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ORIGINAL RESEARCH ARTICLE

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Short-term impacts of cover crops in maritime potato (*Solanum tuberosum*) systems

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Abstract

Cover cropping is a soil conservation practice widely investigated in agronomic crops, but less is known about cover crop implications in specialty cropping systems, particularly in a high disturbance system like potato (*Solanum tuberosum* L.). Brassica cover crops are popular in eastern Washington potato production, but brassica seed crop production in western Washington presents issues with use of brassica cover crops in the region's fresh-market potato systems. To identify winter cover crops compatible with regional restrictions and climatic challenges in western Washington potato systems, trials including a no-cover control, eight single species (including brassicas, grasses, and legumes), and a grass–legume mixture were conducted in Mount Vernon, WA, in 2018–2019 and 2019–2020. We examined cover crop and weed biomass production, potato yield and quality, and short-term soil health impacts by measuring permanganate oxidizable carbon (POXC) and inorganic nitrogen before cover crop incorporation and at midseason. Cover crop biomass and weed suppression varied by year, with annual ryegrass (*Lolium multiflorum Lam.*) producing the most biomass in both years despite poorer weather conditions and reduced cover crop biomass in other treatments in 2020, making it a good cover crop candidate for western Washington. Both POXC and inorganic nitrogen were greater at midseason but did not vary among cover crop treatments, suggesting that temporal variation influences POXC and inorganic nitrogen more than a single winter of cover crops. Potato yield and tuber wireworm damage varied by year, but not across cover crop treatments, and tuber symptoms resembling black scurf did not vary by year nor treatment.

1 | INTRODUCTION

Cover crop use is increasing in the United States and exceeded 6 million ha in 2017 (CTIC, 2020). Cover crops provide ecosystem and agronomic benefits by building soil organic matter (SOM), enhancing nutrient cycling, preventing nutrient leaching, increasing water infiltration and retention, and suppressing weeds (Adetunji et al., 2020; Cherr et al., 2006; Sharma et al., 2018). Soil organic matter content is an important indicator of soil health, but it is slow to respond to

Abbreviations: POXC, permanganate oxidizable C; SOM, soil organic matter.

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management changes (Wander & Drinkwater, 2000), making it difficult to measure the impact of short-term management changes. The labile SOM and nutrient fractions quantified by permanganate oxidizable C (POXC) and inorganic N analyses have been found to be both inexpensive and sensitive to short-term management changes (Culman et al., 2013), making them useful metrics to study the impact of management practices on soils.

Cover crops can help mitigate soil degradation in rotations based around crops that have limited compatibility with other soil health-promoting practices. Potato (*Solanum tuberosum* L.) systems present many soil health challenges because they often have intensive soil disturbance, short rotations between potato crops, and minimal crop residue that can contribute to SOM. Because soil conservation practices like no-till are not applicable, winter cover crops may fit into potato systems to provide soil health benefits.

In 2019, Washington state produced approximately 5.4 million Mg ha^{-1} of potato on 66,368 ha (USDA NASS, 2020). While most Washington potato are grown for processing in the Columbia Basin of eastern Washington, fresh-market and seed potato are valuable crops grown in northwestern Washington. Producers in this region are interested in growing cover crops, but the environment presents specific challenges to finding suitable options. With potato harvest often occurring in September and October, it can be a difficult to plant and establish a cover crop before the wet winter conditions bring months of cold, saturated soil. In addition, important rotational crops in the region can constrain available options. Mustard green manures [*Sinapis alba* L. and *Brassica juncea* (L.) Czern.] are commonly used in eastern Washington potato systems (Hills et al., 2018) because their biofumigant properties can reduce effects of pathogens (McGuire, 2003) and parasitic nematodes (Ploeg, 2008). In western Washington, however, flowering brassica cover crops are discouraged due to brassica seed production in Skagit County and the associated risks of cross-pollination. Brassica seed can also be infected and contribute to pathogen spillover of important diseases, such as black leg (*Leptosphaeria maculans* and *L. biglobos*). In addition to influencing soilborne diseases, cover crops can increase soilborne pests like wireworm (*Agriotes* spp.; Blua et al., 2018).

To date, cover crop research in Pacific Northwest potato systems has focused on disease management (e.g., Davis et al., 1996; Davis et al., 2010; McGuire, 2003) in eastern Washington with little attention to soil health metrics. Soil-focused cover crop research in western Washington has been conducted using barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), vetch (*Vicia* spp.), and barley/rye-vetch mixtures (Lawson et al., 2013; Lawson et al., 2015; Wayman et al., 2015) but has not included other species nor been conducted in potato systems. The primary objectives of this study were to evaluate cover crop biomass production, weed suppression, and the short-term effects of winter cover crops on POXC, inorganic N, and potato yield and quality to determine cover crop suitability in northwestern Washington's potato production area.

Core Ideas

- Cover crops that produced higher biomass more effectively suppressed weeds in both years.
- Soil permanganate oxidizable C was influenced by sampling date but not by cover crops.
- Soil inorganic N at midseason was not affected by cover cropping.
- Cover crops did not affect potato tuber yield nor tuber quality.

2 | MATERIALS AND METHODS

2.1 | Site description

Field trials were established at Washington State University's Northwestern Washington Research and Extension Center in Mount Vernon, WA (48 ° 43 ′ 24 ″ N, 122 ° 39 ′ 09 ″ W, elevation 6 m). The soil is mapped as Skagit silt loam, classified as fine-silty, mesic Fluvaquentic Endoaquepts. Prior to trial establishment, soil pH was 6.4, SOM content was 2.8%, and the fields had been fallowed for a year. Located in the maritime Pacific Northwest with a Mediterranean-type climate, the mean air temperature is 7 ° C from October through April and 15 ° C from May through September, and the mean precipitation is 91 mm from October through April and 38 mm from May through September (10-yr average; AgWeatherNet, 2021).

