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Effective Cover Crop Species and Early Establishment Techniques for Reducing Winter Erosion in Muck Soil of the Holland Marsh

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Title: Effective Cover Crop Species and Early Establishment Techniques for Reducing Winter Erosion in Muck Soil of the Holland Marsh

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ABSTRACT

The Holland Marsh is the largest cultivable area of high organic matter content (muck) soil in Ontario, Canada. Soil loss by wind erosion, particularly during fall and winter months, is a major soil management concern for this region. Incorporating cover crops into the production system is a proposed strategy to reduce wind erosion. However, cool fall temperatures and a short growing window, especially after carrot harvest, is a challenge, as is the preference for a cover crop that dies over the winter and does not interfere with following year's main crop. Field trials assessed various cover crop species and methods for their establishment after onion and carrot harvests. Barley (*Hordeum vulgare* L.) (55%) and barley/daikon radish (*Raphanus sativus* L. var. *longipinnatus)* mixtures (60%) produced higher canopy coverage when seeded after onions, supporting the current farmer practice of using mainly barley as a cover crop in this area. Barley seeded at a high seeding rate (420 seeds m^{-2}) before carrot harvest achieved greater canopy coverage compared to barley or fall rye (*Secale cereale* L.) seeded after harvest. Transplanting barley after carrot harvest provided the highest canopy coverage (25-31%), but the associated cost is a concern. Seed priming did not enhance cover crop establishment in field. Direct seeding of cover crop before or after carrot harvest produced canopy coverage below 30%, the critical level of residue cover for reducing soil loss by erosion. Future research on cover crop agronomy in the Holland Marsh including additional species and methods for establishment is recommended.

KEY WORDS:

Muck soil, wind erosion, cover crops, canopy coverage

INTRODUCTION

Organic soil is developed under wetland (anaerobic) condition and has more than 17% soil organic carbon (SOC) (Kroetsch et al. 2011), while mineral soil generally contains less than 3.4% SOC (Shonk et al. 1991). The Holland Marsh, located in the watershed of the Holland River in King Township and Simcoe County (45°05’N, 79°34’W) (Nicholls and MacCrimmon 1974), is the largest continuous area of organic soil reclaimed for agriculture in Ontario, Canada and covers an area of about 3000 ha, supporting ~125 farmers (Bartram et al. 2007). The SOC content in these soils ranges from 17–48%. The area was diked and drained starting in the late 1920s and 1930s for agricultural purposes (Jackson 1998). Carrot (*Daucus carota* L.) and onion (*Allium cepa* L.) are the major crops grown in rotation in the Holland Marsh (70 % of total production), while some farmers also grow Chinese leafy greens, celery, beet, and greenhouse vegetables and flowers (Holland Marsh Growers’ Association 2019). About 50% of Ontario’s fresh market carrot and 60% of Ontario’s dry onion are produced here (OMAFA 2022). These highly productive organic soils are of significant agricultural importance. However, the continuous loss of the organic layer (subsidence) due to the natural decomposition of SOC coupled with soil loss from factors such as wind erosion present a substantial concern.

Subsidence is a gradual reduction in thickness of the SOC layer after a wetland is drained (Stephens 1956). Subsidence rates of 1 to 3.3 cm per year have been recorded in the Holland Marsh (Smith 1962; Mirza and Irwin 1964). The subsidence rate can vary greatly because of secondary influences, which include frost action, water table fluctuations (Mirza and Irwin 1964) and soil loss by wind erosion (Zandstra and Warncke 1993). Strong wind continuing for one to two hours can erode 2 to 5 cm of bare and dry organic soil (Zandstra and Warncke 1993). An average annual loss of 2 cm of organic soil has been reported for the organic soils reclaimed for agriculture in Montreal, Quebec due to wind erosion (Aygün et al. 2021)

Ontario cropland is prone to wind erosion during the fall and winter when the primary crop is absent, and wind speed is higher (OMAFA 2022c). Flatter regions, where there is nothing to obstruct the wind, such as the Holland Marsh, are more prone to soil loss due to wind erosion, particularly when soil is loose, dry, and uncovered (Zobeck 1991). Further, organic soil has low bulk density (0.1 to 0.35 g cm^{-3}) (Lucas 1982), which makes it lighter and susceptible to wind erosion (Campbell et al. 2001). Organic soil in the Holland Marsh is also dark in colour (Zandstra and Warncke 1993) and is typically tile drained. These conditions can accelerate the drying of surface soil, hindering surface sealing and crust formation, making it more prone to wind erosion (Zobeck 1991).

Cover crops including crop residues can be used to provide ground cover to limit wind speed and potential erosion (Fryrear 1985; Stevens and Quinton; Baets et al. 2011; Blanco-Canqui et al. 2015;). However, standing vegetation, such as a living cover crop, in the field is more effective than flat crop residues, as it can play a role in reducing wind speed, while also providing cover (Bilbro and Fryrear 1994). Grass species of cover crops such as barley (*Hordeum vulgare* L.), fall rye (*Secale cereale* L.), forage sorghum (*Sorghum bicolor* L.), and triticale (× *Triticosecale* Wittmack), that can produce greater biomass and height and have fibrous roots that can hold soil firmly, are more beneficial than other cover crops in areas prone to wind erosion (Blanco-Canqui et al. 2015). Cover crops also can reduce the rate at which the soil surface dries, as compared to soils without a cover crop, making the soil more resilient to wind erosion (Campbell et al. 2001).

Cover crops are currently grown in about 25% of area in the Holland Marsh and are generally grown after onions or other early maturing vegetables such as celery. The major cover crops grown in the Holland Marsh included spring barley, oat (*Avena sativa* L.), daikon radish (*Raphanus sativus* L. var. *longipinnatus)*, and a cover crop mixture that includes cereal, legumes, and radish (Kevin Vander Kooi, personal communication, October 2023). Among these, barley is the most common fall cover crop observed after onions in the Holland Marsh. However, growing cover crops after carrots, which are generally harvested in late October or later, is not common. Farmers want to harvest carrot when the temperature is low, so there will be low field heat, which is important for longer storage life of carrot in cold storage (Bachmann and Earles 2000; McDonald and Telfer 2019). Besides this consideration, onion, which is generally grown the year after carrot in the Holland Marsh, is photoperiod sensitive and starts to bulb when day length starts to decrease after the summer solstice (Mondal et al. 1986). Thus, farmers need to seed onion as early as possible in the spring to provide time for vegetative growth and high yields (Mondal et al. 1986). This limits the use of winter species as a cover crop after carrot since these survive the winter and need to be sprayed with herbicide or disked under in the spring, both of which could delay onion seeding. This makes the choice of cover crop after carrots very difficult.

