CLIMATE CHANGE
ADAPTATION PROGRAM

Too Much Water or Too Little: Climate Resilient Vegetable Farming

Project Report

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Executive Summary

The climate patterns that farmers have learned to manage are starting to break down globally. In British Columbia shifting precipitation patterns are becoming increasingly unpredictable and volatile. Wetter spring and fall shoulder seasons are impeding farmers' ability to prepare and harvest their fields while warmer drier summers challenge their ability to provide their crops with sufficient water during the production season. We designed this project to identify practices that would improve organic vegetable farmers capacity to adapt to these changing conditions of too much or too little water. Over a three-year period we evaluated the field performance of a suite of novel soil management practices relative to, and in combination with, existing practices, on soil-water dynamics in a coordinated set of studies that includes controlled replicated experiments, and on-farm regional trials. Specifically, our project objectives were to:

- **Objective 1:** Quantify the effects of overwinter cover on soil physicochemical properties
- **Objective 2:** Evaluate the interaction between overwinter cover and three nutrient amendment strategies on plant available nitrogen, volumetric water content and crop yield
- **Objective 3:** Investigate the interactions between amendment application timing and tile drainage spacing on their effects on soil moisture and salinity and crop yield

A combination of experimental and regional trials allowed for the comparison of management strategies under realistic conditions which is critical in evaluating their performance. Field trials were conducted on 15 organic-practicing farms in BC to evaluate overwinter cover options, amendment application rates and timing and tile drainage across a variety of climates and soil types. These trials are referred to as experimental and regional to describe differences in on-farm replication and controlled conditions. Three experimental (mother) sites hosted trials with on-farm treatment replication where fertility amendments, irrigation type, and crop type were controlled. Regional (daughter) sites hosted non-replicated trials with a subset of treatments where management decisions during the growing season were at the discretion of the individual farms. Both the experimental and regional trials began in October 2019. Data collection was completed in May 2021 in the regional trial and remained ongoing at two of the experimental trials through the end of the project, January 2023. Throughout this project, we engaged with participating farmers to ensure that our results were shared, discussed, and contextualized for their conditions as much as possible. Results were shared through annual project reports, presentations, podcasts, field days and videos.

Key project outcomes:

- The use of plastic silage over the winter conserved soil nitrate and provided a significantly greater source of plant available nitrogen in the spring relative to cover crops or bare fields.
- We observed no increase in soil salinity after two winters of silage tarp use.
- Silage tarps showed meaningful impacts on field soil water, keeping fields drier during the winter rains than uncovered fields and then wetter as the production season started in the spring.

- We observed no interaction effect on plant available nitrogen between silage tarp use and various amendment treatments. Amendment treatments had minimal impacts on crop yields.
- Tile drains at 15 ft spacing significantly reduced spring soil moisture and electrical conductivity compared to 30 ft spacing but had no interaction effect with compost either fall or spring applied.
- There were no significant differences in crop yields due to fall or spring applied compost.

1. Introduction

1.1 Climate change and organic vegetable production

The varying climates and ecological zones within British Columbia (BC) create a unique and diverse agricultural landscape. Common to all of BC's agricultural industries is their dependence on natural resources and favorable weather conditions for continued production. Climate change poses a threat to agricultural systems by increasing extreme weather events, shifting weather patterns, and generally creating an increased uncertainty to what the weather will bring next (Government of Canada, 2020). In the face of these challenges, building resilience into the agricultural system is key to adapting to these inchoate changes. Adaptation is imperative as agricultural systems are tasked with multifaceted goals, including the production of food, maintenance of biodiversity, and facilitation of ecological services. Maintaining soil health is central to the resilience of agricultural systems. The soil supports crop growth in a variety of ways, including structural support for root growth, supply of water, cycling and storage of nutrients, and providing habitat for organisms involved in decomposition and organic matter transformation (Brady & Weil, 2010).

While soil health is important for building resilience in all types of land-based agriculture, strategies for doing so will depend greatly on the type of production. Annual vegetable farms, particularly organic farms, tend to be diversified, growing a variety of different crops over the course of a growing season. Each of these crops may differ in the timing of planting, days to maturity, fertility requirements, and relationships with weeds, pests, and diseases. As organic production, these systems are mandated to be heavily reliant on biological sources of nutrients, which are typically sources from cover crops and/or composts and manures. This reliance creates an additional level of complexity that their conventional counterparts using synthetic sources of nutrients may not face as the availability of organic nutrients for crop production is mediated by microbial processes. Furthermore, organic vegetable systems are heavily reliant on tillage to transition from cover crops to production and to control weeds. The complexity of these systems is tied directly to their resilience but also creates management challenges for growers in terms of labor, equipment, and the maintenance or building of soil health.

Managing these biologically based, complex systems effectively is a dynamic process for growers. Much of how organic soil systems function or how to make them more efficient is relatively unknown. Most research funding and emphasis remains on conventional producers, and there is a growing demand for solutions to issues that are present in organic systems. This sentiment is clearly expressed by producers who identified evaluating the effects of organic management practices on soil health as a top priority (Jerkins & Ory, 2016).

Vegetable production, which takes place on ~6500 hectares (ha) within BC, is one of the agricultural industries experiencing the effects of climate change. Nationally, BC ranks third behind Ontario (48,660 ha) and Quebec (36,320 ha) in total area under vegetable production (Statistics Canada, 2016). The climate and soils of BC support the growth of a wide variety of vegetable crops including sweet corn, cole crops (e.g. broccoli, cauliflower, cabbage), beans, and carrots. Farm gate value of field vegetables grown in BC was $103 million in 2019 (Government of Canada, 2019). BC ranks third in total certified organic production in Canada behind Quebec (71.5%) and Ontario (14.8%) with 5.6% of the total Canadian organic production area equaling ~240 ha (Statistics Canada, 2020). This estimate is likely lower than the present reality because it excludes potato, greenhouse, and seed production, which are all important organic industries in BC. There are also many uncertified vegetable operations employing the fundamental principles of organic management that are not captured by these statistics. Despite the relatively small land area currently devoted to organic production, the demand for organic food in Canada continues to grow. Between 2011 and 2016, farms reporting as certified organic increased 4.1% across Canada (Statistics Canada, 2017). This increase mirrors the continued growth in demand for organic food in Canada as BC has the highest demand for organic goods per capita (Export Development Canada, 2020).

Organic production within BC is not evenly distributed geographically. The Lower Mainland – Southwest BC region accounts for 69% of BC's vegetable production and 26% of organic or transitioning farms representing the majority of both organic and non-organic production in the province. Comparatively, the Vancouver Island – Coast region accounts for 11% of the province's vegetable production and 16% of farms reporting as certified organic or transitioning, while the Kootenay Mountain region is responsible for 3% of total provincial production but 10% of the BC's organic production (Statistics Canada, 2016). While regions such as Vancouver Island and the Kootenay Mountains account for a small amount of total vegetable production area, they have comparatively high rates of organic production making them important yet underserved research areas.

The seasonal flow of annual production dictates the timing of soil and crop management. Organic vegetable production in BC operates with distinct on- and off-seasons. During the on-season or growing season typically beginning April-May and concluding as late as November, cash crops are grown in the field. The light and temperature conditions of fall and winter restrict the growing of cash crops. Further, most of the precipitation falls during the off-season, raising concern for soil erosion, compaction, and leaching of nutrients if soils are left fallow or otherwise unprotected. Shifting seasonal patterns of temperature and precipitation due to climate change are of consequence to established production systems. It is predicted that in BC the fall and spring rainfall will increase, less precipitation will fall as snow in the winter, and summers will become hotter and drier (Climate Action Initiative, 2015). These conditions exacerbate the soil management challenges for many organic growers and introduce new ones to others. Increased precipitation will alter growers' ability to work the soil with machinery without causing damage to the soil's structure because of increased soil moisture conditions. In organic agriculture, tillage is typically used to control weeds and prepare seedbeds because herbicides cannot be used for these purposes as they are on conventional farms thus making them particularly susceptible to shifting precipitation. Changes to soil moisture do not just affect tillage, for example, soil moisture has important impacts on soil biological functioning. Microbially-mediated processes in the soil, such as organic matter decomposition and nutrient cycling, are influenced by both soil temperature and moisture conditions, again making organic growers particularly susceptible to the impacts of climate change. Changes in weather patterns will alter the tools available to organic growers for soil management and the timing of their annual production systems, both potentially impacting crop yield.

In short term comparisons, organic agriculture trails behind the conventional model in terms of yield (Gomiero et al., 2011). While short-term yield increases may be achieved under an industrial agricultural system, it is also associated with socioenvironmental problems that undermine the ecological foundations of food systems (Martin & Isaac, 2015; Méndez et al., 2013; Tomich et al., 2011). Soil degradation, water contamination, greenhouse gas emissions, and loss of biodiversity rank among the detrimental impacts (Mostafalou & Abdollahi, 2017; Sage, 2011; Tillman et al., 2002). Nutrient management has been identified as one of the primary barriers to increased yield and is the topic of continued study (Seufert & Ramankutty, 2017). Information and tools are needed for organic growers to optimize yield while protecting the environmental underpinnings of production systems. These tools should be geared toward the challenges that are expected to be exacerbated by climate change. Because new tools and technologies developed to help farmers adapt to climate change with be utilized within their existing production systems, management suggestions born from research results require ground-truthing on working farms and validation by farmer participatory work with researchers. Collaboration between academic and grower communities can catalyze management innovations and farmer adoption of new techniques.