2.2 | Treatment description

The first cover crop trial took place 2018–2019 and was then repeated in an adjacent field in 2019–2020. Both trials followed a randomized complete block design with 10 winter cover crop treatments and four replications per treatment. Treatment randomization was independent for each trial. A no-cover control was compared with nine winter cover crop treatments representing different plant types (brassicas, grasses, legumes). Treatments and seeding rates were chosen to represent typical or adapted winter cover crops in western Washington and in other regions of the United States. Cover crops were grown as single species, except for one mixture treatment that included 50% fava (*Vicia faba* L.),

TABLE 1 Cover crop treatments and seeding rates for autumn-planted experimental trials in Mount Vernon, WA, 2018–2020

Category	Common name	Scientific name	Seeding rate
			kg ha^{-1}
No-cover	Control	–	–
Brassica	Field mustard	*Brassica rapa*	25
	Daikon radish	*Raphanus sativus*	27
Grass	Annual ryegrass	*Lolium multiflorum*	22
	Cereal rye	*Secale cereale*	112
Legume	Crimson clover	*Trifolium incarnatum*	22
	White clover	*Trifolium repens*	22
	Hairy vetch	*Vicia villosa*	45
	Winter pea	*Pisum sativum* subsp. *arvense*	112
Mixture	Mixture	–[a]	54

[a]The mixture included *Vicia faba, x Triticosecale*, *Pisum sativum* subsp. *arvense*, *Avena sativa*, *Vicia sativa*, *Lolium multiflorum*, and *Trifolium incarnatum*.

TABLE 2 Chronology of field operations in experimental trials in Mount Vernon, WA, 2018–2020

Field operation	Field season	
	2018–2019	2019–2020
Cover crop planting	28 Sept. 2018	1 Oct. 2019
Cover crop incorporation	2-6 May 2019	20 Apr. 2020
Broadcast fertilizer application	2-6 May 2019	5 May 2020
Potato planting	7 May 2019	8 May 2020
Potato harvesting	20 Sept. 2019	29-30 Sept. 2020

17% triticale (*xTriticosecale* W.), 13% winter pea (*Pisum sativum* subsp. *arvense*), 12% oat (*Avena sativa* L.), 5% common vetch (*Vicia sativa* L.), 2% annual ryegrass (*Lolium multiflorum* Lam.), and 1% crimson clover (*Trifolium incarnatum* L.) by weight. Single species included field mustard (*Brassica rapa* L.), daikon radish (*Raphanus sativus* L.), annual ryegrass, cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), white clover (*Trifolium repens* L.), hairy vetch (*Vicia villosa* Roth.), and winter pea. See Table 1 for more details about cover crop treatments. Each plot was 15.2 m long and 4 m wide with 3 m wide fallow buffers around each plot.

2.3 | Crop cultivation

The dates of major field operations are listed in Table 2. Cover crops were planted on 28 Sept. 2018 and 1 Oct. 2019 with a Nordston CLA 2.50 to 4.00 m drill seeder. No weed management was conducted while the cover crops were growing to evaluate the effect of cover crop treatments on weed biomass. No fertilizer was applied to the cover crops before nor after establishment. After growing over the winter, the cover crops were flail mowed, rototilled, chisel plowed, fertilized, then rototilled prior to planting potato (cultivar Chieftain).

Potato fertilization in each year was based on spring soil fertility tests and recommendations from local agronomists, and all plots received the same fertilizer rates. The field was broadcast fertilized with 99 kg ha^{-1} N, 202 kg ha^{-1} P, 215 kg ha^{-1} K, and 4.2 kg ha^{-1} B in May 2019 and 128 kg ha^{-1} N, 85 kg ha^{-1} P, 142 kg ha^{-1} K, 4.7 kg ha^{-1}, and 25 kg ha^{-1} S in May 2020. Nutrients were applied in the forms of 397 kg ha^{-1} 11-51-0 monoammonium phosphate, 304 kg ha^{-1} 0-0-22 Trio potash, 247 kg ha^{-1} 0-0-60 muriate of potash, 49 kg ha^{-1} 20-0-0, 99 kg ha^{-1} 46-0-0 urea, and 28 kg ha^{-1} boron 15% maxi granular in 2019, and 164 kg ha^{-1} 11-52-0 monoammonium phosphate, 173 kg ha^{-1} 0-0-22 Trio potash, 168 kg ha^{-1} 0-0-62 muriate of potash, 103 kg ha^{-1} 20-0-0-24s ammonium sulfur, 195 kg ha^{-1} 46-0-0 urea, and 31 kg ha^{-1} boron 15% maxi granular in 2020. Fertilizer formulations were developed and applied by a local agronomic company, as is customary by farmers in the area.

Potato was planted on 7 May 2018 and 8 May 2019 from previously cut seed every 23 cm on 0.97 m-row spacing, and 10-34-0 liquid ammonium phosphate was applied at planting at 73 kg ha^{-1}. Irrigation was not used except for a single event on 3–5 Aug. 2020 where approximately 25.4 mm of water was applied using a big gun sprinkler to alleviate water stress not seen in 2019.