For a production system with a relatively short growing window, there are strategies that can be adopted for early cover crop establishment such as: intercropping (Bourgeois et al. 2022), using a cold tolerant and winter or winter resistant species as a cover crop, or full season cover cropping where the soil is taken out of commercial crop production for an entire year (Stivers et al. 1999). Another approach could be seed priming, as this could reduce the number of days required for seed germination or emergence (Heydecker et al. 1977). Transplanting plug seedlings of a cover crop could also be an option mainly in high value cropping systems where the cost of the plants and labour may be less of a concern. Transplanting cover crops could become more economical in the future as growers use more agricultural robots. Robots could do the transplanting in the Fall when they are not in use for other agricultural tasks.

Seed priming is a technique where seeds are partially hydrated to activate pre-germination metabolic activities and then dried again to nearly the original stage of moisture content to prevent final germination (Paparella et al. 2015). Priming can expedite seed emergence, assist in uniform plant establishment, and protect seedlings from exposure to unfavorable growing environments and diseases (Osburn and Schroth 1988). Seed priming (hydro-primed with deionized water or osmo-primed with KNO_3 at 5 mg L for 24 h) of barley, oat, and triticale, assessed in growth rooms trials, resulted in faster germination and emergence especially at lower temperatures (5°C and 10°C) (Pandey 2024).

The objectives of this study were to assess the performance of various cover crop species and mixtures for canopy coverage and biomass production in the Holland Marsh and to evaluate the efficacy of other methods to establish cover crops: pre-harvest seeding of barley into the carrot canopy before harvest, seed priming of barley, oat, and triticale for rapid cover crop establishment after carrots, and barley and alyssum (*Lobularia maritima* L.) transplants after carrots in the Holland Marsh. Flowering plants such as alyssum have multiple ecological benefits and can provide a nutritional and habitat resource for pollinators such as wasps (*Cotesia vestalis* L.), which can act as a parasitoid to the diamond black moth (*Plutella xylostella* L.), a globally significant pest affecting brassica plants (Chen et al. 2020). While alyssum is cold tolerant, it cannot survive through winter (Gilman and Howe 1999). Furthermore, it belongs to the Brassicaceae family, distinct from that of onions and carrots, and has few or none of the same insect pests and diseases of the main crops, which is important for pest management (Gilman and Howe 1999).

MATERIALS AND METHODS

Three field trials were conducted, each over two of three years 2021- 2023: 1) cover crops after onion (2021 and 2022); 2) cover crops after carrot (2022 and 2023); and 3) cover crop species and techniques for rapid cover crop establishment after carrot (2022 and 2023). Trials were conducted at a rented site on Jane St. (44°02'41.5"N 79°35'04.9"W), one of the commercial farms in the Holland Marsh. The field had organic soil (Terric Humisol with SOC ~ 28% and a soil pH of 6.4). Onion and carrot have been grown in rotation on the site for many years. The field is tile drained (1.2 m deep and 10 m apart). Total precipitation and average temperature data for the years when field trials were run is shown in Fig. 1. All field trials were arranged in a randomized complete block with four replications per treatment.

Cover crops after onion

Onion, cv. Traverse was seeded on 8 May 2021 and cv. Milestone was transplanted on 18 May 2022. Onion was mechanically harvested on 20 September in 2021 and 9 September in 2022. The plot size for each experimental unit was 17 m x 14 m. The treatments were: daikon radish (Quality Seeds Ltd., Woodbridge, ON) at 90 seeds m^{-2}, NITRO Plus (General Seed Company Ltd., Alberton, ON) at 190 seeds m^{-2}, barley (bought from grower) and daikon radish mix at 160 and 60 seeds m^{-2}, respectively and barley alone at 210 seeds m^{-2}. The seeding rates were chosen to be consistent with the rates used by vegetable growers in the Holland Marsh. Grower practice of spreading cover crops varies. Barley is often broadcast- seeded, as is a cover crop mixture such as NITRO Plus. Daikon radish is often seeded with a seed drill (K. Vander Kooi personal communication). The NITRO Plus is a mixture of legumes, cereal grains, and radish which includes six different species: 5% faba bean (*Vicia faba* L.), 10% nitro radish (*Raphanus sativus* L. *var. longipinnatus*), 15% crimson clover (*Trifolium incarnatum* L.*)*, 10% Austrian winter peas (*Pisum sativum* L.), 10% forage peas (*Pisum sativum ssp. arvense* L. Poir.)*,* and 50% oat. In 2021, cover crops were broadcast seeded using 50 lb (22.7 kg) light duty broadcast spreader on 21 September into lightly disked soil. An additional 10% (by weight) of extra seed was used to compensate for any probable low crop establishment during broadcasting. In 2022, cover crops were seeded with row spacing of 15 cm using a CASE 5100 seed drill at a depth of 3-5 cm into lightly disked soil on 22 September.

Cover crops after carrot

Carrot, cv. Navedo was seeded on 26 May in 2022 and 17 May in 2023. Timings for pre- and post-harvest seeding, carrot harvest, and sampling are shown in Table 1. Carrot was mechanically harvested both years. The treatments were: bare ground (control), over-seeding of barley into the carrot canopy before carrot harvest at 420 seeds m^{-2} (pre-harvest barley), barley seeded after carrot harvest at 210 seeds m^{-2} (barley) and fall rye seeded after harvest at 210 seeds m^{-2} (fall rye). Seeding rates were determined based on common farmer practice using barley as a cover crop, and suggested seeding rates from seed dealers for fall rye. The high seeding rate of barley seeded prior to carrot harvest was selected knowing that there would be significant loss of plants during mechanical carrot harvest. Barley and fall rye seeds were obtained from a local farmer. Pre-harvest seeding was done using a broadcaster since using a seed drill was mechanically not feasible into the field with growing carrots. Post-harvest seeding of barley and fall rye was done using a CASE 5100 seed drill to a depth of 3-5 cm into lightly disked soil at 15 cm row spacing.

Cover crop species and techniques for rapid cover crop

Field trials were conducted to assess methods for rapid establishment of cover crops after carrot harvest. The size for each experimental unit was 1.5 m x 4 m. The 11 treatments were: non-primed and hydro-primed oat (cv. CDC Haymaker), barley, and spring triticale, osmo-primed triticale, fall rye, daikon radish (*var. longipinnatus*), and barley and alyssum grown in plugs that were transplanted at the start of tillering and when the top growth filled the plugs cell, respectively, at the same time as other crops were seeded. Barley and fall rye seeds were bought from a grower. Oat and triticale were purchased from Speare Seeds Ltd. (Harriston, ON), daikon radish from Quality Seeds Ltd. and alyssum from PanAmerican Seed North America and International (Chicago, USA). Plugs of barley and alyssum were grown in the greenhouse at the Ontario Crops Research Centre-Bradford. The greenhouse had natural light and heating to maintain night temperature at or above 15^{o}C. Two barley seeds were hand-seeded to a depth of ~ 3.5 cm into each cell of 128-cell plug trays filled with soilless mix (ASB Greenworld Seed and Plug Mix) on 19 and 25 September in 2022 and 2023, respectively. One multi-seed pellet of alyssum was seeded on the surface in each cell of 128-cell plug trays on 12 September 2022 and 22 August 2023. Alyssum plugs were transplanted into 48-cell plug trays, on 25 September in 2023. An earlier seeding (by 20 days) was done in 2023, as the alyssum plugs did not grow enough for transplanting in 2022.