1.2 Types of winter soil cover used in organic agriculture

1.2.1 Cover crops

The use of cover crops is common in organic vegetable production, particularly in the off-season when few cash crops will survive in the field. Cover crops are defined as any plant species used to protect or improve the soil and are generally not harvested for sale. The benefits of cover crops to soil health are well documented (Eshel, 2015; Gabriel et al., 2013; García-González, 2018). Cover crops fulfill several of the principles known to improve soil health, including keeping the soil covered, encouraging living roots, and promoting diversity (i.e. with polyculture cover crops). The use of cover crops can improve soil aggregation (Hermawan & Bomke, 1997; Kabir & Koide, 2002), increase soil carbon (Liu et al., 2005; Reicosky & Forcella, 1998), improve N cycling (Parkin et al., 2006; Sullivan et al., 2019), reduce NO_3^- leaching (Nouri et al., 2022; Odhiambo & Bomke, 2001) and reduce erosion (Kaspar et al., 2001; Malik et al., 2000). Legume cover crops are known to be significant sources of N which is especially important in organic production which cannot use conventional fertilizers (Odhiambo & Bomke, 2001; Sullivan et al., 2019). For these reasons, cover crops are a staple practice of organic production.

Winter cover crops are beneficial in BC in part because of characteristic rainfall patterns, heavy winter precipitation put fields at risk of erosion and compaction if soil is left fallow (Odhiambo et al., 2012). In recognition of the impacts of heavy rainfall, more than 1600 farms in BC reported using winter cover crops in 2016 (Government of British Columbia, 2020). In BC, winter cover crops are typically established in the fall, left to hold in the field or to winter kill, and then are terminated by mowing and tillage in the spring prior to cash crop planting. Depending on the cover crop species and phenological stage at the time of termination, cover crops may take three to four weeks to decompose sufficiently to create the clean seed bed required for direct seeding. While their benefits are numerous, establishing and managing cover crops brings a suite of challenges for growers.

In South Coastal BC, cover crops must be established in early to mid-September for reliable establishment (Odhiambo & Bomke, 2007). When planted later in the fall, most species will not have adequate time to develop root systems capable of protecting the soil through the winter. At the same time, many vegetable crops continue to be harvested into October and November and are important sources of revenue for organic growers. Similarly, growers often want to reserve a portion of the field for early spring production. Under such circumstances, often there is no adequate time for cover crops to be terminated and decompose prior to planting the cash crop. On diversified organic vegetable farms, some portion of the field will likely be unsuitable for winter cover crops. Challenges with both fall and spring windows to manage cover crops are compounded by climate change and regional conditions. Increased shoulder season precipitation temporally aligns with key cover crop management, namely tillage. Tillage is traditionally required to move production fields from cash crop to cover crop and back again. However, there are soil moisture thresholds above and below which tillage is particularly damaging to soil health (Raper, 2005). The soil workability threshold depends on both soil texture and soil organic matter (Obour et al., 2017). When soils are above the soil moisture level threshold for tillage, they are at risk of compaction and loss of soil structure. There are also practical challenges of operating a tractor on wet ground when there is a risk of getting equipment stuck in the field. Increased precipitation that leads to wetter soils will likely shift the window of soil workability earlier in the fall and later in the spring, shortening the production season for growers. There are several regional challenges that limit the use of cover crops in BC. Migratory waterfowl can decimate cover crops in South Coastal BC leaving fallow fields in their wake. In the Kootenay Mountains, hard frost and snow cover shorten the timeline for cover crop establishment in the fall. With the challenges of production timing, climate change, and regional barriers to establishment, more overwinter cover tools are needed by growers. Alternatives to cover crops should similarly protect the soil from winter conditions and be suited to the scale and production models of organic farms.

1.2.2 Plastic silage tarps

Changes to soil moisture have led to innovations in winter soil cover, one being the use of plastic silage tarps, which are UV-resistant polyethylene, durable, and opaque. Originally developed for silage production, they are impermeable to water and typically black on one side and white on the other. Most growers who use silage tarps as soil cover place the black side up to facilitate solar radiation absorption and warm the soil (Kubalek et al., 2022). Silage tarps are held in place with rock bags, sandbags, concrete blocks, or other methods. Plastic silage tarps will be referred to as 'tarps' throughout this document, although it should be noted that a variety of plastic soil covers exist in organic production. Silage tarps were popularized by organic farms in Quebec, notably with Jean-Martin Fortier and Marie Bilodeau's publication of *The Market Gardener: A Successful Grower's Handbook for Small-Scale Organic Farming* in 2014.

Tarps fall under the suite of "plasticulture" practices that have become common since their initial introduction to North American agriculture in the 1940s (Orzolek, 2017). Plasticulture refers to the agricultural use of plastic products, including greenhouses, low tunnels, irrigation systems, mulch, and drainage tiles. In BC, silage tarps can be purchased new from agricultural distributors and suppliers across the province. There are also several avenues for sourcing used tarps, primarily second-hand from dairy or nursery operations. The lifespan of these tarps on organic farms is reported to be six or more seasons (Kubalek et al., 2022) which aligns with reports from BC growers. While reusable over multiple seasons, the use of plastic tarps does increase the reliance of small-scale farms on petroleum products which is an environmental concern as no current recycling options exist for BC growers and the pollution potential from microplastics and agrochemicals increases with tarp use (Steinmetz et al., 2016). Another concern with the prolonged use of plastic soil covers is the increase in electrical conductivity (EC). Research has shown that because impermeable plastics decrease water movement through the soil, salts can build up with fertilizer application having potentially detrimental impacts to crop yields (Hu et al., 2012).

Tarps serve several purposes as ground cover on organic farms. Two underlying mechanisms make these tarps useful for soil management: they inhibit photosynthesis and prevent water infiltration. Tarps can be used to clear new ground for production from hay or sod by being left in place for a year or more while plant matter dies and decomposes beneath them. In season, tarps can be used for weed control. When tarps are applied to tilled plot, weed seeds germinate and die within 3 weeks resulting in a 95-100% weed-free seedbed (Kubalek et al., 2022). Of emerging interest is the use of tarps in organic no- and low-till systems, particularly those that use cover crops. In the Pacific Northwest maritime climate, the use of high biomass cover crops for mulch causes several production challenges including low spring soil temperature, high weed pressure, and high pest occurrence (Kubalek et al., 2022). Black plastic tarps have been shown to increase yield in such systems by suppressing weeds and facilitating biological activity that leads to residue breakdown (Lounsbury et al., 2018; 2022). Tarps provide an alternative to between succession tillage for some crops; since tarps are generally applied after crop residue has been mowed. Tarps can also be used as overwinter cover with the aim to protect soil from erosion and prevent leaching of nutrients. Field trials in the Northeastern United States showed that overwinter tarp cover increased soil nitrate (NO_3^-) and beet yield (Rylander et al., 2020a; 2020b). Winter tarps may ameliorate tensions between fall and spring soil cover management. Tarps are not constrained to the same timing windows as winter cover crops. This allows vegetable production to begin earlier in the spring and continue later into the fall. Attempting to protect the soil from exposure over the winter, small-scale producers cover sections of fields that are ill-suited for a cover crop with plastic silage tarps (Rylander et al., 2020a). In BC, increased shoulder season precipitation is expected to continue to challenge successful overwinter cover crop establishment.

Studies have shown that tarps and plastic mulch may increase soil temperature and modulate soil moisture (Snyder et al., 2015), although most studies have investigated the impact of tarps employed during the growing season and often with under tarp irrigation (Canul-Tun et al., 2017; Gordon et al., 2008; Ruíz-Machuca et al., 2015). These studies primarily examine tarps through a lens of weed management and utilize semi-permeable fabrics or plastics (Chalker-Scott, 2007; Dong et al., 2018). Because of their impact on soil conditions, tarps alter soil processes such as decomposition and nutrient cycling (Brockett et al., 2012; Frey et al., 2013; von Lützow & Kögel-Knabner, 2009). Rylander et al. (2020a) indicated that long-term tarping may elevate concentrations of plant available nitrogen (PAN), this is of particular importance in the spring when temperature conditions inhibit microbial transformations of nitrogen (N). These results remain unverified in different agricultural regions defined by different winter conditions. Overall, there is a lack of information about the impacts of tarps when used as overwinter ground cover, particularly when winters are characterized by heavy rainfall. To date no studies have been published that measure the impacts of overwinter tarping in BC.

Winter cover is important to protect soil from the impacts of heavy fall and winter rainfall of South Coastal British Columbia (BC). In the temperate Mediterranean climate of the region, three quarters the annual precipitation falls between November and April (Government of Canada, 2021). The timing of this precipitation corresponds to the off-season for most vegetable growers when field production is limited by daylight hours, temperature, and soil moisture. Without the protection provided by crop above- and below-ground biomass, bare soil is susceptible to nutrient leaching and erosion. The loss of residual nitrate (NO_3^-) is of particular concern because it is highly mobile in the soil and prone to leaching; the severity of leaching is correlated with precipitation (Lu et al., 2019). Leaching contributes to the contamination of ground water resources and poses a threat to human and animal health. In the Lower Fraser Valley (LFV), agricultural contamination of freshwater aquifers and rivers from over-application of soil amendments has been repeatedly reported (Berka et al., 2001; Wassenaar et al., 2006). Climate change is altering precipitation patterns in BC and intensifying challenges associated winter soil cover for growers. Increased shoulder season precipitation increases NO_3^- leaching risk and shifts timing of soil workability.