2.4 | Cover crop and weed biomass sampling and analyses

Cover crop and weed biomass samples were collected just before mowing and incorporation on 29–30 Apr. 2019 and 15–16 Apr. 2020. Cover crops were incorporated later in 2019 due to higher precipitation in that year and inability to get in the field, a common issue for producers. Between 1 Apr. and 16 Apr. 2019, the site had received 46 mm of precipitation whereas it received only 16 mm in the same time period in 2020 (AgWeatherNet, 2021). On 27 Mar. and 3 Apr. 2020, daikon radish and field mustard treatments, respectively, were sampled for biomass and then mowed before the other treatments to prevent blooming from occurring and cross-pollenating with brassica seed crops. Aboveground biomass samples were collected from three 25 × 25 cm quadrats per plot. All vegetation within the quadrat was cut at the soil surface and separated into individual cover crop and weed paper bags. Biomass samples were oven-dried at 40 ˚ C to a constant weight and weighed.

2.5 | Soil sampling and analyses

In each year, soil samples (0–30 cm) were collected prior to cover crop incorporation (29–30 Apr. 2019 and 15–16 Apr. 2020) and midseason (11 Jun. 2019 and 14 Jul. 2020). Eight cores per plot were collected in a random pattern and homogenized into a single composite sample per plot. Soil samples were air-dried, then sieved to 2 mm prior to analyses.

Permanganate oxidizable carbon analysis was based on the method described by Weil et al. (2003) but was modified to use 2.5 g of air-dried soil instead of 5.0 g. Each soil sample was analyzed in duplicate. Briefly, 18.0 mL of deionized water and 2.0 mL of 0.2 M potassium permanganate ($KMnO_4$) stock solution were added to a 50-mL polypropylene screw-top centrifuge tube with the soil. The tubes were then shaken for 2 min at 240 oscillations per minute, followed by settling for 10 min in the dark. After settling, 0.5 mL of the supernatant was added to 49.5 mL of deionized water in a 50-mL polypropylene screw-top centrifuge tube. These tubes were stored in a dark cabinet for up to 8 h until duplicate aliquots (270 µl) of each were added to a 96-well plate and absorbance values were determined at 550 nm with a Synergy LX Multi-Mode Reader (BioTek Instruments). Inorganic N (NH_4^+-N and NO_3^--N) was analyzed by SoilTest, Inc. (Moses Lake, WA) using a 2 M potassium chloride (KCl) extraction on air-dried soil samples with analysis via FIA Flow Injection (Gavlak et al., 2005).

2.6 | Tuber yield and quality

Potato tubers were harvested on 20 Sept. 2019 and 29–30, Sept. 2020, approximately 30 d after Reglone (active ingredient: diquat dibromide) herbicide was applied for vine kill at 1.75 L ha^{-1}. In 2019, two 0.762 m long sections running the row length were hand harvested from each plot, while in 2020, one 9-m section was machine dug with a one-row digger for yield samples. Differing harvest methods were due to equipment availability.

Residual soil was removed from all tubers before being weighed in bulk by plot to calculate yield. All harvested tubers in 2019 and a randomly selected subset of 50 tubers in 2020 were assessed for symptoms resembling black scurf (caused by *Rhizoctonia solani*) and wireworm (*Agriotes* spp.) damage. Black scurf severity was determined visually using a 0-to-3 rating scale, with 0 = no symptoms, 1 = less than 10% tuber surface covered, 2 = 10–25% tuber surface covered, and 3 = more than 25% tuber surface area covered. Wireworm damage severity was also visually determined using a 0-to-3 rating scale, with 0 = no damage, 1 = less than 10 holes, 2 = 10–15 holes, and 3 = 16–45 holes. Severity indices were calculated using the midpoint of each rating level (Tsror et al., 2001). The black scurf severity index was calculated as follows: (number of rating 0 tubers × 0) + (number of rating 1 tubers × 5) + (number of rating 2 tubers × 17.5) + (number of rating 3 tubers × 63)/total number of tubers. The wireworm damage severity index was calculated as follows: (number of rating 0 tubers × 0) + (number of rating 1 tubers × 5) + (number of rating 2 tubers × 12.5) + (number of rating 3 tubers × 30.5)/total number of tubers.

2.7 | Statistical analyses

Statistical analyses were conducted in R with mixed models using the *lmer()* function and analysis of variance in the *lme4* package (Bates et al., 2015; R Core Team, 2019) for cover crop biomass, weed biomass, soil POXC, soil NO_3^--N, soil NH_4^+-N, tuber yield, and black scurf and wireworm damage severity indices. A mixed model with treatment and year as fixed factors and block as a random factor was applied to each response variable. For analyses of POXC, NO_3^--N, and NH_4^+-N, plot was added to the model as a random effect because of repeated measures within each year. Year was significant for all response variables, so each year was examined separately with timepoint included as a fixed effect in the model. If a significant treatment × timepoint interaction occurred ($p < .05$), timepoints were examined separately. Assumptions of normality and homogeneity of variance were tested through Shapiro-Wilk and Levene's tests and visual inspection with the *qqPlot()* function. Data were log or square root transformed if normality assumptions were not met. A post hoc Tukey's honestly significant difference test determined means separation at $\alpha = 0.05$ using the *emmeans()* package (Lenth, 2019). All plots were generated using the R package *ggplot2* (Wickham, 2009).