De-ionized water was used for hydro-priming and potassium nitrate (KNO_3) solution at 5 g L^{-1}(Junhaeng et al. 2015) was used for osmo-priming. Priming was done by soaking seeds for 24 h at room temperature (~ 22°C). After 24 h, seeds were taken out of the priming solutions, thoroughly rinsed with de-ionized water, and left to air dry overnight at room temperature. Both primed and non-primed seeds of barley, oat, and triticale, and non-primed fall rye seeds were direct seeded at 210 seeds m^{-2} using an Earthway push cone seeder on 14 October in both 2022 and 2023. Daikon radish was seeded at 90 seeds m^{-2} on the same day using the same method. Barley and alyssum plugs were transplanted by hand using trowels at 8 and 15 cm plug-to-plug distance, respectively same day. The between row distance was 15 cm for all treatments.

Sampling and measurements

Cover crop biomass sampling was done before the weather became cold enough for frost to kill the cover crop. Cover crops after onion were assessed on 2 and 9 November in 2021 and 2022, respectively, while cover crops after carrot were assessed on 11 and 13 November in 2022 and 2023, respectively. Percent canopy coverage, plant above-ground biomass (dry weight), and plant counts were evaluated for all trials. A 0.25 m^2 quadrat was used for sampling the aboveground biomass in all trials. Quadrats were randomly placed in each replicate plot at one quadrat for trials to assess cover crop species and techniques for rapid cover crop establishment, two quadrats for cover crops after onions, and three quadrats for cover crop after carrots. Plants were cut at ground level and both fresh and dry weight of samples were assessed. Sampling was done avoiding the area 1.5 m from the plot edge to prevent the edge effect in trials with a larger plot size (cover crops after onion and carrot). For small plot trials (cover crop species and techniques for rapid cover crop establishment), sampling was done avoiding the row closest to the edge of the plot. Sub-samples from each quadrat within a plot were pooled for biomass evaluation. For dry weight, samples were dried at 60℃ for three days. The samples included dead and living plant material. Plants within each quadrant were counted to assess plant counts.

Canopeo, a mobile cell phone application developed at Oklahoma State University, was used to assess percent canopy coverage (Patrignani and Ochsner 2015). It is a non-destructive method of assessment that uses image analysis to provides the average percent canopy coverage of the image as an output (Patrignani and Ochsner 2015). The percent canopy cover was measured in two areas in each replicate plot. Canopy readings were taken using a smartphone camera (Apple iPhone 11), held 80-100 cm above the cover crop canopy and parallel to the ground as explained on the official website https://canopeoapp.com/.

Statistical analysis

Data were subjected to mixed model analysis of variance (ANOVA) using the lmer function from the lme4 test package (Bates et al. 2015) in R Software version 4.1.0. Cover crop treatments for all fields trials were the fixed effect and blocks the random effect. A two-way ANOVA was used to determine if the data from two years could be pooled. Data from the two years were pooled whenever no significant interactions between year and treatment were found. Before conducting ANOVA, all assumptions for the model were assessed and met which included that experimental errors were random, normally distributed, independent of treatments and design effect, had common covariance (homogenous) and had a mean of 0. The F-statistic ($p < 0.05$) was used to test the significance of different treatments in ANOVA. Mean separation was carried out using Tukey's Honestly Significant Difference test at a 5% level of significance. Relationships between the average percent canopy coverage and aboveground biomass were estimated using Pearson's correlation coefficient at $\alpha = 0.05$ using the cor function in R.

RESULTS

Temperature and rainfall

The weekly average temperature and rainfall for the period when cover crops were grown in the field, from 21 September to 15 November, were recorded (Fig. 1). The site had total precipitation of 209 mm, 64 mm, and 39 mm and average temperatures of 10.7°C, 9.4°C, and

9.8°C during the cover crop growing period in 2021, 2022, and 2023, respectively. The first two weeks of November were warmer in 2022 as compared to 2021, 2023, and 10-years average temperature, while the first two weeks of October were warmer in 2021 than in 2022-, 2023-, and 10-years average. There was a notably heavy rain during the first week after cover crop seeding in 2021 (Fig. 1).

Cover crops after onion

Daikon radish was not included in the combined analysis for the two-year data as it was accidently killed in the 2021 trial because of an application of oxyflorfen (GOAL 2XL, 240 g ai L^{-1}) herbicide at 140 mL ha^{-1}. The two-way ANOVA on cover crop treatments and year showed no significant interactions for percent canopy coverage and plant counts, while there was a significant interaction of cover crop treatments and year for dry weight (Table S1). Therefore, the data on percent canopy coverage and plant counts from the two years were pooled for analysis. Even though seeding method changed from broadcasting to seed drill between years, plant counts were not significantly different between the years. The barley (55 ± 4.99%) and barley/daikon radish mix (60 ± 4.99%) had greater percent canopy coverage than NITRO Plus (40 ± 4.99%) (Fig. 2). Both the barley (890 ± 71 kg ha^{-1}) and barley/daikon radish mix (970 ± 71 kg ha^{-1}) had significantly higher dry weight as compared to NITRO Plus (490 ± 71 kg ha^{-1}) in 2022 (Fig. 3). The biomass of barley and the barley daikon radish mix was higher in 2022 than in 2021 (Fig. 3). A separate analysis on the 2022 data including the daikon radish treatment showed higher canopy coverage and dry weight of barley/daikon radish mix and barley compared to NITRO Plus and daikon radish (Table S2). Pictures of all the treatments in 2022 taken before the sampling are shown in Fig. S1.

Cover crops after carrot

There were significant interactions of cover crop treatments with year for percent canopy coverage and dry weight, but no interaction of cover crop and year on plant counts. Plant count was significantly affected by cover crop treatment and year (Table S1). Percent canopy coverage ranged from 4% for fall rye in 2023 to 20% for pre-harvest barley in 2022 (Fig. 4A). Similarly, barley produced the lowest dry weight (32 ± 11.5 kg ha^{-1}) in 2022, and pre-harvest barley had the highest dry weight (176 ± 11.5 kg ha^{-1}) in 2023 among all treatments and years (Fig. 4B). Percent canopy coverage and dry weight were significantly higher for pre-harvest barley for both years when compared to other treatments in the same year (Fig. 4A and B). Dry weight was significantly higher in 2022 when compared to 2023 for all treatments. The pre-harvest barley treatment had a significantly higher plant count compared to barley and fall rye after harvest. Plant count was significantly higher in 2023 compared to 2022 (Fig. S2). Pictures of all the treatments in 2023 taken before the sampling are shown in Fig. S3.