1.3 Organic nutrient management

While most of the global N pool is found in the atmosphere as dinitrogen gas over 95% of N in the soil is held in an organic form as soil organic matter (SOM) (Berry et al., 2002). To become available for plant uptake, N must be mineralized into an inorganic form, namely ammonium (NH_4^+) or NO_3^-. N mineralization is a process mediated by soil microbes involving two primary steps orchestrated by different bacterial and archaeal species: organic N is first converted to NH_4^+ through ammonification and then NH_4^+ is converted to NO_3^- through nitrification (Brady & Weil, 2010). Levels of soil NH_4^+ are generally low because nitrification tends to proceed rapidly in the soil. NH_4^+ and NO_3^- ions tend to behave differently because of their opposite charges. NH_4^+ is generally not lost to leaching because it can be held by the net negative charge of soil colloids such as clay and organic matter. Conversely, NO_3^- is highly mobile and at a high risk of leaching with water percolation through the soil profile. Improved fertility management was identified as a top research priority for organic growers in 2016 by Jerkins and Ory.

One of the primary roles of the soil in supporting plant growth is to supply nutrients. Macronutrients, such as N and phosphorus, are absorbed by roots from the soil solution or acquired through microbial symbiotic relationships. The adequate supply of nutrients at the appropriate time is of primary concern to growers because there are environmental and economic impacts. N has been identified as a primary yield-limiting factor on organic farms (Berry et al., 2002). Insufficient fertility can lead to yield reduction, having negative economic repercussions for growers in a business with an already narrow return on investment. Excess application of N and P have been linked to damaging environmental impacts. N and P can contaminate surface and groundwater sources via run-off and leaching processes where they can cause eutrophication and human health issues (Chambers et al., 2001; Ward et al., 2018). The heavy winter precipitation that characterizes South Coastal BC creates a high risk of leaching residual N, particularly NO_3^-, left in the soil after the harvest of cash crops (Odhiambo et al., 2012; Zhang et al., 2019).

These environmental repercussions are observed in BC. The Lower Fraser Valley (LFV) in South Coastal BC is one of the most rapidly developing areas of Canada (Schreier et al., 2003), where high applications of both manure and commercial fertilizer are reported. In most areas applications rates are 200 to more than 300 kg N ha^{-1} yr^{-1} (Schindler et al., 2006). Nitrate concentrations in the Sumas River have increased steadily from 1970-2003 related to animal stocking density and surplus agricultural N application in the LFV (Berka et al., 2001). Leaching from agricultural fields amended with high rates of poultry litter has led to the contamination of the Abbotsford-Sumas Aquifer in the Lower Fraser Valley (Wassenaar, 1995). Beyond water contamination, N application can increase nitrous oxide emissions through denitrification processes (Sun et al., 2016); nitrous oxide is a potent greenhouse gas with 273 times the global warming potential of carbon dioxide (Forster et al. 2021). These environmental impacts highlight the tension between under and over application, N can be the most difficult nutrient to manage because it is highly mobile yet also needed in high quantities by plants.

Nutrient management strategies are a defining difference between organic and conventional farms (Oelhaf, 1978). Organic farms must use carbon-based fertility amendments, such as compost, manure (raw composted), and cover crops, and specialty organic fertilizers such as feather meal, bone meal, or seed meals. Compost, manure, and organic fertilizers can be spread in granular or bulk form on the surface of the soil. Cover crops contribute N in two ways, (1) N can be released from decomposing plant material after they are terminated and, (2) through N-fixing species such as legumes. N can also be made available by the decomposition and mineralization of soil organic matter (SOM); organic farms tend to have higher SOM because of their emphasis on carbon-based fertility amendments (Gomiero et al., 2011). While carbon-based soil amendments are used as fertility sources across agricultural models, conventional farms rely on annual applications of synthetic N fertilizers which are prohibited in organic production. Synthetic fertilizers are characterized by a quick release of plant available N (PAN) into the soil in predictable quantities. A diversity of N inputs on organic farms has been shown to encourage tight coupling of soil-plant N cycles (Bowles et al., 2015), however, the complexity of predicting N release timing and quantity from carbon-based sources is a hallmark of organic agriculture and can cause growers to tend towards overapplication of nutrients. Norgaard (2020) found high levels of post-harvest NO_3^--N on organic vegetable farms in BC when farmer-calculated compost rates were applied. N estimation is complicated in part by the differing qualities of compost and manures. Each may have a different C:N ratio which impacts the rate of N mineralization and total N released. N cycling in the soil is mediated by microbial activity and therefore influenced by soil moisture and temperature conditions. In a study of nine organic farms in the United Kingdome that each had enough PAN from SOM alone to fulfill crop demands (i.e. more than 300 kg N ha^{-1} yr^{-1}), yield could still be limited due to asynchrony between N mineralization and crop demand (Berry et al., 2003).There are likely important interactions among off-season overwintering cover strategies and their impact on N retention, soil moisture, and temperature and subsequent PAN for crop production in the on-season. There is however little research focused on these complex interactions. As a result, farmers are currently applying overwinter cover and crop fertility management in relative isolation with limited guidance.

Some organic vegetable farmers in areas of the Lower Fraser Valley (LFV) have shown interest in using alternative timing for applying amendments to address the challenges they are facing to establish cover crops and deal with wet spring soils. Instead of applying high composts with high available N in the spring they are interested in using the dry period in the fall after crop harvest to apply low-nutrient compost to improve the flexibility of their field preparation operations. This approach however has not been evaluated for potential impacts on crop production or the environment. Given low nutrient availability, it is thought that compost could be added without losing mineral N through fall rains while adding a sizable amount of organic N that could be mobilized in the spring. This approach could be further enhanced by the use of tile drainage. Tile drainage has been used widely in LFV as a means of addressing challenges when it comes to water management and maintaining soil health. Tile drainage may help to moderate soil moisture and increase shoulder-season workability and increase the overall flexibility of the farmer to decide when to apply amendments. There is likely an interaction between compost application timing and tile drainage as changes in soil moisture and temperature can impact the decomposition rates of applied compost but these interactions have not been evaluated in the region.

1.4 Project objectives

Our project objectives were developed to provide organic vegetable farmers with viable strategies for dealing with shifting precipitation patterns that are likely to become increasingly unpredictable and volatile. The objectives that were initially proposed for the project were co-developed through farmer consultation but because of the COVID-19 pandemic, which started just as we were entering our first production season, had to be adapted. The pandemic substantially changed our team's ability to travel to field sites, establish experimental treatments, and interact with farmers. The shift in resources incurred by the pandemic ultimately also limited our capacity to evaluate the economics and model the long-term impacts of the management practices we investigated. Our revised specific project objectives were to:

- **Objective 1:** Quantify the effects of overwinter cover on soil physicochemical properties in a controlled and replicated field study on two farms and assess the consistency of these effects at twelve additional sites across three important agricultural regions of BC with differing soil textures and climates.
- **Objective 2:** Evaluate the interaction between overwinter cover and three nutrient amendment strategies on PAN, VWC, and crop yield in a controlled and replicated field study on two farms in South Coastal BC with differing soil textures with legacy nutrient applications.
- **Objective 3:** Investigate the interactions between amendment application timing and tile drainage spacing on their effects on soil moisture and salinity and crop yield in a controlled, replicated field study on a single commercial farm in Delta, BC.

The combination of experimental and regional trials allowed for the comparison of management strategies under realistic conditions which is critical in evaluating their performance. Working relationships between farmers and researchers can also create pathways to disseminate research findings and facilitate future collaborations. Throughout this project, we engaged with participating farmers to ensure that our results were shared, discussed, and contextualized for their conditions as much as possible. Results were shared through annual project reports, presentations, podcasts, field days and videos.

2. Research Methods

2.1 Project design

A mother-daughter field trial was conducted on 15 organic-practicing farms in BC to evaluate overwinter cover options, amendment application rates and timing and tile drainage across a variety of climates and soil types. These trials are referred to as experimental and regional to describe differences in on-farm replication and controlled conditions. Three experimental (mother) sites hosted trials with on-farm treatment replication where fertility amendments, irrigation type, and crop type were controlled. Regional (daughter) sites hosted non-replicated trials with a subset of treatments where management decisions during the growing season were at the discretion of the individual farms. Both the experimental and regional trials began in October 2019. Data collection was completed in May 2021 in the regional trial and remained ongoing at two of the experimental trials through the end of the project, January 2023.

Photo 1. Silage tarps and cover crop experiments at (left) the University of British Columbia Farm and (right) Green Fire Farm (Cowichan Valley).

2.1.1 Experimental trials

Two experimental studies were conducted to address the project's three objectives. The first study focused on cover and amendment rates was established at two farm sites: The University of British Columbia (UBC) Farm and Green Fire (GRF) Farm (Cowichan Valley). One field on each farm was selected as the study site for this experiment. Total field area was 48.8 × 11.2 m at UBC and 56.0 × 7.6 m at GRF. A randomized complete block design with overwinter cover treatments applied at the subplot level was used on each farm (0). Treatments were randomized within four blocks to account for topographical, shade, and soil variability. Sixteen plots, 6.1 × 5.6 m at UBC and 7.0 × 3.8 m at GRF, were divided in half to accommodate randomly assigned overwinter cover treatments. Overwinter cover treatments were (1) cover crop and (2) tarp. Nutrient amendment treatments were applied at the plot level. Overwinter treatments were applied in October of 2019 and 2020 when tarps were installed and cover crops seeded. Overwinter treatments were removed in the April or May of 2020 and 2021 when the tarps were removed, and cover crops mowed and tilled.