3 | RESULTS AND DISCUSSION

3.1 | Cover crop and weed biomass

Cover crop biomass differed between 2019 and 2020 ($p = .0001$; Figure 1). White clover biomass increased by 1.5 times and annual ryegrass biomass remained constant from 2019 to 2020, while all other cover crops had reduced biomass production in 2020. The greatest reductions in biomass between years occurred with crimson clover (90%), winter pea (83%), and cereal rye (80%). The mixture and daikon radish biomass yields were 34% and 45% less, respectively. Differences between years are likely due to annual variation in temperature and moisture conditions. In September and October 2019, the site received 240 mm of precipitation, which was 2.5 and 1.7 times more precipitation than the same time

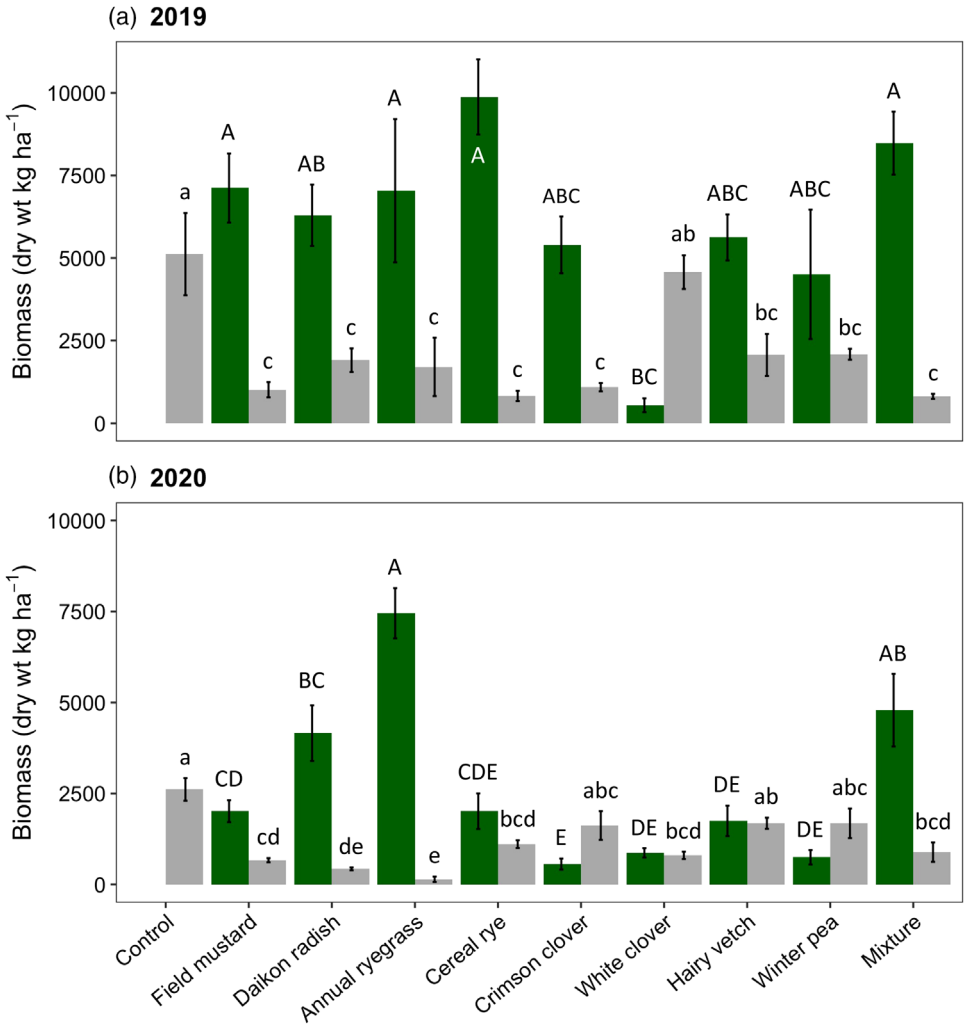


FIGURE 1 Cover crop and weed above-ground dry weight biomass (kg ha^{-1}) pre-incorporation in April 2019 (A) and 2020 (B). Bars represent means and error bars indicate standard error. Different capital and lowercase letters indicate significant differences in cover crop and weed biomass, respectively, for each year (Tukey honestly significant difference, $p < .05$)

period in 2018 (93 mm) and the 10-yr average, respectively (144 mm; AgWeatherNet, 2021). This additional precipitation in 2019 created unusually wet soil conditions and was coupled with slightly cooler temperatures in October (2018 = 10 ˚ C; 2019 = 9 ˚ C; 10-yr average = 11 ˚ C), reducing cover crop establishment and autumn growth measured the following spring. Similarly, Luna et al. (2020) measured an 80% reduction in hairy vetch biomass and 69% reduction in overall biomass among all species [oat, common vetch, phacelia (*Phacelia tanacetifolia* Benth)] in the wetter year of a 2-yr trial near Corvallis, OR. Cover crops were also incorporated 12 d later in spring 2019 than in 2020 due to wet conditions in April 2019 that prevented earlier incorporation of cover crops, an issue that is common for growers in the region. Therefore, differences between years may also be attributed to a slightly longer cover crop growing period and accumulation of cumulative thermal units in the first year (2,158 ˚ C d in 2019 vs. 2,003 ˚ C d in 2020; AgWeatherNet, 2021). We found that annual ryegrass was less affected by the wet and cool autumn and spring conditions compared with the other cover crops in these trials. Therefore, annual ryegrass is a good candidate cover crop for western Washington based on biomass production.

Within each year, cover crop treatments differed in their biomass production ($p < .0001$). Excluding the no-cover control, cover crop biomass ranged from 546 to 9,880 kg ha^{-1} and 561 to 7,453 kg ha^{-1} dry weight in 2019 and 2020, respectively (Figure 1). These values are within the range of biomass production observed in other studies in western Washington (Cogger et al., 2016; Lawson et al., 2013; Lawson et al., 2015; Wayman et al., 2015). In 2019, all cover crops produced more biomass than white clover ($p < .0001$). Excluding white clover, the remaining biomass values ranged from 4,507 (winter pea) to 9,880 (cereal rye) kg ha^{-1} dry weight with no statistical differences. Variation in cover crop biomass among plots within each treatment limited the detection of differences.