Cover crop species and techniques for rapid cover crop establishment

Alyssum plugs did not establish in 2022, so this treatment was not included in the combined analysis of the two years of data. There were significant interactions of cover crop treatment and year for percent canopy coverage, plant counts, and dry weight (Table S1). Percent canopy coverage was significantly higher for the barley plugs than other treatments across both years (Table 2). Similarly, dry weight of barley plugs was higher compared to other treatments except alyssum plugs (Table 2 and S3). Alyssum plugs produced comparatively higher dry weight (Table S3) as they were seeded in a greenhouse about two months earlier than the direct seeded treatments. Among the direct seeded treatments, the non-primed barley had the highest dry weight and percent canopy coverage (Table 2). Overall, for both years, percent canopy coverage ranged from 1.5 ± 1.2% for alyssum plugs and daikon radish in 2023 to 31 ± 1.2% for barley plugs in 2022. Dry weight was highest for barley plugs (200 ± 7.8 kg ha^{-1}) in 2022 followed by alyssum plugs (171 ± 7.8 kg ha^{-1}) and non-primed barley (111 ± 7.8 kg ha^{-1}) in 2023 among all treatments and years (Table 2 and S3). Additionally, oat, primed triticale, and daikon radish had lower stand counts than rye and non-primed barley in 2022 (Table 2). Pictures of all the treatments in 2023 taken before the sampling are shown in Fig. 5.

Canopy coverage and above ground biomass

There were significant positive correlations between percent canopy coverage and dry weight of cover crops for all trials. However, in the case of alyssum plugs, data points within a circle in Fig. 6 C and D, had comparatively higher biomass but lower canopy coverage. These plugs were seeded about two months before transplanting into the field. Results were similar when data were combined from all field trials and years (Fig. 6).

DISCUSSION

Reducing or preventing wind erosion is crucial for preserving the muck soil in the Holland Marsh, Ontario, particularly when the soil surface is bare and dry. Soil erosion can be reduced by protecting soils from direct exposure to wind, reducing wind speed, and binding soils more firmly by using cover crops (Fryrear 1985; Stevens and Quinton; Blanco-Canqui et al. 2015). While some farmers in the Holland Marsh grow cover crops after onions or leafy vegetables, growing cover crops after carrot harvest is uncommon because there are few or no crops that will establish and grow when seeded in October or November.

In field trials exploring cover crops following onion harvest, barley alone or a barley/daikon radish mix outperformed daikon radish and the NITRO Plus cover crop mixture for percent canopy coverage and aboveground biomass in one of the two years (Table S2).

Barley is a grass species with a fibrous root system that can effectively bind soil particles, helping to reduce soil erosion. Furthermore, its higher carbon-to-nitrogen (C:N) ratio slows decomposition rate, maintaining residue on the soil surface longer than legumes (Blanco-Canqui et al. 2015). This prolonged ground cover is important to minimize soil loss from wind erosion. Daikon radish produces deep taproots and dies over winter, leaving large channels in the soil that enhance water infiltration and create favorable conditions for early spring seeding or planting (OMAFA 2023a). Therefore, using a barley/daikon radish mix as a cover crop after onions seems more beneficial than barley alone. Similarly, non-primed barley in field trials for cover crops after carrots outperformed all other direct seeded treatments. Field observations and discussions with farmers also showed that barley is the most used cover crop species grown after onions or carrots in the Holland Marsh. The minimum and optimum cardinal temperature for spring barley, spring oat, and fall rye are 0.02°C and 20°C (Cao and Moss 1989), 4°C and 22°C (Mantai et al. 2017), and - 4.5°C and 25°C (Pessotto et al. 2023), respectively. Spring barley is also considered very effective in reducing soil erosion because it is fast-growing. Barley is comparatively more frost tolerant than other warm season cover crops such as sorghum and pearl millet and continues producing biomass until December before it is winter-killed (Bilbro 1989). The current research confirmed what growers have discovered on their own. Barley is a strong choice for a cover crop in the Holland Marsh because of its reliable establishment and growth, providing valuable protection against soil loss by wind erosion.

The findings that the NITRO Plus mixture did not perform well compared to barley or the barley daikon radish mix in the Holland Marsh) is in line with the findings of Elhakeem et al. (2021) based on experiments done on sandy and sandy clay soils in the Netherlands and Germany. They found no difference in aboveground biomass produced by cover crops seeded as pure stands or in mixtures and suggested that, if the best performing species of cover crop is known for a specific region, then this species planted alone can produce equivalent or better results than a cover crop mixture in that area.

Pre-harvest seeding of barley into the carrot crop provided higher stand counts, canopy coverage, and dry weight compared to fall rye or barley seeded post-harvest). Seeding the pre-harvest barley 9 and 21 days earlier than post-harvest treatments provided an additional 49 and 168 GDD in 2022 and 2023 respectively. Studies show a positive correlation between cover crop biomass and GDD, as expected (Brennan and Boyd 2012; Baraibar et al. 2018). Moreover, the higher seeding rate for pre-harvest barley (420 seeds m^{-2}) as compared to 210 seeds m^{-2} for barley and fall rye post-harvest, could have contributed to better performance for this treatment. Other than the broadcast seeding, there were no additional field passes required for this treatment. The field was leveled and compacted using a roller after carrots were harvested, which is the usual practice. So, if adopted, pre-harvest broadcast seeding will be the only extra work added to establish cover crops after carrots. Barley was seeded 8- and 17-days before carrot harvest in 2022 and 2023 respectively, indicating that the seeding date can take place about one to two weeks before mechanical carrot harvest, but future research might optimize the seeding date. The cost associated with a higher seeding rate may not be a concern for farmers producing high value crops such as onions and carrots.

There was no difference between spring barley and fall rye in canopy coverage, plant counts, and dry weight after carrots. This is crucial for Holland Marsh farmers as using winter species such as fall rye as a cover crop could delay onion seeding and cause production loss the following year (Mondal et al. 1986). Use of fall rye as a fall cover crop can also affect carrot productivity. Total and marketable carrot yield decreased in the plots where fall rye was grown the previous year compared to other cover crops such as mustard and pearl millet that do not over winter (Pandey 2024). Research shows, if a vegetable crop is seeded less than two weeks after fall rye is terminated, decomposing fall rye may exhibit an allelopathic effect on vegetable crops, leading to seedling decay and seed maggot damage (Stivers et al. 1999). Thus, cover crops such as barley, which does not overwinter, fits better into the production system as it will not interfere with onion seeding the following spring. However, if different crop rotations are considered in the future that do not require early spring seeding after a cover crop, fall rye may be considered as an effective cover crop option for the Holland Marsh.