At both farm sites, the following three nutrient amendment strategies and one control were evaluated:

- **High Compost (HC):** compost applied to meet crop N removal assuming a N mineralization rate of 15% of total N in the first growing season after application (Gale et al., 2006).
- **Low Compost (LC):** compost applied to meet crop N removal assuming a N mineralization rate of 30% of total N in the first growing season after application.
- **Compost + Fertilizer (C+F):** compost applied to meet crop P demand plus feather meal fertilizer to meet crop N removal.
- **Control (CON):** No nutrient application of any kind.

The treatments were applied at the plot level resulting in four replicates of each nutrient treatment on each farm. Estimates of crop-specific N and P removal by harvest were determined from the yield expected by farmers and nutrient concentration from local data when available (0). In the circumstance that crops grown in each year had varying N and P removal rates, the crop with the greatest nutrient requirement was used for calculation. The compost used by each farm was dictated by regional availability and therefore unique to each farm site. Net Zero Waste Inc. (Abbottsford, BC) provided the compost for UBC Farm. Net Zero compost substrate is primarily municipal green waste. At GRF Farm, Earthbank Fish Compost (Parksville, BC) was used as the compost amendment consisting of waste from both aquaculture and forestry industries. Gaia Green (Grand Forks, BC) certified organic feather meal fertilizer (13-0-0) was used on both GRF and UBC Farms in the C+F treatment. Fertilizer calculations were based on the total N reported by the manufacturer and 100% of the total N was assumed to be mineralized within one growing season.

Compost and fertilizer were weighed and applied by hand to HC, LC, and C+F plots using shovels, 5-gallon buckets, and a field scale. Nutrient applications were applied after mowing and tilling (disk) to terminate overwinter cover crops and weeds. Nutrient applications were incorporated into the soil using a rototiller prior to planting. Nutrient treatments were applied 0-22 days before direct seeding crops.

These research plots have been a part of nutrient management trials for several years. Nutrient trials began in the described research plots beginning in 2015 at UBC Farm and 2018 at GRF Farm. Soil sampling in April 2020 prior to nutrient application served as a baseline for this study to accommodate for potential legacy effects of previous nutrient trials.

The second experimental study was established to investigate the interaction between amendment application timing (either fall or spring) and tile drainage. Plots were established in the fall of 2019 in Delta, BC. A 2-factor randomized complete block design (n=3) was established to compare two levels of tile drainage spacing and three levels of amendment application. Tile drainage treatments included a 15- and 30-ft tile spacing, and amendment application treatments included a fall compost application (municipal compost), a spring compost application (chicken manure compost), and control (no compost application). Fall compost application occurred on October 1st, 2019 and spring compost application occurred on April 27, 2020, by manure spreader according to the rates defined in Table 1. The area of each treatment plot was 100 m^2.

Table 1. Compost amendment and plant-available nitrogen (N) application rates for fall 2019 and spring 2020 in kg or Mg compost per hectare and kg plant-available N per hectare.

Season / Year	Compost Moisture Content	Compost Applied (dry weight Mg/ha)	Plant Available N Applied (kg/ha)	Total N Applied (kg/ha)
Fall 2019	0.41	15.49	61	281
Spring 2020	0.51	10.37	106	270

2.1.2 Regional trial

The regional trial was conducted on 12 organic-practicing farms in three key agricultural regions in BC: the LFV, Vancouver Island (VI), and the Kootenay Mountains (KM) (see appendix). Participating farms grow primarily vegetables and/or flowers and several have integrated livestock operations. The scale of participating farms ranges from 0.8-16.1 ha. Each farm hosted one trial plot containing two equal-sized subplots to which one of two randomly assigned treatments were applied, (1) tarp and (2) no-tarp. Trial plots varied in dimension and area between farms (see appendix). Treatments were applied on the regional farms in September-November of 2019 and September-December of 2020. Tarps were removed in the spring in April of 2020 and March-May of 2021. Removal timing was based on the crop type planted on each farm.

2.2 Site descriptions

The UBC Farm is located in Vancouver, BC (49°15'N 123°14'W) on the UBC campus and the traditional, ancestral, and unceded land of the xʷməθkʷəy̓əm (Musqueam) people. UBC Farm is certified organic, grows primarily mixed vegetable crops in addition to seed crops, raises laying hens, and hosts educational programing. The soils are primarily a well-drained Bose Gravel and Sunnyside Sand mixture developed on glacio-marine deposits with a texture ranging from gravelly sandy loam to gravelly loamy sand (Duric Humo-Ferric Podzol) (Luttmerding, 1981). Historically, this site was a coastal Douglas-fir, western redcedar and western hemlock forest and is in the CWHwh1 biogeoclimatic zone (Meidinger & Pojar, 1991). Agricultural production began in 1970 after the logging of the second-growth forest. The Mediterranean climate of Vancouver is characterized by dry summers and wet, mild winters (see appendix).

The GRF Farm is located near Duncan, BC (48°46'N 123°46'W) in the Cowichan Valley on Vancouver Island on the traditional and unceded land of the Cowichan Tribes. GRF Farm is a certified organic mixed vegetable and livestock operation. The soils at GRF are imperfectly to moderately well-drained and of the Fairbridge series. Formed on marine deposits, the texture ranges from silt loam to silty clay (Gleyed

Eluviated Dystric Brunisol) (Jungen et al., 1985). Historically, this site was a coastal Douglas-fir forest (Meidinger & Pojar, 1991).

Out third experimental site (Delta) was located on 54 ha commercial farm field near the City of Delta, BC (49.08 N, 123.06 W), within the traditional, ancestral, and unceded land of the scəw̓aθən (Tsawwassen) First Nation. The field had known salinity and drainage problems documented by Paul et al. (2019). The study site was located on Rego Gleysol and Orthic Humic Gleysol (Umbric Gleysol) formed predominantly from fluvial parent materials. This area is characterized by a humid maritime climate with a mean annual temperature of 11.1 °C and a mean annual precipitation of 928 mm based on 30-year climate record (Environment Canada, 2019).

Soil types in the regional trial vary widely. The soils of the Lower Fraser Valley, range from silt loam to silty clay loam and are poorly drained. These soils developed on fluvial deposits and are classified as primarily Humic Luvic Gleysols, Orthic Humic Gleysols, and Rego Humic Gleysols, except for one site located on a well-drained and coarse textured Duric Humo-Ferric Podzol (Luttmerding, 1981). The Lower Fraser Valley and Vancouver Island farm site have moderate maritime climates characterized by wet, mild winters and dry summer (see appendix).

On Vancouver Island, the farm sites range from the Cowichan Valley to the Saanich Peninsula. Because of the wide geographic spread of study sites on Vancouver Island, the soils are the most varied in this region. Soils developed on marine and moraine (till) deposits under coastal Douglas-fir, western red cedar, and western hemlock forests. Soils range from poorly to well drained and vary in texture from silty clay loam to sandy loam. Soil classifications include Duric Dystric Brunisol, Gleyed Eluviated Dystric Brunisol, and Orthic Humic Gleysol (Jungen et al., 1985).

Farm sites in Kootenay Mountain region are located in both the Selkirk Range and Slocan Valley. The soils in this study region are primarily formed on fluvial or glacio-fluvial materials under interior western hemlock and cedar complex forests with soil textures ranging from silt loam to loamy sand and are generally moderately well to rapidly drained. The primary soil classifications in this region are Orthic Regosol and Orthic Dystric Brunisol (Jungen, 1980). Farm sites in the Kootenay Mountains experience a humid continental climate of cold and snowy winters and warm summers and range from 535-670 m above sea level (0).

2.3 Cover establishment and removal

The tarp material used in this study was selected based on previous research (Lounsbury et al. 2020; Rylander et al. 2020a) and the input of BC vegetable farmers. Siloform® Silage Sheeting (BPI Agriculture, Edmonton, AB) was used in this study and is available through distributors in most agricultural regions in BC. Reusable silage bunker covers are made from opaque polyethylene, are 0.15 mm (5-6 mil) thick, and are black-on-white plastic. Tarps were cut to the dimensions of the subplots and installed in the fall of 2019. Tarps were laid out black side up by hand and secured with row cover bags (DuBois Agrinovation, Saint-Rémi, QC) filled with 5-8 kg of rocks without burying tarp edges. Bags were placed every 1.5-3.0 m around the perimeter and auxiliary bags were used to secure the tarp interior when the tarp width exceeded five meters. The tarps were stored under cover or in the field during the growing season and reused on the same subplots in the second trial year.

Cover crops were seeded in mid-October of 2019 and late September of 2020 at UBC and GRF Farms (0). Fall rye (*Secale cereale*) and crimson clover (*Trifolium incarnatum*) were selected as cover crop varieties; both are commonly used as a polyculture by growers in the region. Seeds were provided to farmers and seeded at a rate of 4.45 kg ha^{-1} (fall rye) and 0.75 kg ha^{-1} (crimson clover). Cover crop seed was pre-mixed and hand broadcast onto the plots. Seed was incorporated with a shallow disking.

Not all growers participating in the regional trial were able to establish an overwinter cover crop stand. The primary reason for cover crop failure was late planting date. No-tarp conditions were either cover cropped, bare fallow, or mulched with crop residue depending on the production needs and climatic constraints of the individual farm. Treatments were applied on the regional farms in September-November of 2019 and September-December of 2020.