In 2020, annual ryegrass produced more biomass than all other cover crops except the mixture treatment, and the brassicas produced more biomass than the legumes ($p < .0001$). Cereal rye and annual ryegrass produced the greatest mean biomass in 2019 and 2020, respectively. Despite producing half as much biomass in 2020 as 2019, the mixture had the second greatest mean biomass in both years. Annual ryegrass and triticale (17% of the mixture at planting) are cool season grasses and produced more biomass during the cooler and less favorable weather, making them good candidates for western Washington.

Weed biomass also differed by treatment ($p < .0001$) and year ($p = .009$) while the cover crops were growing. Like cover crop biomass, there was generally a decrease in weed biomass from 2019 to 2020 (Figure 1). The no-cover control had nearly 50% lower weed biomass in 2019 than 2020, with 5,120 and 2,613 kg ha^{-1} dry weight in each year, respectively. This suggests that weed pressure was lower in 2020 than 2019. Excluding the no-cover control, weed biomass ranged from 813 to 4,573 kg ha^{-1} and 143 to 1,681 kg ha^{-1} in 2019 and 2020, respectively. In 2019, the control had more weed biomass than all treatments except white clover, and white clover had more weed biomass than the grasses, brassicas, and mixture ($p < .0001$). In 2020, the control, crimson clover, hairy vetch, and winter pea had similar weed biomass, which were all greater than annual ryegrass and daikon radish ($p < .0001$). Greater weed suppression occurred in treatments with higher cover crop biomass. This is consistent with many studies assessing weed suppression by cover crops (e.g., Baraibar et al., 2018; Hayden et al., 2012; Wayman et al., 2015)

3.2 | Permanganate oxidizable carbon

Cover crops will increase soil organic C pools, particularly when used over multiple years (Ladoni et al., 2016; Mazzoncini et al., 2011; Poeplau & Don, 2015). However, this increase can also occur shortly after cover crops are added to a production system (Strickland et al., 2019). Because our study was conducted after one winter of cover cropping, POXC was analyzed because it has higher sensitivity to short-term management changes than total organic C and other labile C pools like particulate organic C and microbial biomass C, and therefore is a useful short-term indicator of potential long-term changes in soil C (Culman et al., 2012).

In our study, POXC varied by year ($p = .0003$) and timepoint within the growing season ($p < .0001$). Because of a year × timepoint interaction ($p < .0007$), 2019 and 2020 were examined separately. No treatment × timepoint interaction was present in either year ($p_{2019} = .82$; $p_{2020} = .94$). Despite the sensitivity of POXC to management changes (Culman et al., 2012), perhaps more than one season of cover cropping is needed to observe differences among cover crops in a tillage intensive system like potato and will take multiple years of cover crop use before differences can be observed like with many other soil parameters. In 2019, POXC across treatments generally remained constant from pre-incorporation to midseason and decreased at postharvest ($p < .0001$; Figure 2). In 2020, POXC across treatments was highest at midseason ($p < .0004$). Similar bell-curve temporal variation has been measured by others and is thought to be caused by plant growth and/or soil temperature (Culman et al., 2013; Diederich et al., 2019). Wang et al. (2017) suggested that higher root density leads to more of the SOM being made up of root exudates from rhizodeposition, thus increasing POXC. Perhaps the potato root activity at midseason was greater than the cover crop root activity pre-incorporation, which therefore increased POXC.

The impact of cover crop species on POXC is inconclusive. In our study, despite differences in biomass production, POXC did not differ across treatments after a single season of cover crops. Similarly, soft red winter wheat (*Triticum aestivum* cultivars Hass Cover and ForageMax) and crimson clover cover crops did not influence POXC after 2 yr in organic vegetable production in Tennessee (Butler et al., 2016). In contrast, Ghimire et al. (2019) measured differences in POXC by cover crop species, with oat and oat-containing cover crop mixtures increasing POXC over pea and canola (*Brassica napus*) after 2 yr in New Mexico. They associated greater cover crop biomass and C input with higher POXC, whereas Butler et al. (2016) suggested that the study period was too short for the cover crop biomass to break down enough to impact POXC. Climate and management history could explain the differences between these studies. In our study, mean POXC values were higher in 2019 than 2020 ranging from 370.9 to 448.8 and 320.6 to 374.3 mg kg^{-1} dry soil, respectively. POXC values ranging from 374 to 618 mg kg^{-1} dry soil have been measured in other Entisol soils from Florida and California (Wade et al., 2020), putting our values at and below the lower end of this range, possibly because of differences in climate, cropping history, and the high disturbance nature of potato systems.

3.3 | Soil nitrogen availability

Soil inorganic N is influenced by multiple addition and loss pathways, and therefore responses to management may be less evident than for POXC (Culman et al., 2013), but the impacts of cover crops can still be observed under some conditions (Wayman et al., 2015). Soil NO_3^--N and NH_4^+-N concentrations both varied by year ($p < .0001$ and $p < .0001$, respectively) and timepoint ($p < .0001$ and $p < .0001$, respectively) with lower inorganic N at pre-incorporation than midseason ($p_{2019} < .0001$, $p_{2020} < .0001$) in both years (Table 3).