In field trials on seed priming and barley and alyssum transplants, barley transplants outperformed other treatments for canopy coverage and dry weight, as expected (Table 2). This approach could be optimal for cover crop establishment after carrots, however, the cost, time, and labor involved in growing and transplanting barley are concerns. This treatment was included as a proof-of-concept and not as a treatment expected to be immediately adopted by growers in the Holland Marsh. Growers in the area are starting to look at agricultural robots for seeding, spraying and cultivating, and autonomous robots for transplanting vegetables are being developed and tested. If these robots become commonly available in the future, they could be used to transplant cover crops in the Fall when they are not needed for other tasks. Conversely, alyssum plugs did not establish well and produced lower canopy coverage compared to barley plugs (Table S3). Additionally, alyssum seeds are significantly more expensive than barley seeds making it a more costly option. Alyssum also needs many more weeks of growth in the greenhouse before it is ready for transplanting, which would increase costs. It is frost tolerant but did not grow quickly in cool temperatures.

Seed priming did not improve emergence or canopy coverage in the 2022 field trial for all three species, and only for primed oat in 2023, although the effects were seen in growth room trials. In a growth room trial, seed priming for 24 h resulted in early germination or emergence of barley, oat, and triticale at lower temperatures (5°C) (Pandey 2024). The varying temperatures in the field conditions compared to the consistent temperatures in the controlled environment may have contributed to the differences in results between field and growth room. Lower plant counts were also confirmed for all three species in the 2022 trial and for barley in 2023 in the primed seed treatment compared to the non-primed seed treatment (Table 2). Future research to assess the potential of seed priming including different methods and priming times would be useful.

The current study confirmed that early planting, in late August or early September, of cover crops after onions in the Holland Marsh allows for good establishment because of the greater GDD for cover crop growth and biomass production. Establishing cover crops in October after carrot harvest is very challenging due to low temperatures. Previous studies showed that covering 30% of soil with flat residues lying on the surface can reduce erosion by 70% (Fryrear et al. 2000). In trials on cover crops after onions, the percent canopy coverage ranged from 34 to 76%, and was notably higher than 30% for all treatments during both years. However, in both trials on cover crops after carrots, only barley plugs produced canopy coverage above 30% (31%) in 2022. However, there are studies that show percent canopy coverage of 10-15% is also helpful in reducing wind erosion, if the canopy is provided by living cover crops instead of flat residues (Lancaster and Baas 1998; Munson et al. 2011). In both years of the current trial, pre-harvest broadcast seeding of barley produced canopy coverage of greater than 10% (20% in 2022 and 12% in 2023) indicating this could be a useful method of establishing cover crops in the Holland Marsh in carrot production.

The significant positive correlations observed between percent canopy coverage and dry weight of cover crops across all trials showed that canopy coverage is a reliable indicator of biomass (Rosen et al. 2024; Prabhakara et al. 2015). Measuring canopy coverage using the Canopeo App is simple, efficient and inexpensive compared to biomass measurement (Patrignani and Ochsner 2015). Future research includes evaluating more species of cover crops for use after onions; these may include species such as buckwheat, hairy vetch, sorghum, clover (red and white), peas (forage and field), sunflower, turnips, faba bean, and phacelia, which are commonly grown cover crops in Ontario, (Morrison and Lawley 2020). Future research could also explore different broadcasting dates and seeding rates, to find the growth stage of barley that would be least affected during mechanical carrot harvest. Additionally, other potential species of cover crops such as oat, triticale, and red clover can also be tested for this approach.

CONCLUSION

The best cover crops for seeding after onion in the Holland Marsh in early September were barley and a barley/daikon radish mix. Barley is the most commonly used as a fall cover crop in the Marsh, so these results confirmed the experience of the growers. Some growers are using oat, purple top turnips, or daikon radish and these establish well, but are probably seeded earlier than in the current trials. For carrots, pre-harvest broadcasting of barley at a high rate, one to two weeks before carrot harvest, could be used for late fall establishment of the cover crop. The use of spring barley that dies over the winter is consistent with the expectations of farmers. They do not want a cover crop that will have to be controlled in the spring and potentially cause a delay in onion seeding. Barley transplants were effective as a cover crop after carrots but are not recommended at this time because of the associated labor and cost. Seed priming did not improve emergence or cover crop growth over the two years of the field experiment.

In conclusion, barley or a barley/daikon radish mix is recommended as cover crops for seeding in early to mid-September, consistent with grower practice. Growers are encouraged to try pre-harvest seeding of barley into carrots one to two weeks before harvest, to establish a cover crop after carrots. Priming the seed of cereal crops did not improve emergence or growth under field conditions. Transplanting barley plugs is effective but is not practical currently. It may have a place in the future if there is wider use of agricultural robots that could do the transplanting.

COMPETING INTERESTS

The authors have no competing interests that might bias these results.

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DATA AVAILABILITY

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Table 1. Seeding date of different treatments before and after carrot harvest, carrot harvest date, and sampling dates for cover crops.

Year	Pre-harvest seeding	Carrot harvest	Post-harvest seeding	Sampling
2022	28 September	5/6 October	7 October	11 November
2023	26 September	12/13 October	17 October	13 November

Table 2. Percent canopy coverage, plant counts, and above ground biomass (dry weight) of cover crops seeded after carrots in the Holland Marsh in 2022 and 2023.

Treatments	**Canopy coverage (%)**	**Plant counts m^{-2}**	**Dry weight (kg ha^{-1})**
	2022		
Hydro-Oat	2.6 abc[a]	71 a	22.5 a
Oat	2.6 abc	98 ab	25.8 a
Osmo-Triticale	3.5 bcd	96 ab	32.2 ab
Hydro-Triticale	4.2 cde	77 a	33.8 ab
Triticale	5.9 d-g	191 cd	55.8 bc
Daikon radish	6.9 e-h	86 a	61.6 c
Fall rye	9.5 f-i	233 def	78.5 cd
Hydro-Barley	10.5 ghi	182 bcd	82.9 cd
Barley	11.5 hi	233 def	87.0 cd
Barley plugs	31.2 k	137 abc	268.8 e
	2023		
Daikon radish	1.5 a	80 a	28.6 a
Oat	2.1 ab	142 abc	25.0 a
Triticale	3.3 bcd	186 bcd	31.8 ab
Hydro-Oat	5.1 def	196 cde	51.9 bc
Hydro-Triticale	5.1 def	198 cde	55.7 bc
Osmo-Triticale	6.2 d-h	219 c-f	62.2 c
Fall rye	9.5 f-i	308 f	90.6 cd
Hydro-Barley	10.7 ghi	192 cd	87.9 cd
Barley	13.7 ij	286 ef	111.3 d
Barley plugs	24.9 jk	132 abc	200.9 e
SE[b]	1.2	18.8	7.8

[a] Numbers in a column followed by same letter are not significantly different at P = 0.05, Tukey HSD test. [b] Standard error of the means.

FIGURE LEGENDS

Fig. 1. Weekly average temperature, and rainfall from 21 September to 15 November**,** during cover crop growth for the year 2021, 2022, and 2023 the Ontario Crop Research Centre-Bradford.

Fig. 2. Mean (+/- SE) percent canopy coverage of cover crops seeded after onion at Ontario Crops Research Centre- Bradford, data from 2021 and 2022 pooled. Within a comparison, bars topped with different letters are significantly different based on a Tukey–Kramer test ($p < 0.05$).