The timing of overwinter cover removal was determined by the farmer on each individual trial site. Factors contributing to tarp removal timing included the planting date of the subsequent crop, snow cover, and spring precipitation. The method of cover crop termination was also determined by each farm site; however, this protocol was standardized at the experimental sites (0). Cover crops were mowed, disked, and rototilled prior to direct seeding of the cash crop.

2.4 Crop establishment and harvest

In the experimental trials at UBC and GRF in 2020, equal areas (one bed each) of Red Ace beets (*Beta vulgaris*), Touchstone Gold beets (*Beta vulgaris*), and Finale fennel (*Foeniculum vulgare*) were grown within each subplot. All three varieties were seeded on June 2, 2020 at UBC Farm and June 8, 2020 at GRF Farm. In 2021, Teggia barlotto beans (*Phaseolus vulgaris*) and Biei soybeans (*Glycine max*) were grown in each subplot. Both bean varieties were direct seeded on June 4, 2021 at UBC Farm and May 26, 2021 at GRF Farm. All crops were direct seeded using an EarthWay Precision Seeder (EarthWay Products, Inc., IN, USA). Crop sampling occurred at the time of crop maturity (0). One sample (1 × 1 m) of each crop variety was taken from each subplot at crop maturity. In 2020, beets and fennel were harvest once; in 2021, ripe beans were harvested once a week for three consecutive weeks.

The field at the Delta site, as part of its vegetable rotation, had been planted with field peas during the 2019 growing season. Silage corn was planted in the spring of 2020. A cover crop mixture (tillage radish, sunflower, and vetch) was also planted during the over-winter period. The silage corn crop was harvested from 3 m x 3 m subplots within the center of each plot to determine crop biomass. Biomass sampling was completed just prior to the harvesting of silage corn, in October 2020.

2.5 Field sampling

In the experimental trial, soil samples were collected using either a soil probe with a 1.9 cm inner diameter (Oakfield Apparatus Inc., WI, USA) or soil auger with a 5.5 cm inner diameter depending on soil moisture conditions and presence of coarse fragments. Five to ten subsamples were taken from each subplot when using a probe or 3-5 subsamples when using an auger to account for differences in core volume. Samples were collected at a depth of 0-15 cm at collected at four agronomically important points during the growing season at UBC and GRF: (1) early spring (at the time of tarp removal and prior to cover crop incorporation; 1-TR), (2) planting date (2-PL), (3) mid-season (3-MS), and (4) post-harvest (4-PH). Samples were collected at a depth of 0-15 cm except for post-harvest samples which were collected at 0-15 and 15-30 cm depths. At the Delta site soil sampling was collected on April 7th and April 13th, 2020 and cores were measured for volumetric water content (VWC) and electrical conductivity (EC). Samples were collected at the regional farms at 1-TR in 2020 and 2021 (0).

In the regional trial, due to travel restrictions associated with the COVID-19 pandemic, soil sampling methodologies were adapted for farmer participation. Three to five subsamples were taken from each subplot using a hand trowel at a depth of 0-15 cm. In both cases, coarse materials, roots, and plant matter were removed from the sample and the remaining soil hand homogenized. Soil samples were collected at the time of tarp removal in the spring of 2020 and 2021.

Composite samples were stored in a cooler on ice and shipped overnight to A&L Laboratories (London, ON, CA), the Ministry of Environment Analytical Chemistry Services (MOE) Laboratory (Victoria, BC, CA), or the UBC Sustainable Agricultural Landscapes (SAL) Laboratory (Vancouver, BC, CA). Soil samples were analyzed for NH_4^+-N, NO_3^--N, EC, and VWC.

Soil bulk density was measured at the time of tarp removal in spring 2021 on both regional and experimental farms (0). One undisturbed soil core was taken from the center of the 0-15 cm depth in each subplot. Samples were collected using 7.5 cm diameter cores using a double-cylinder, drop hammer sampler.

Volumetric water content was measured in both the experimental and regional trial at the time of tarp removal in the spring of 2020 and 2021 at a depth of 0-8 cm. Volumetric water content was measured using a Spectrum Technologies (Aurora, IL, USA) FieldScout TDR 100 soil moisture probe. Three measurements were taken at random locations in each subplot on all farms. Due to travel restrictions associated with the COVID-19 pandemic in the spring of 2020, VWC was not measured in the Kootenay Mountain region. At UBC Farm, VWC measurements were taken every 2-3 weeks from November 2019 to October 2021 from one location in every subplot.

At the experimental sites, compost samples were collected directly from on-farm compost piles two weeks prior to application. Composite samples were collected by combining five subsamples taken from different locations on the compost pile at a depth of ~0.5 m. Composite samples were thoroughly hand homogenized in a bucket and immediately put on ice in a cooler until transported to the UBC SAL Lab or shipped to A&L or MOE Labs. Compost samples were analyzed for total N, total carbon (C), N, P, and water content.

Crop yield was estimated from a subsample of crop biomass harvested at crop maturity from each subplot. Crop biomass sampling spanned the bed top in width and varied in length depending on crop type, 2 m for fennel and 1 m for beets and beans. One crop biomass sample was taken for each variety grown in each subplot. Crop varieties were harvested and weighed separately. Total biomass, marketable biomass, and an individual plant count were recorded and standardized to kg or plants ha^{-1}.

Crop sampling at UBC Farm occurred August 27 - September 16, 2020 and August 30 - September 5, 2021. At GRF, yield was measured on September 1, 2020 and August 16-30, 2021.

To compare the yield of the different varieties grown in the subplots each year, subsamples were relativized as a percent of the maximum yield (kg ha^{-1}) was calculated for each variety on each farm in each year and the maximum value recorded. Yearly relative yield (%) was calculated by dividing the measured yield from each variety in each subplot by the maximum yield of the same variety at the same farm in the measurement year. The result was multiplied by 100 to calculate the percentage of the maximum yield observed in each subplot. Calculated relative yields were averaged within year, farm type, and overwinter cover type.

Equation 1. Relative yield.

$$\boldsymbol{Relative\ yield}\ (\%) = (Subplot\ yield_{variety}\ (kg\ ha^{-1})\ /\ Maximum\ yield_{variety}\ (kg\ ha^{-1})) * 100$$

2.6 Laboratory analyses

Plant available nitrogen (PAN), NO_3^--N, and NH_4^+-N, was measured from composite soil samples collected at the subplot level at each of the sampling timings described in 0. Samples were extracted using 2 *M* KCl then analyzed by colorimetry (Doane & Horwath, 2003; Maynard et al., 2008; Weatherburn, 1967). Gravimetric water content was determined by oven drying soil subsamples at 105°C for 48 hours or until weight stabilization (Blake & Hartge, 1986).

Electrical conductivity (EC) was measured from composite soil samples collected at the subplot level at the time of tarp removal. Samples were read on a conductivity meter and small volume flow-through cell (Hendershot et al., 2008a).

Bulk density cores were oven dried at 105°C and weighed as outlined by Throop et al. (2012). Soils were sieved to 2 mm and fine and coarse fragment fractions were weighed and recorded. Bulk density calculations were performed using the mass of all the material in the total core volume.

2.7 Statistical analyses

Data analysis was conducted using R (R Core Team, 2021). To assess the effect of overwinter cover and nutrient amendment treatents on PAN, EC, VWC, and crop yield, linear mixed-effects (LME) models were used. Analysis was run with the *lme* function in the *nlme* package version 3.1-143 (Pinheiro, 2019) using the restricted maximum likelihood (REML) method. Separate models were used for data collected from the experimental and regional trials to accommodate differences in their experimental design. Data from UBC and GRF farm was analyzed separately due to the differences in soil texture. Data from 2020 and 2021 were modeled separately. As the primary explanatory variable of interest, overwinter cover type was included in all models as a categorical fixed effect with two levels (cover crop, tarp OR no-tarp, tarp). Region (LFV, VI, KM) and winter cover × region interaction were included as fixed effects in analyses of the regional study.

To account for spatial and temporal correlation of data at UBC and GRF, block (1-4), plot (1-16), and subplot (1-32) were incorporated as random effects. In the regional trial, farm site ID was included as a random effect. To assess 2-year VWC from UBC, year (2020, 2021), season (off season, growing season), and their interaction were incorporated into an LME model. To account for spatial and temporal correlation of data, day of the year, block (1-4), and plot (1-16) were incorporated as random effects. The impact of overwinter cover to VWC during the time of cover at UBC Farm was assessed in each year individually. Date and subplot were incorporated as random effects to account for spatial and temporal dependence of measurements. To assess overwinter cover influence on growing season PAN, experimental farms and years were assessed separately, day of the year, block (1-4), and plot (1-16) were incorporated as random effects. Model assumptions of linearity and equal variance were assessed using a plot of residuals. The normality assumption was assessed using a Q-Q plot and Shapiro-Wilk test. Data that did not meet assumptions was transformed using log10, square, or square root functions. Significant differences were determined using ANOVA with a significance level of $P < 0.05$ (see appendix).

3. Results

3.1 Plant available nitrogen (PAN)

3.1.1 Spring nitrate

Spring NO_3^--N was significantly higher under the tarp treatment than the cover crop or fallow treatments in both 2020 and 2021 in the experimental and regional trials (Figure 1). This finding was consistent across the three regions. The observed amount of NO_3^--N under overwinter tarps is agronomically sizable ranging from 19.3 to 39.8 kg N ha^{-1}. At the higher end of the range, this would represent >70% of the recommended 54.9 kg N ha^{-1} for a beet crop in BC. No significant differences were observed in NH_4^+-N in either trial or in either year (data not shown).