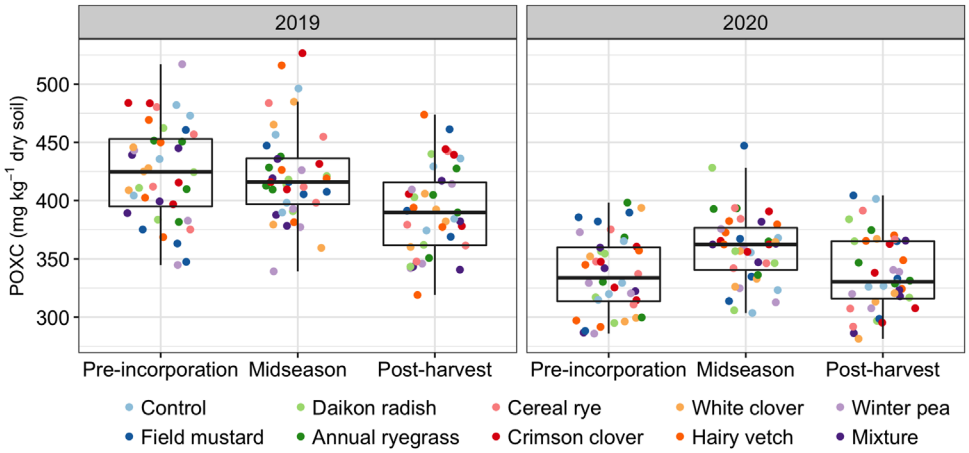


FIGURE 2 Mean permanganate oxidizable carbon (POXC; mg kg^{-1} dry soil) at a depth of 0–30 cm at pre-incorporation of winter cover crops, midseason, and postharvest of potato in experimental trials in Mount Vernon, WA in 2019 and 2020. Points represent POXC concentrations in each of 4 plots per treatment, and boxplots show medians (dark middle line) and first and third quartiles (box edges) among all values at each timepoint

TABLE 3 Mean soil NO_3^--N and NH_4^+-N (0–30 cm) at pre-incorporation of winter cover crops and midseason in potato system experimental trials in Mount Vernon, WA in 2019 and 2020

	Soil NO_3^--N (mg kg^{-1} dry soil)				Soil NH_4^+-N (mg kg^{-1} dry soil)			
	Pre-incorporation		Midseason		Pre-incorporation		Midseason	
Treatment	2019	2020	2019	2020	2019	2020	2019	2020
Control	1.0 (0.1) ab	0.7 (0.07) bc	69.3 (6.4)	62.8 (15.8)	0.9 (0.3)	0.8 (0.1) ab	35.8 (15.6)	8.5 (1.2)
Field mustard	1.4 (0.4) a	1.0 (0.16) ab	76.3 (7.1)	44.9 (6.26)	1.5 (0.4)	1.0 (0.1) ab	22.2 (12.7)	5.3 (0.5)
Daikon radish	1.1 (0.1) ab	1.4 (0.10) a	65.3 (6.6)	43.9 (12.7)	1.0 (0.2)	1.3 (0.3) ab	11.2 (5.3)	6.4 (2.3)
Annual ryegrass	0.5 (0.1) b	0.4 (0.03) d	63.7 (8.0)	32.5 (11.1)	0.7 (0.4)	0.7 (0.1) b	53.8 (23.2)	6.3 (1.2)
Cereal rye	0.9 (0.1) ab	0.7 (0.05) bc	60.4 (5.0)	70.3 (17.5)	0.7 (0.3)	0.9 (0.1) ab	18.1 (7.4)	13.0 (7.6)
Crimson clover	1.3 (0.2) a	0.8 (0.10) bc	78.1 (6.6)	63.1 (6.2)	0.7 (0.3)	1.1 (0.1) ab	20.4 (7.8)	7.1 (1.8)
White clover	0.8 (0.2) ab	0.8 (0.07) bc	73.0 (11.0)	56.1 (12.4)	0.7 (0.3)	1.0 (0.2) ab	28.0 (11.3)	5.3 (1.7)
Hairy vetch	1.3 (0.3) a	0.7 (0.04) bc	68.7 (4.7)	45.9 (8.9)	1.0 (0.6)	0.9 (0.3) ab	17.2 (3.7)	4.3 (1.1)
Winter pea	1.0 (0.2) ab	1.0 (0.06) ab	73.4 (6.6)	46.0 (12.4)	0.3 (0.1)	1.5 (0.3) a	35.1 (20.5)	4.8 (1.8)
Mixture	0.7 (0.1) ab	0.6 (0.05) cd	61.6 (4.8)	29.4 (8.4)	0.6 (0.2)	0.9 (0.2) ab	38.9 (15.3)	4.0 (1.3)

Note. Standard error value is in parenthesis next to corresponding mean. Different lowercase letters indicate significant differences in values within a given timepoint and year (Tukey honestly significant difference, $p < .05$).

In addition to cover crop incorporation, fertilization occurred between these timepoints, adding additional N to the soil and potentially masking subtle treatment effects. A timepoint × year interaction occurred for both NO_3^--N ($p < .02$) and NH_4^+-N ($p < .0001$) as the mean midseason 2019 values were higher than 2020 values for both NO_3^--N (average across treatments of 69.0 vs. 49.5 mg kg^{-1} dry soil) and NH_4^+-N (average of 28.1 vs. 6.5 mg kg^{-1} dry soil). Because midseason soil samples were collected in June 2019 and July 2020, we hypothesize that the additional month of plant growth consumed more inorganic N, causing reduced inorganic N concentrations at midseason in 2020.

At pre-incorporation in 2019, soil NO_3^--N was 61–64% lower in the annual ryegrass treatment than field mustard, crimson clover, and hairy vetch ($p = .02$), but no differences in soil NH_4^+-N occurred across treatments. In 2020, NO_3^--N was 40–71% lower in annual ryegrass and mixture than field mustard, daikon radish, and winter pea ($p < .0001$), and NH_4^+-N was 53% lower in annual ryegrass than winter pea ($p = .02$). However, these differences are likely not agronomically relevant because mean values were very low and ranged from 0.4 to 1.4 mg kg^{-1} dry soil for NO_3^--N and 0.3 to 1.5 mg kg^{-1} dry soil for NH_4^+-N for both years combined.