Fig. 3. Mean (+/- SE) above ground biomass (dry weight in kg ha^{-1}) of cover crops planted after onion harvest at the Ontario Crops Research Center-Bradford for the years 2021 and 2022. Bars topped with different letters are significantly different based on a Tukey–Kramer test ($p < 0.05$).

Fig. 4. Mean (+/- SE) percent canopy coverage (A) and above ground biomass (dry weight) (B) of cover crops seeded after carrots at Ontario Crop Research Centre- Bradford for 2022 and 2023. Bars topped with different letters are significantly different based on a Tukey–Kramer family-wise error rate of $p < 0.05$.

Fig. 5. Barley transplants (A), non-primed barley (B), hydro-primed barley (C), fall rye (D), osmo-primed triticale (E), hydro-primed triticale (F), hydro-primed oat (G), triticale (H), oat (I), daikon radish (J), and alyssum plugs (K) planted in the Holland Marsh in 2023. Planting date: 14 Oct 2023, picture date: 13 Nov 2023.

Fig. 6. Pearson correlation scatter plot with fitted regression line and 95% confidence interval, showing correlation between above-ground dry biomass (dry weight) and percent canopy coverage by cover crop treatments for field trials comparing cover crops planted after onions (A) and carrots (B), seed priming and barley transplant trial (C), and overall, for all trials (D) at the Ontario Crops Research Center-Bradford. Data points within the circle in Figure C and D are for Alyssum plugs.

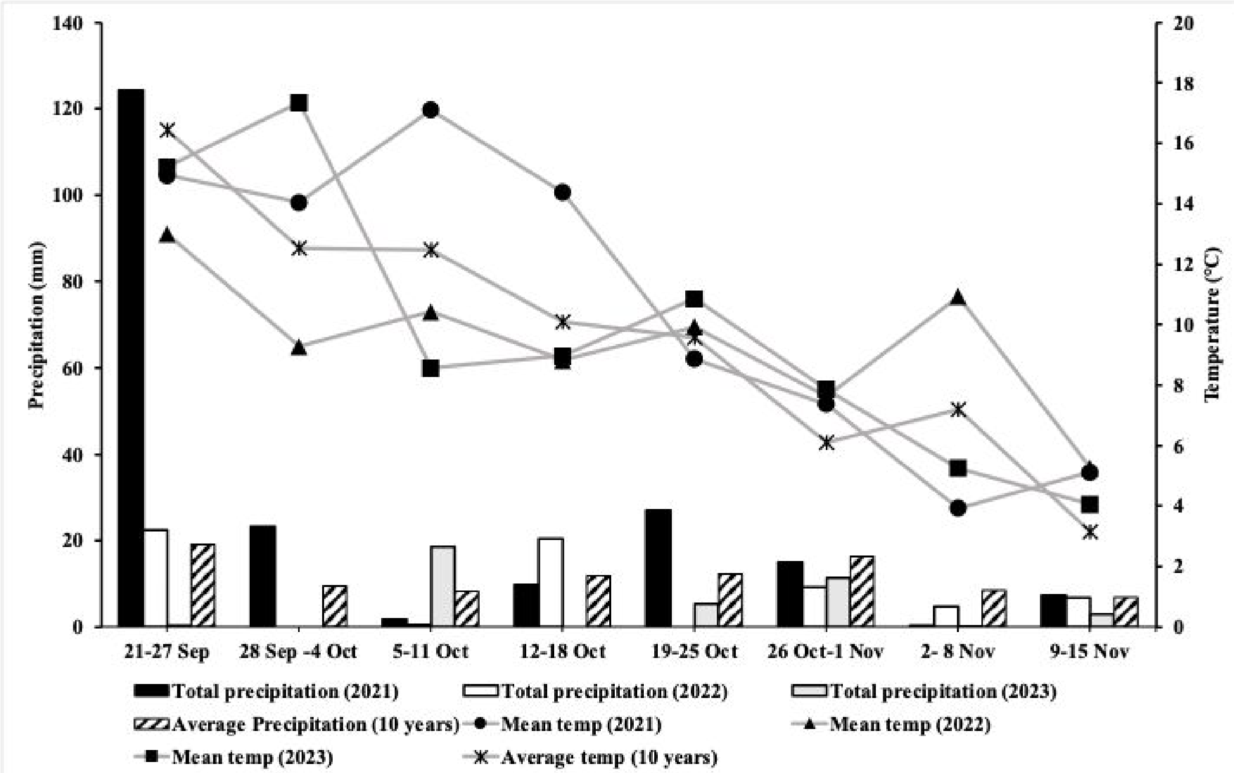
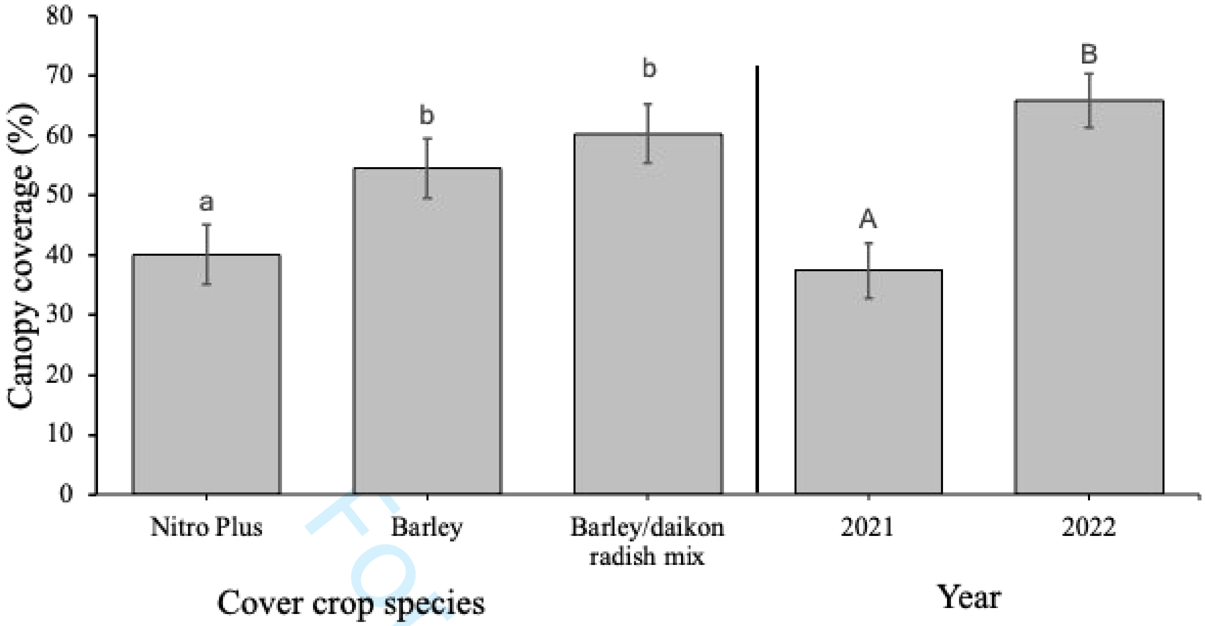