In both years of study at UBC and GRF, NO_3^--N following overwinter cover crops were comparably low. However, these sites differed in NO_3^--N under tarped conditions; UBC averaged 58% greater than GRF in 2020 and 42% greater in 2021. Generally, more variation was observed under tarps compared with cover crop or no-tarp conditions; however, this difference in variation was more pronounced in the regional study. This was expected due to the smaller sample size, greater geographical spread, and increased variability in soil type as compared to the experimental sites. Nevertheless, region and region-treatment interaction were not significant in either year of study, indicating that the effect of the overwinter cover treatment was significant despite the described variability.

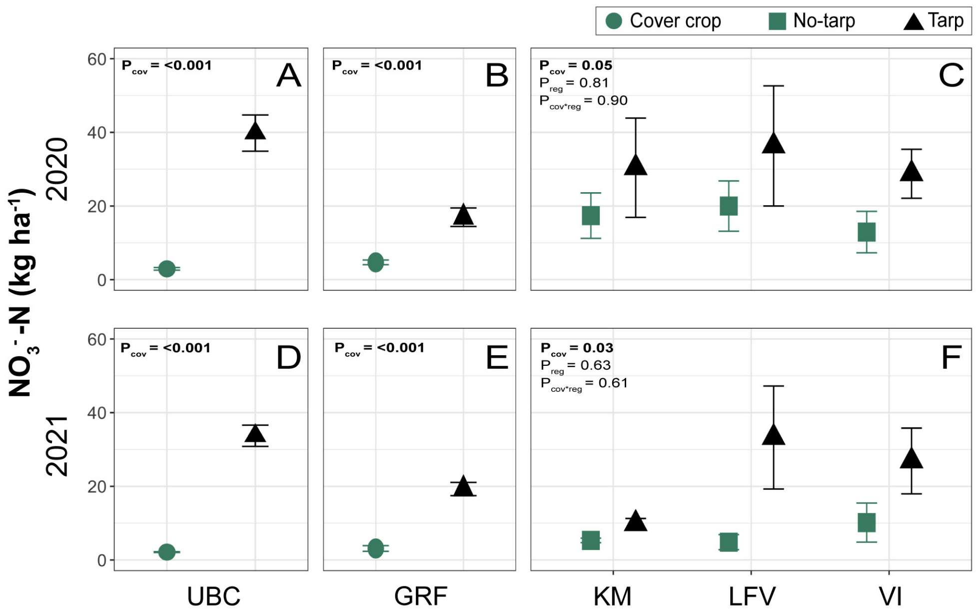

Figure 1. Soil nitrate (NO_3^--N; kg ha^{-1}) means ± one standard error measured at the time of tarp removal to a depth of 0-15 cm. Results are shown for the experimental trial at the University of British Columbia Farm (UBC; n=16; A, D) and Green Fire Farm (GRF; n=16, B, E) and the regional study with sites in the Kootenay Mountain (KM; n=4, C, F), Lower Fraser Valley (LFV; n=4, C, F), and Vancouver Island (VI; n=6, C, F) by overwinter cover type (cover crop, tarp, no-tarp). P-values determined by linear mixed-effect models show the significance of cover type (cov) treatment and/or region (reg) and their interactions. Significant findings (P<0.05) are shown in bold.

3.1.2 Growing season PAN

At UBC and GRF Farm, PAN dynamics changed over the course of the growing season and between years (Figure 2). Significant differences in PAN were observed at GRF in 2020 and UBC Farm in 2021. No significant interactions were found between nutrient amendment strategy and overwinter cover type. At GRF in 2020, PAN in the C+F treatment was significantly higher than HC, LC, and CON. This is likely due to the spike in PAN observed at 3-MS sampling; this was not observed on either farm in 2021. At UBC Farm in 2021, CON was significantly lower than all three nutrient treatments. The greatest differences observed between some treatments were observed at UBC Farm in 2021. Generally, PAN was lowest prior to planting in the spring. In 2020 on both farms, post-harvest PAN was measured at or below spring levels. However, on both farms in 2021 post-harvest PAN was notably greater than in the previous spring for every nutrient treatment including the control. Measures of PAN were generally greater in the 2021 growing season than in 2020. While both farms followed a similar arc in 2021 with PAN increasing throughout the growing season, at UBC Farm PAN decreased slightly post-peak measurement mid-season and PAN at GRF Farm did not decrease from mid-season levels after harvest. No interactions between the nutrient amendment strategies and the overwinter cover treatments were observed in PAN measurements. At the time of tarp removal, the first sample date each spring, measures of PAN at the time of tarp removal were always greater in the tarp treatment within each nutrient treatment on each farm.

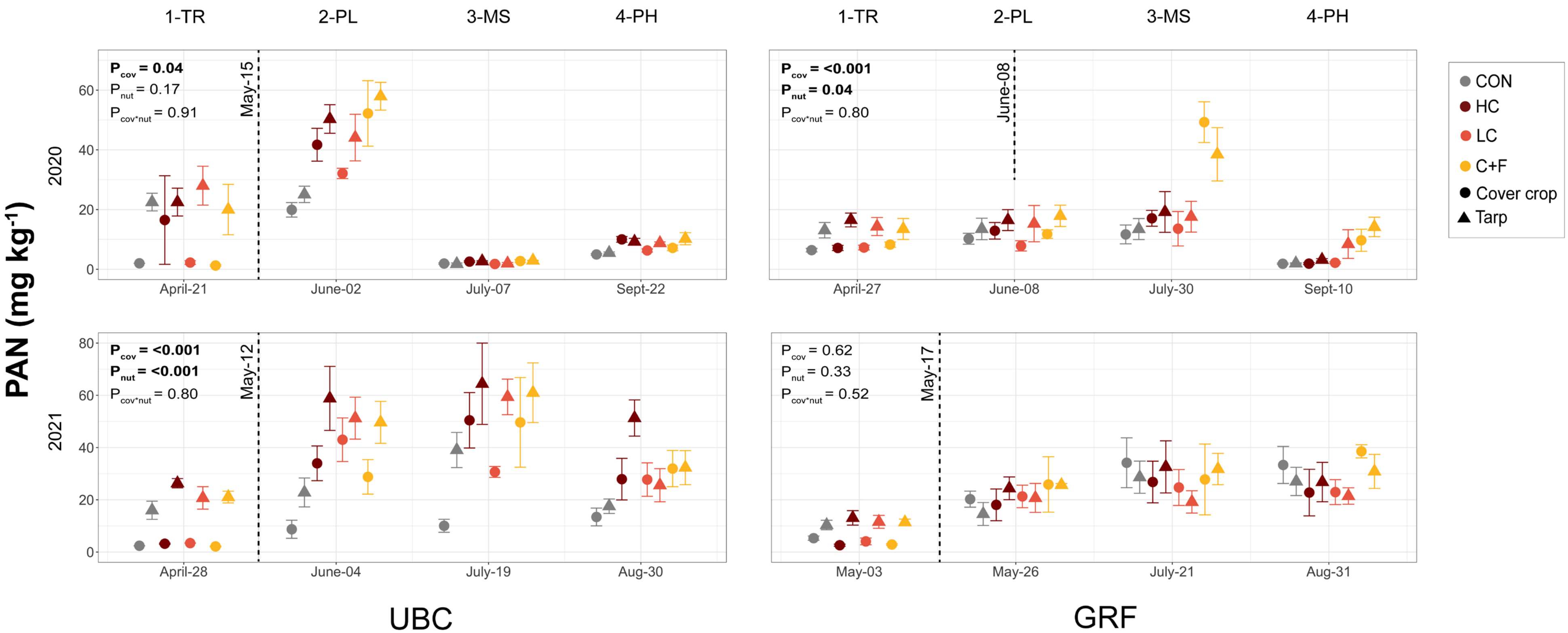

Figure 2. Plant available nitrogen (PAN; mg kg-1) means ± one standard error measured over the growing season in 2020 and 2021 to a depth of 0-15 cm. Samples timing aligns with dates of tarp removal (1-TR), planting (2-PL), mid-season, (3-MS), and post-harvest (4-PH) in each year. Results are shown for the University of British Columbia Farm (UBC; n=16) and Green Fire Farm (GRF; n=16). Significant findings (P<0.05) are shown in bold and were determined by linear mixed-effect models to show the significance of the nutrient (nut) treatments, high compost (HC), low compost (LC), compost + fertilizer (C+F), and the control (CON). Dashed line indicates date of nutrient amendment application.

3.1.3 Post-harvest (PH) PAN

Significant differences in 4-PH PAN were observed in 2020 at both GRF and UBC Farms but at neither farm in 2021 (Figure 3). Most of the differences between treatments were observed at the 0-15 cm depth while little variation was observed at 15-30 cm. At UBC Farm in 2020, PAN was significantly greater in the C+F treatment than the CON, but not significantly different from the compost only treatments, HC and LC. At GRF Farm in 2020, post-harvest PAN was significantly greater in the C+F treatment than HC, LC, and CON. While no significant differences were observed between treatments in 2021, observations of total PAN across all treatments on both farms were greater in 2021 than 2020. At UBC Farm, 0-30 cm post-harvest PAN was 172-242% greater in 2021 than 2020. The increase was more marked at GRF; post-harvest PAN from treatment plots was 136-391% greater while post-harvest PAN increased more than seven-fold in the control plot between 2020 and 2021. Most of the increase in PAN between 2020 and 2021 was observed at a depth of 0-15 cm, however, PAN increased at 15-30 as well. No interactions were observed with nutrient treatments and overwinter cover treatments at UBC or GRF Farms. Both nutrient treatment and cover type were significant on both farms in 2020 but on neither farm in 2021. In 2021, the HC treatment at UBC Farm and C+F treatment at GRF Farm were close to 100 kg N ha^{-1}, representing a potential environmental hazard.