Cover crop treatments had inconsistent effects on inorganic N at midseason. In 2019, soil NO_3^--N following the legume cover crops was numerically higher than following both grass treatments ($p = .5$), which is consistent with other studies

(Lenzi et al., 2009) though it was not statistically significant in our study. Despite the wide range in mean values at midseason in 2020, variability within treatments obscured treatment differences for NO_3^--N ($p = .2$; Table 3). In 2020, soil NO_3^--N following legumes was again numerically higher than annual ryegrass but was less than following cereal rye. Cereal rye biomass was 80% lower in 2020 than in 2019 (2,013 vs. 9,880 kg ha^{-1}), reducing the C addition and potential for N to be immobilized. The cereal rye was incorporated during the jointing phenological stage in both years, so biomass C:N ratio, which increases as phenological stages progress (Odhiambo & Bomke, 2001), was likely similar. Some studies have found N immobilization after cereal rye cover crops (Kuo et al., 1997; Odhiambo & Bomke, 2000), while others have not (Lawson et al., 2013), possibly due to differences in biomass production and timing of incorporation.

Daikon radish has been found to beneficially influence soil N cycling, but we did not find that it influenced soil inorganic N. While actively growing, daikon radish can scavenge inorganic N with taproot formation and, · once incorporated, increase soil inorganic N through mineralization of the previously scavenged N (Jahanzad et al., 2017). In our study, daikon taproot formation was minimal (data not presented), which limited its ability to scavenge residual N and add it back into the soil after incorporation.

Similarly, variability in NH_4^+-N at midseason in 2019 ($p = .43$) hindered the ability to detect differences among treatments. Field mustard, daikon radish, cereal rye, crimson clover, and hairy vetch had mean NH_4^+-N values less than 25 mg kg^{-1} dry soil, while annual ryegrass had 53.8 mg kg^{-1} dry soil. NH_4^+-N concentrations were at least four times higher in 2019 than 2020 in most treatments, ranging from above 17 to below 8.5 mg kg^{-1} dry soil, in each year, respectively. The exceptions to this were daikon radish, cereal rye, and crimson clover, where the concentrations were 1.75, 1.4, and almost 3 times higher in 2019 than 2020, respectively.

3.4 | Tuber yield and quality

Tuber yield ranged from 53.6 to 64.1 Mg ha^{-1} in 2019 and 37.1 to 45.1 Mg ha^{-1} in 2020, but there were no statistical differences among treatments in either year ($p_{2019} = .6$; $p_{2020} = .9$; Table 4). Higher tuber yields have been measured following cereal rye, daikon radish, winter pea, red clover, and alfalfa (*Medicago sativa*) cover crops compared with fallow when a low rate of N fertilizer is applied to the potato, indicating that cover crops used for one winter or long-term can reduce the need for N fertilizer (Jahanzad et al., 2017; Neeteson, 1989). Because our trial was fertilized at the industry standard rate, potential N limitations in the no-cover crop treatment were prevented, leading to similar yields among treatments. At the industry standard fertilizer rate, higher tuber yields have been measured following a sorghum–sudangrass (*Sorghum bicolor* × *S. sudanense*) cover crop compared with mustard (*Brassica* sp.), canola, and fallow after the first winter of cover cropping, but no difference among treatments after the second winter (Essah et al., 2012), suggesting yearly variations can have more influence than short-term cover cropping on potential increases in tuber yield. In our trial, tuber yield varied by year ($p < .0001$), with the 2019 yield being about 1.5 times greater than 2020 yield. Differences between years may have been due to differences in yield data collection methods, as two short sections per plot were hand-dug in 2019 and one longer section was machine harvested in 2020 due to equipment availability. However, the latter method is considered more common and representative and therefore unlikely to have underestimated yield. The more likely explanation is due to weather differences between years. Griffin et al. (2009) also found that tuber yields differed by year but not across treatments of red clover and annual ryegrass cover crops and no-cover control after three 2-yr rotation cycles, citing precipitation patterns for yearly yield differences. Our study also experienced different yearly precipitation patterns with approximately 2.7 and 1.5 times more precipitation in May and June of 2020 (157 mm) than 2019 (58 mm) and the 10-yr average (102 mm; AgWeatherNet, 2021), respectively. July 2019 and 2020 both had 21 mm of precipitation occur, which was 6 mm more than the 10-yr average. Precipitation in August 2019 (22 mm) and the 10-yr average (23 mm) were similar, but less precipitation in August 2020 (16 mm) required supplemental irrigation. The increased moisture in 2020 delayed tuber emergence in May and slowed growth in June, which, coupled with reduced soil moisture in August, led to overall lower yields compared with 2019. The mean monthly air temperatures during the potato growing season in 2019 and 2020 were within 2 degrees of the 10-yr average every month, suggesting the differences in monthly precipitation rather than temperature influenced tuber growth.

Symptoms resembling black scurf did not vary by year ($p = .2$) nor treatment ($p = .3$). Large variability between samples obscured the ability to detect statistical differences; however, numerically, the crimson clover treatment had the highest severity index value in 2019 of 4.36, and the annual ryegrass treatment had the highest severity index value in 2020 of 6.64 (Table 4). Field mustard, cereal rye, and hairy vetch had lower severity in both years, ranging from 0.10 to 0.33 in 2019 and 0.13 to 0.94 in 2020. Similarly, reductions in incidence and severity of black scurf on tubers has occurred with cereal rye, mustard, canola, rapeseed (*Brassica napus* 'Dwarf Essex') and sorghum × sudangrass hybrid cover crops in 2- and 3-yr rotations compared with continuous potato, oat, and forage grass (Larkin & Griffin, 2007; Larkin & Honeycutt, 2006; Larkin et al., 2010; Larkin et al., 2017).