Fig. 1. Weekly average temperature, and rainfall from 21 September to 15 November**,** during cover crop growth for the year 2021, 2022, 2023, and ten years (2014 to 2013) average in the Ontario Crop Research Centre- Bradford



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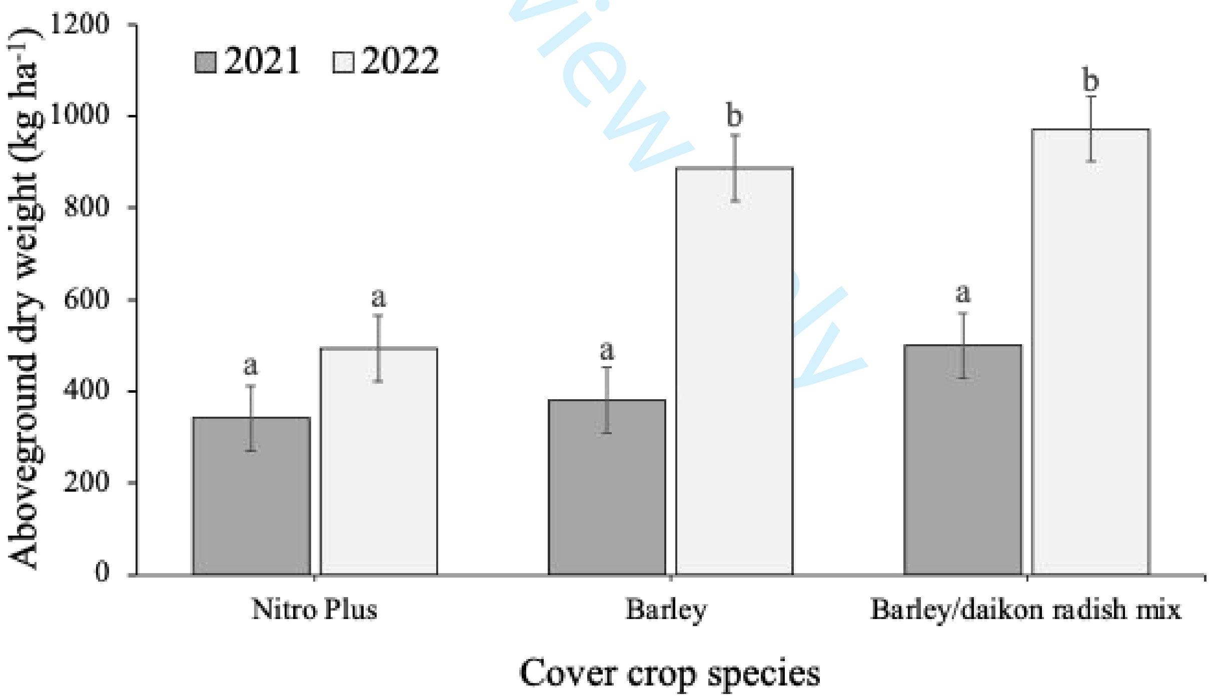

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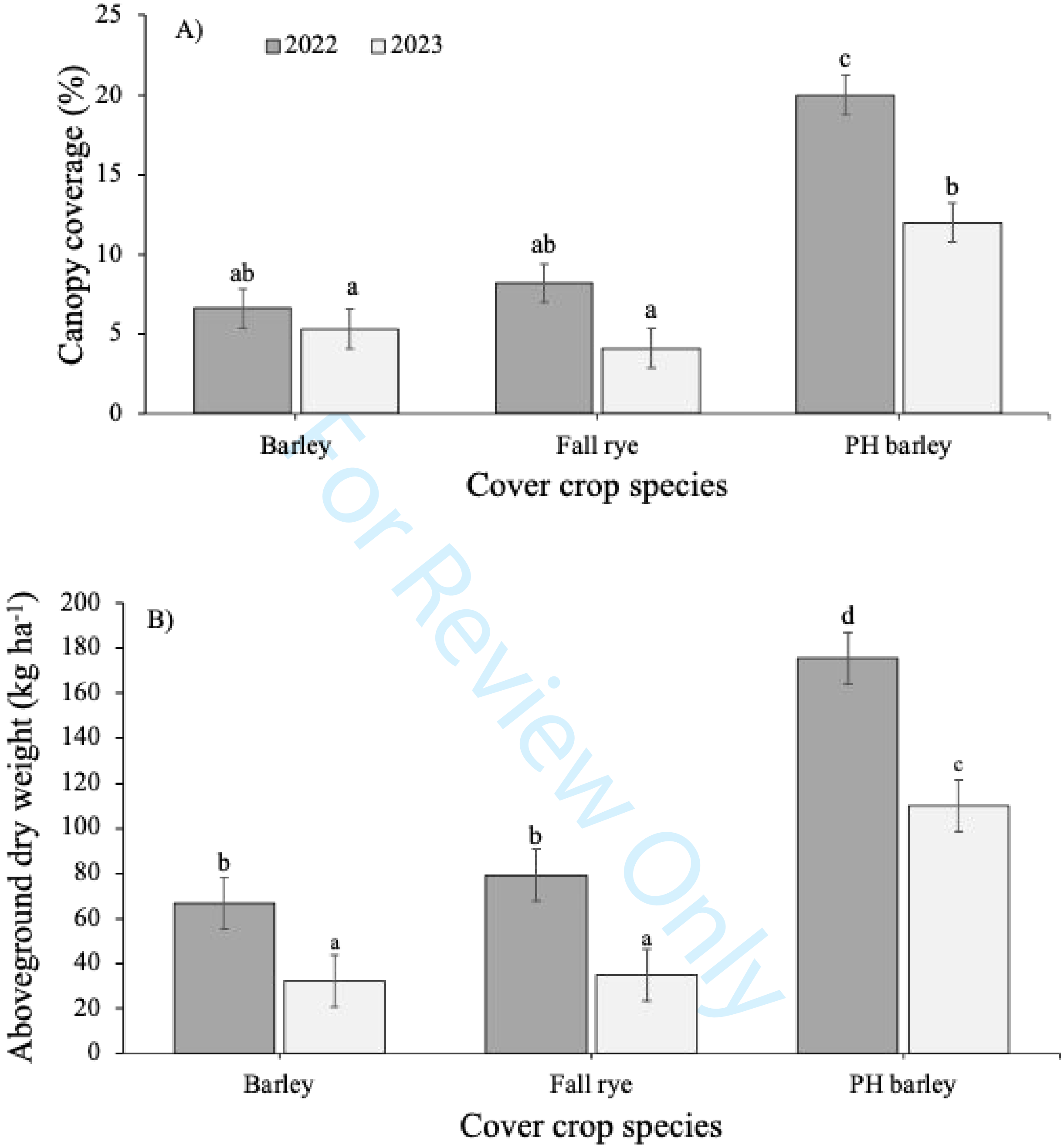

