is low in the first month of the crop cycle, the cereal rye may be unable to significantly reduce soil nitrate levels before large winter rain events leach it below the cover crop's root zone. Furthermore, mild winter temperatures result in further mineralization of incorporated crop residues and soil organic matter that continues to supply the soil with nitrate, increasing the nitrate pool even in winter (Jackson et al., 1994). If the soil nitrate pool is greater than the uptake capacity of the cover crop, soil nitrate will still be at risk of leaching. This is a problem where soils tend to have high residual nitrate concentrations at the beginning of the winter.

Because of tight production schedules, most growers only will only grow cover crops on a small portion of their ground. Most cover crops in the region are seeded in November so that fall rains can germinate the crop and are incorporated in March to prepare for spring planting. By winter-killing the cover crop in early January with an herbicide, growers may be able to experience the benefits of a cover crop, including a reduction in nitrate leaching, without the residue impeding late winter and early spring planting schedules. In contrast to the Full-season cover crop treatment, the ability of the Partial-season cover crop to minimize nitrate leaching through N uptake was limited by the need to kill the crop when it was "young" (61 DAE). Early in the growth cycle (≈2 months after emergence), the Partial-season cover crop reduced soil nitrate levels compared with Fallow to a depth of 60 cm in both years. Although the Partial-season cover crop was able to uptake significant residual soil nitrate early in the growth cycle, it lost the capacity to remove further soil nitrate after the crop was killed with an herbicide. When the crop was sprayed, it had a high N content (5.0% to 5.5%), and as a result, decomposing tissues rapidly released the N stored in plant tissues back into the soil. This was equivalent to a release of 54% and 81% of aboveground biomass N when the cover crop was sprayed in Year 1 and Year 2, respectively. Because 37% (4.8 inches) of precipitation in the Salinas area historically falls in February and March (National Oceanic and Atmospheric Administration, 2013), this mineralized N is at risk of leaching once the cover crop is killed. Despite this release of N back to the soil, the Partial-season treatment reduced nitrate leaching by 52% relative to the Fallow because of the low rainfall in Year 2.

In this study, transpiration, not N uptake, was the most important factor involved in the ability of the Partial-season treatment strategy to reduce nitrate leaching. Nitrogen uptake by the Partial-season treatment was never great enough to reduced lysimeter nitrate concentrations relative to the Fallow treatment. Therefore, the main factors controlling Partial-season treatment's ability to minimize nitrate leaching were transpiration, and amount and timing of precipitation. In Year 1, because of large storm events early in the crop cycle, the soil water content was at field capacity when the Partial-season cover crop was treatment was sprayed. Being unable to further transpire water, the soil remained wet and was unable to store additional water when it rained later in the season, resulting in leaching. In Year 2, due to minimal early season precipitation, the soil water content in the profile had been depleted before when the Partial-season cover crop was sprayed. Therefore, the profile could store a large amount of rainfall before any leaching occurred.

Because of the need to kill the cover crop in early January, the Partial-season cover crop strategy likely has minimal benefit at reducing nitrate leaching in a normal to wet rainfall year. If the crop were planted earlier (such as October), it would be able remove more residual nitrate from the soil before the onset of winter rains. But an earlier planting may necessitate irrigation to germinate the crop and the increases in residue may impede spring bed shaping operations. Although the Partial-season cover crop strategy cannot consistently or even significantly reduce nitrate leaching from year to year, the residues may be beneficial. In Year 1 and 2, there was 31 and 14 lb/acre N, and 0.55 and 0.21 ton/acre of aboveground biomass DM, respectively, remaining in the field at the termination of the study. These residues can contribute to N needs of the subsequent crop, reduce soil crusting, increase infiltration, and decrease nutrient and sediment losses (Jackson, 2000; Joyce et al., 2002; Lundquist et al., 1999; Smuckler et al., 2012). In a concurrent study in the Salinas Valley conducted by the authors, a winter-killed cover crop (similar to the Partial-season treatment) on listed (peaked, unshaped) beds dramatically reduced runoff, and nutrient and sediment loss (unpublished data).

Although this winter-kill strategy to control biomass accumulation of cover crops may not consistently reduce nitrate leaching, it fits the constraints of the production system in the coastal valleys of California and may encourage more widespread use of cover crops in intensively cropped vegetable systems. Further research is needed to determine the additional benefits of this strategy (i.e., runoff reduction, soil tilth, increased nutrient cycling, etc), and if the remaining residue will impede bed shaping equipment for early spring vegetable production.

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