TABLE 4 Mean potato (*Solanum tuberosum* cv. Chieftain) yield and severity indices for symptoms resembling black scurf (caused by *Rhizoctonia solani*) and wireworm (*Agriotes* spp.) damage in experimental trials in Mount Vernon, WA, in 2019 and 2020

	Yield (Mg ha^{-1})		Black scurf severity index[a]		Wireworm damage severity index[b]	
Treatment	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Control	59.4 (2.7)[c]	44.5 (7.8)	0.49 (0.26)	2.56 (2.56)	4.87 (0.59)	0.05 (0.05)
Field mustard	61.8 (2.8)	44.2 (6.1)	0.18 (0.08)	0.28 (0.18)	3.38 (0.60)	0.03 (0.03)
Daikon radish	62.3 (5.5)	40.8 (4.3)	0.29 (0.13)	1.52 (1.05)	3.66 (0.37)	0.00 (0.00)
Annual ryegrass	64.1 (4.1)	37.1 (1.9)	2.46 (2.36)	6.64 (5.61)	2.63 (0.32)	0.00 (0.00)
Cereal rye	57.0 (2.4)	45.1 (6.2)	0.33 (0.18)	0.94 (0.94)	4.04 (0.60)	0.08 (0.08)
Crimson clover	65.0 (3.0)	38.6 (3.6)	4.36 (4.33)	3.12 (2.94)	2.94 (0.50)	0.13 (0.13)
White clover	54.7 (7.2)	37.0 (2.6)	2.88 (2.53)	2.69 (1.96)	3.38 (0.73)	0.05 (0.05)
Hairy vetch	60.0 (4.7)	39.5 (2.7)	0.10 (0.08)	0.21 (0.18)	3.14 (0.44)	0.03 (0.03)
Winter pea	53.6 (6.9)	39.6 (4.5)	0.34 (0.17)	3.50 (3.25)	3.46 (0.31)	0.00 (0.00)
Mixture	56.0 (0.8)	41.3 (3.7)	2.22 (1.99)	0.13 (0.08)	3.10 (0.49)	0.00 (0.00)

[a]Black scurf severity index was calculated as follows: (number of rating 0 tubers × 0) + (number of rating 1 tubers × 5) + (number of rating 2 tubers × 17.5) + (number of rating 3 tubers × 63) / total number of tubers.
[b]Wireworm damage severity was calculated as follows: (number of rating 0 tubers × 0) + (number of rating 1 tubers × 5) + (number of rating 2 tubers × 12.5) + (number of rating 3 tubers × 30.5) / total number of tubers.
[c]Standard error value is in parenthesis next to corresponding mean.

Wireworm damage varied by year ($p < .0001$), but not treatment ($p = .7$; Table 4). In 2019, the wireworm damage severity index values ranged from 2.63 (annual ryegrass) to 4.87 (control), whereas all values in 2020 were less than 0.13 (crimson clover) with daikon radish, annual ryegrass, winter pea, and the mixture with no wireworm damage. Clover and small grains can increase wireworm populations (Blua et al., 2018), which occurred with higher severity index values in cereal rye, crimson clover, and white clover in 2020, but only cereal rye in 2019.

4 | CONCLUSIONS

Cover crops successfully reduced weed biomass in spring before potato planting compared with the no-cover control in both years of our study, despite reduced cover crop biomass production in 2020. In particular, annual ryegrass and the grass-legume mixture produced a large volume of biomass and effectively suppressed weeds during both years despite suboptimal weather conditions, making them good cover crop candidates for western Washington. Yearly variation in uncontrollable factors, such as temperature and precipitation, had a greater impact on POXC, NO_3^--N, NH_4^+-N, and tuber yield than a single winter of cover crops. Within-season temporal variation in soil metrics did occur with higher POXC, NO_3^--N, and NH_4^+-N values at midseason than prior to cover crop incorporation. These parameters were chosen for their ability to show short-term changes, but additional physical and biological properties such as aggregate stability and microbial biomass would be valuable to include in future studies. Yearly variation in field conditions influenced tuber yield and wireworm damage more than the cover crop treatments. Though not statistically significant, symptoms resembling black scurf were greatest in the crimson clover treatment in 2019 and the annual ryegrass treatment in 2020, but this should not prevent annual ryegrass from being used as a cover crop. Because effects of cover crops can take years of continuous use to be detected, the lack of treatment differences observed after one winter of cover crops in this study does not imply that no differences will become evident with more cover crop use. Further research is needed to evaluate the longer-term impacts of multiple years of winter cover crops on soil properties like POXC, N availability, and a larger suite of soil health indicators in potato systems of this region, especially since yearly variation appears to have a dominant role and it can take many years of cover cropping to detect effects on soil and tuber yield. In this short-term study, annual ryegrass was the most promising cover crop for the region.

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AUTHOR CONTRIBUTIONS

Toby M. Una: Data curation; Formal analysis; Investigation; Visualization; Writing – original draft. Don McMoran:

Conceptualization; Funding acquisition; Project administration. Steven S. Seefeldt: Conceptualization; Investigation; Supervision; Writing – review & editing. Brian Maupin: Investigation; Supervision. Elizabeth Myhre: Data curation; Investigation; Supervision. Deirdre Griffin-LaHue: Conceptualization; Formal analysis; Funding acquisition; Investigation; Project administration; Resources; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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