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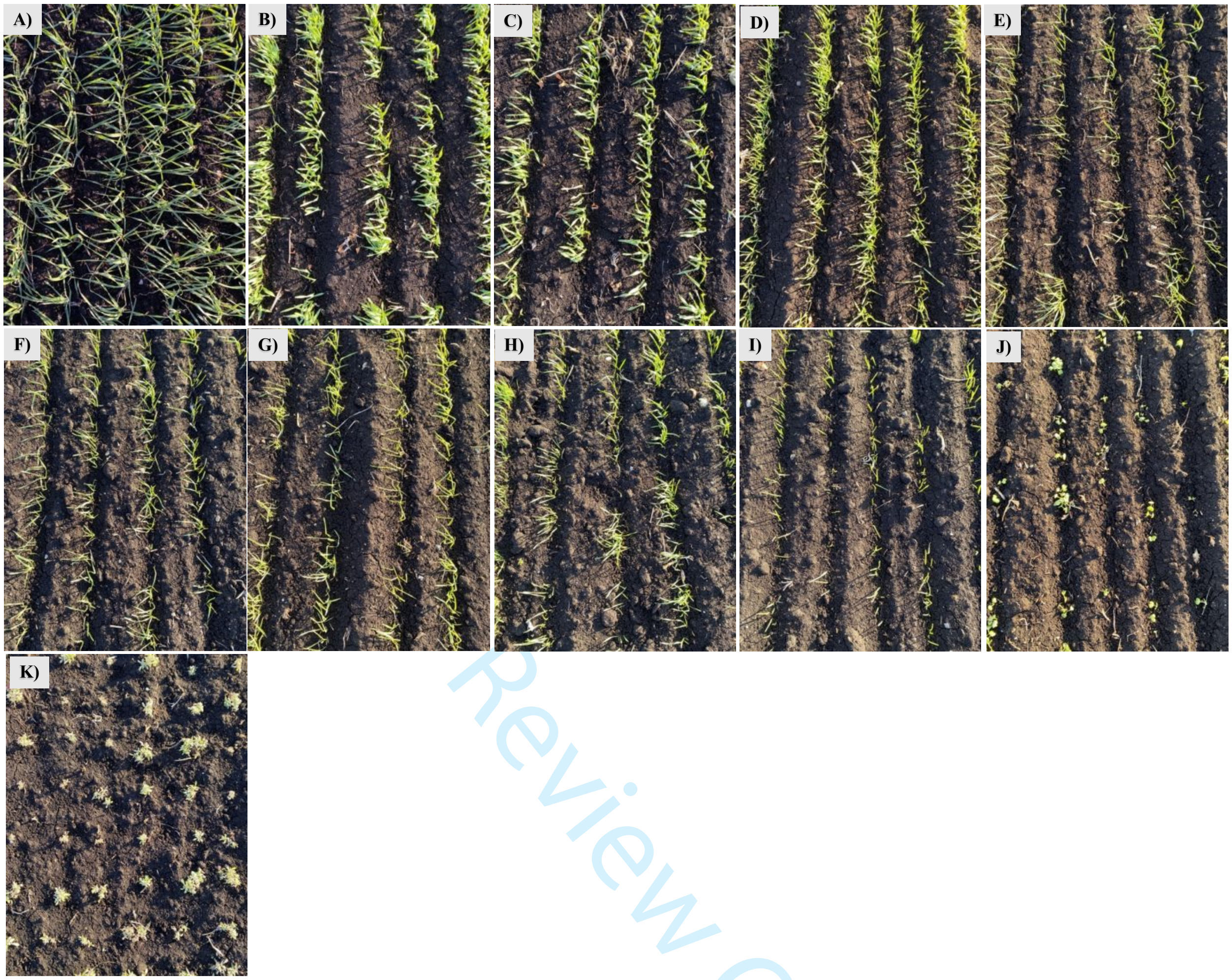

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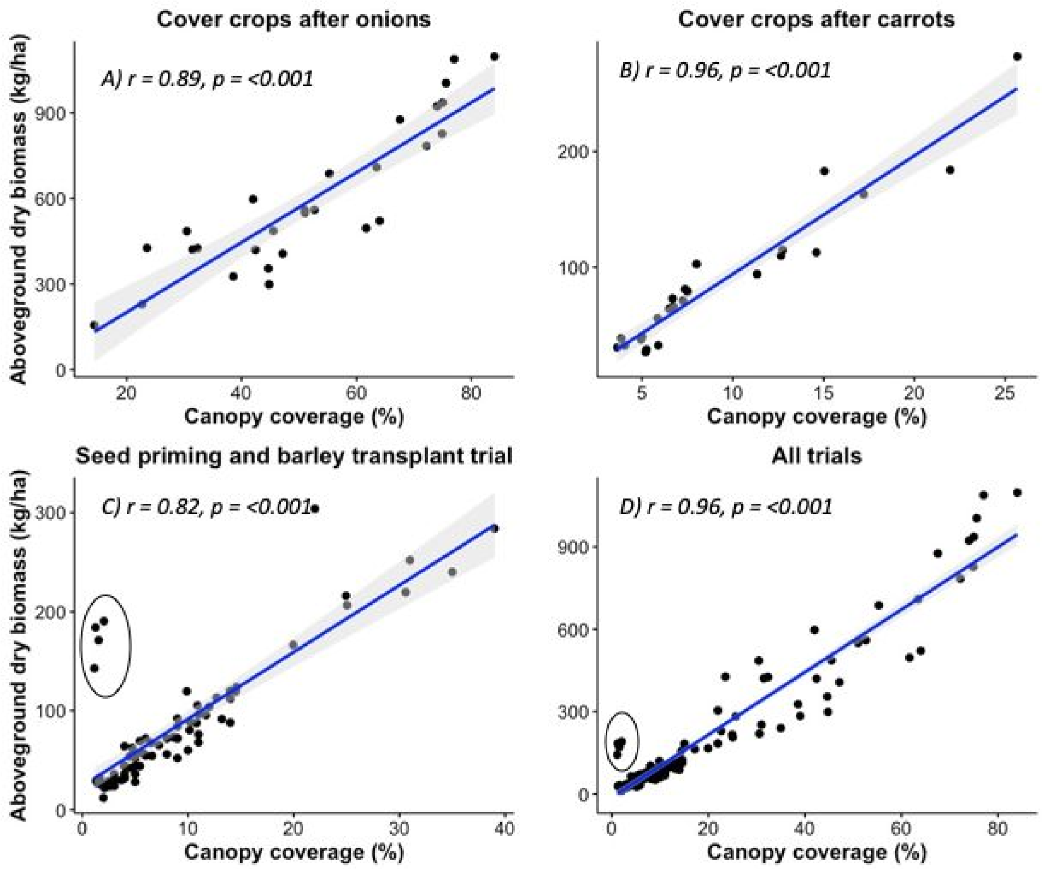

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