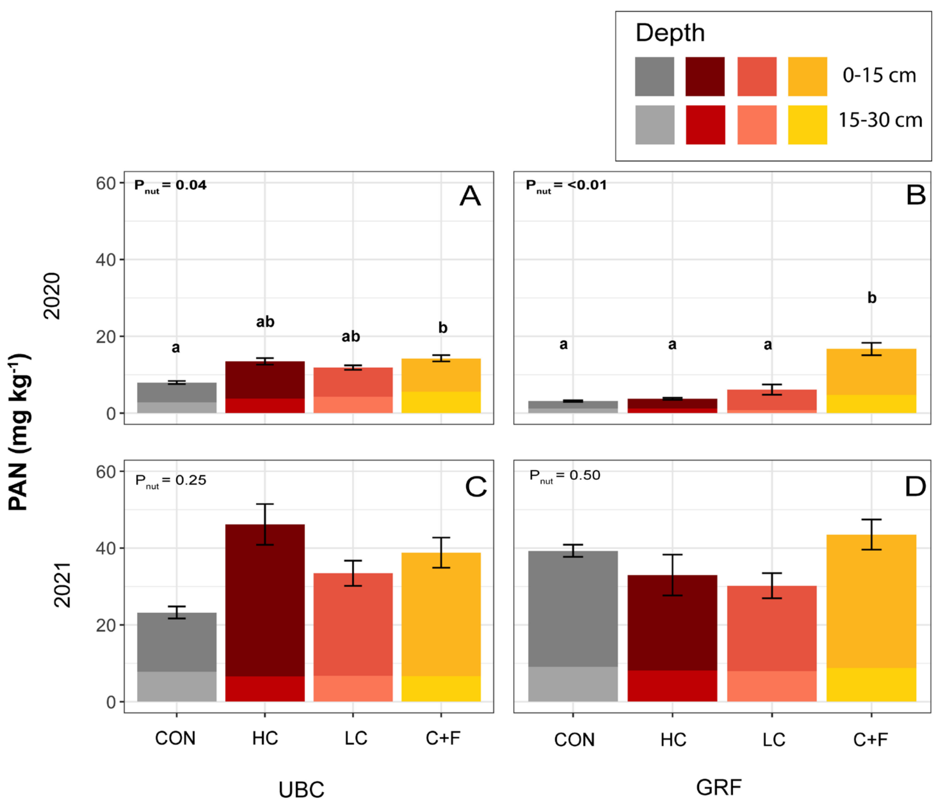

Figure 3. Post-harvest (4-PH) plant available nitrogen (PAN; kg ha^{-1}) means ± one standard error measured at a depth of 0-15 and 15-30 cm. Results are shown for the University of British Columbia Farm (UBC; n=16; A, C) and Green Fire Farm (GRF; n=16; B, D). Significant findings (P<0.05) are shown in bold and were determined by linear mixed-effect models to show the significance of the nutrient (nut) treatments: high compost (HC), low compost (LC), compost + fertilizer (C+F), and the control (CON) at a depth of 0-30 cm.

3.2 Electrical conductivity

Measures of EC mirror the trends observed in NO_3^--N. At both UBC and GRF experimental sites and in the regional trial, soil EC was higher under tarped conditions than cover cropped or no-tarp treatments. Comparable to NO_3^--N observations, the treatment effect was greater at UBC than GRF Farm. Electrical conductivity after overwinter tarping was 47% greater than after cover cropping at UBC Farm in 2020 and 63% greater in 2021. However, at GRF Farm EC was 24% greater after tarping than cover cropping in 2020 and 28% greater in 2021. Overall measures of EC were 34% greater at UBC Farm compared to GRF Farm in 2020 and 25% greater in 2021 for the tarp treatment. In the regional trial, while EC was statistically greater under tarps, region and region × cover were not statistically significant. Measurements do not indicate an increase in EC between years in either overwinter cover treatment type.

On the initial spring sampling date (April 7th, 2020) at the Delta site we observed significantly different EC between 15- and 30-ft tile drainage spacing, but not between amendment treatments (Figure 4). One week later, EC dropped and was unaffected by tile drainage spacing or amendment application.

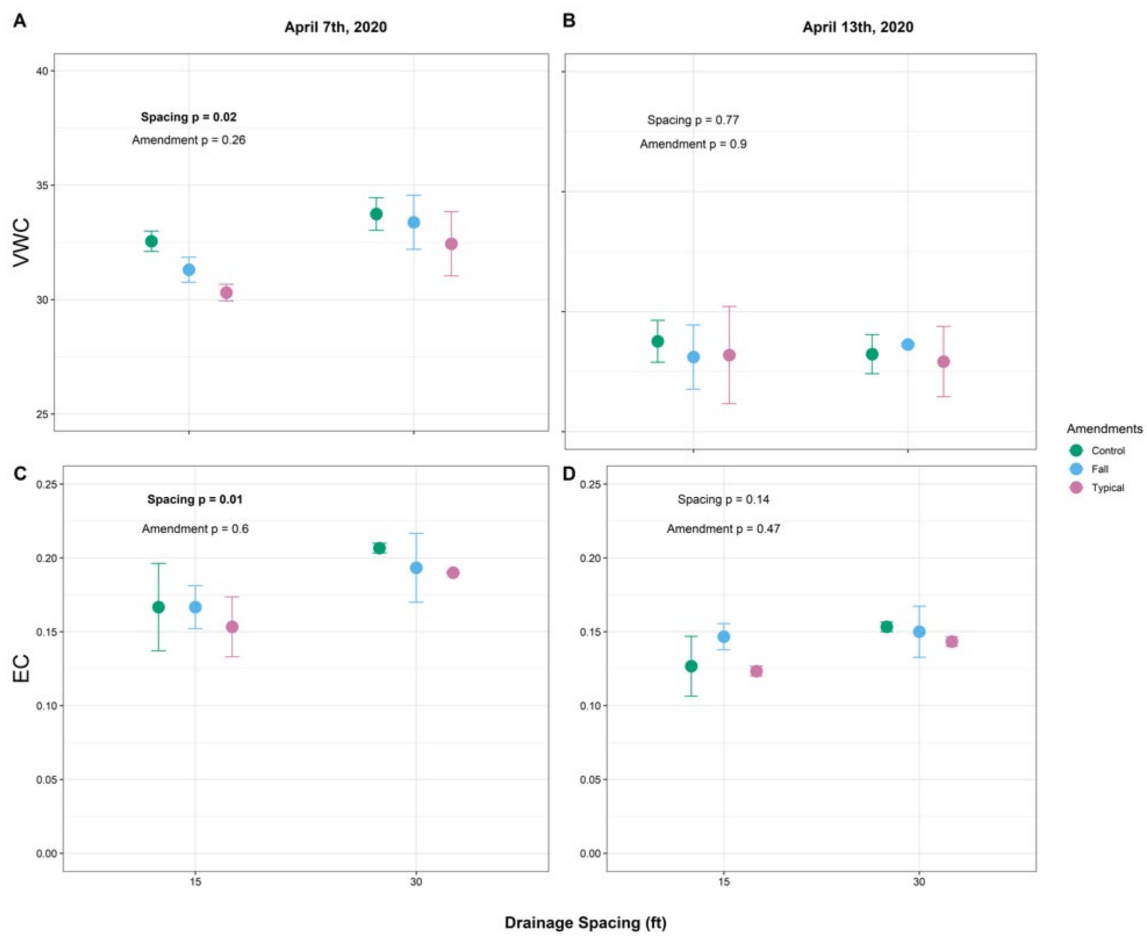

Figure 4. Average volumetric water content (VWC) for each tile drainage spacing treatment at the Delta site on April 7th, 2020 (A) and April 13th, 2020 (F) and average soil electrical conductivity (EC) on April 7th, 2020 (C) and April 13th, 2020 (D). The coloured points represent three amendment application treatments (green-control, blue-fall compost application, and pink-typical (spring) compost application. Significant differences ($p > 0.05$) are indicated in bold for tile drainage spacing. No

significant differences between amendment treatments, at either level of tile drainage spacing. Error bars show ± standard error (SE) of the mean.

3.3 Volumetric water content (VWC)

3.3.1 Spring VWC

Results from spring soil moisture content varied between trials and years. At UBC Farm, soil volumetric water content (VWC) was 19% greater in the tarp treatment than the cover crop treatment in 2020. In 2021, VWC was not significantly different between overwinter cover type at UBC Farm. The inverse was observed at GRF Farm; overwinter cover type did not significantly impact VWC in 2020 while VWC was 23% greater in the tarp treatment than the cover crop treatment in 2021. In both study years in the regional trial, soil VWC was significantly greater under tarps compared to the no-tarp treatment. Region and cover-region interaction were not significant in either year. No significant differences in VWC were observed between nutrient treatments at either UBC Farm or GRF Farm.

At the Delta site, similar to our EC findings, VWC was significantly lower for 15-ft tile spacing than the 30-ft on the initial spring sampling date (Figure 4). Again there no significant differences among amendment treatments or any difference observed one week later.

3.3.2 VWC at UBC Farm

More intensive data collection from UBC Farm provides insight into the variable spring VWC results (Figure 5). Biweekly VWC measurements show that one month after tarp application, tarped plots at UBC averaged lower soil moisture content than the cover cropped plots. Tarp VWC remained lower on average throughout the winter until mid-March in both 2020 and 2021. Between tarp installation and March 15, VWC was 7% greater in cover cropped areas in 2020 and 9% greater in 2021. After mid-March, VWC began to decline in the cover cropped areas while it remained relatively constant in the tarp covered areas. By the time of tarp removal, April 21, 2020 and April 26, 2021, VWC were higher in the tarped areas. Between March 15 and tarp removal, VWC was 9% higher in tarped areas in 2020 and 13% greater in 2021. After tarp removal in 2020, measures of VWC remained slightly higher in the formerly tarped areas for three weeks at which time there was no observable difference in VWC dependent on overwinter cover type. In 2021, differences in VWC values by treatment type were not statistically significant at the time of tarp removal; however, like the trend observed in 2020, VWC was slightly higher in the formerly tarped areas for approximately three weeks after tarp removal. Overall, there were no significant differences in soil VWC between overwinter cover type over the course of the two years of measurement. No significant difference was found when each winter cover period was assessed separately. Similarly, overwinter cover type did not significantly influence soil temperature.

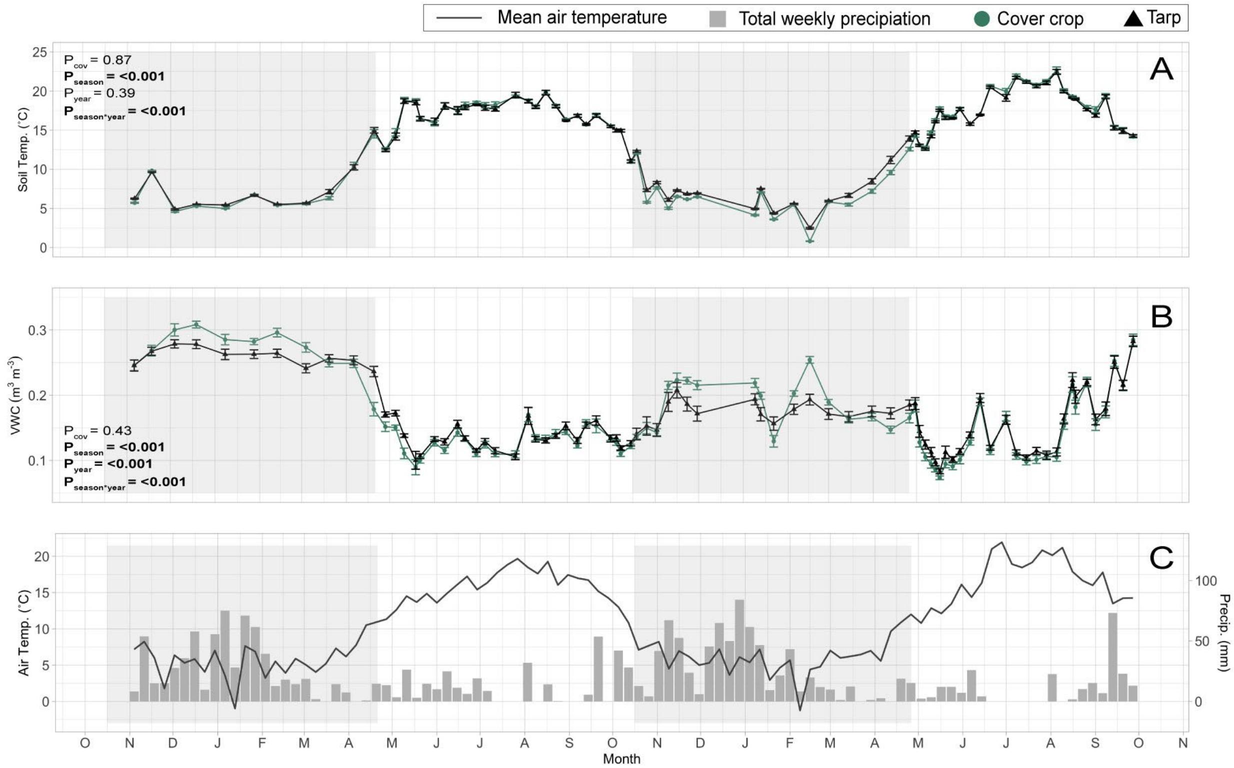

Figure 5. Soil temperature (A), soil water (B), precipitation and air temperature (C) at for University of British Columbia Farm (UBC; n=16) from November 2019 until October 2021. Soil temperature (°C) means ± one standard error by overwinter treatment (cover crop, tarp), volumetric water content (VWC; m^3 m^{-3}) means ± one standard error at a depth of 0-8 cm by overwinter treatments. Total weekly precipitation and mean air temperature from the YVR weather station in Vancouver, BC. Shaded regions indicate timing of overwinter treatments. P-values determined by linear mixed-effect models show the significance of the cover (cov), season (on- and off-season), year (2020, 2021), and the interaction between season and year. Significant findings (P<0.05) are shown in bold.

3.4 Yield

Overwinter cover type did not have a significant impact on relativized crop yield at either the UBC or GRF farms. Significant differences were observed in relative crop yield by nutrient amendment strategy on both farms in 2020 only; no significant differences were observed in 2021 (Figure 6). At UBC Farm in 2020, both CON and C+F produced significantly less crop yield than HC and LC. The difference between the HC and LC treatments and CON was notable, with the CON producing only 40% of the maximum yield (% max.), HC 75% max., and LC 74% max. At GRF Farm in 2021, the crop yield was significantly less in CON than the HC and LC treatments, however, C+F produced yields insignificantly different from all other groups. Nutrient treatment did not significantly interact with overwinter cover on either farm

At the Delta site both silage corn stalk and ear biomass fresh weight significantly differed between 15- and 30-ft tile drainage spacing (Figure 7). We did not observe any differences among amendment treatments for corn yields.

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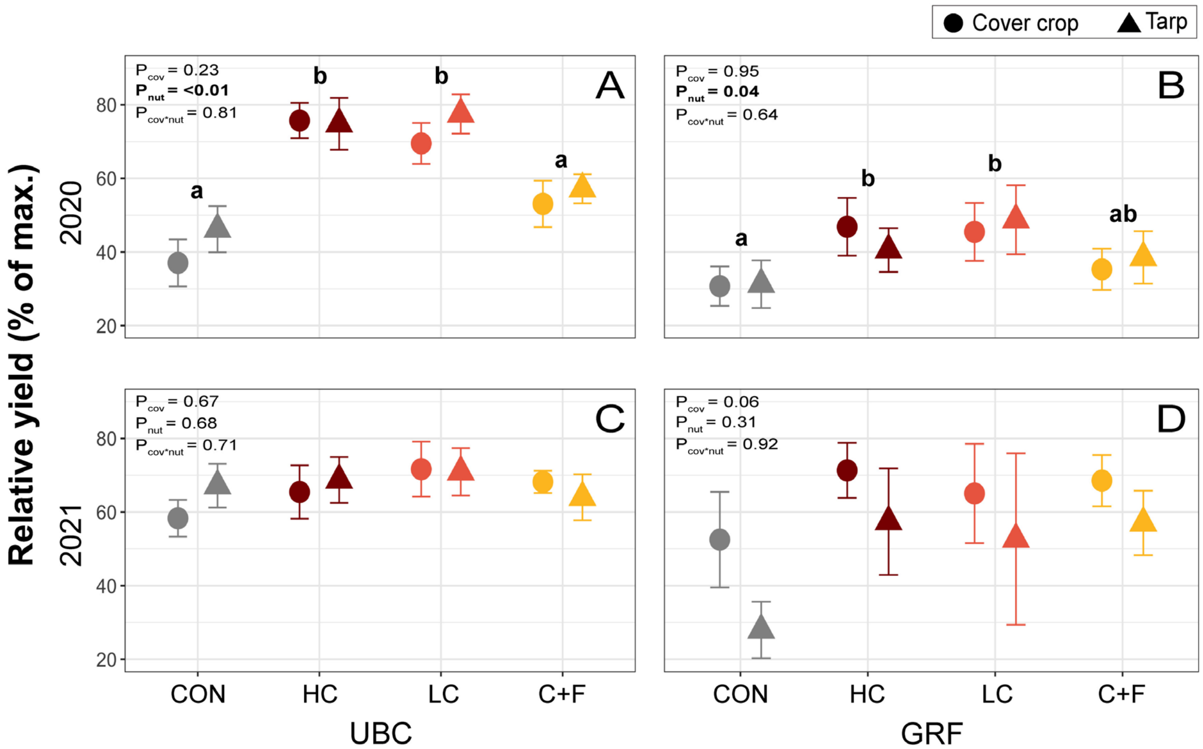

Figure 6. Relative yield (% of maximum) means ± one standard error at the time of tarp removal to a depth of 0-15 cm by nutrient amendment strategy (nut), high compost (HC), low compost (LC), compost + fertilizer (C+F), and the control (CON) and overwinter cover (cov), cover crop and tarp. Results are shown for the University of British Columbia Farm (UBC; n=16; A, C) and Green Fire Farm (GRF; n=16; B, D). Significant findings (P<0.05) are shown in bold and were determined by linear mixed-effect model.

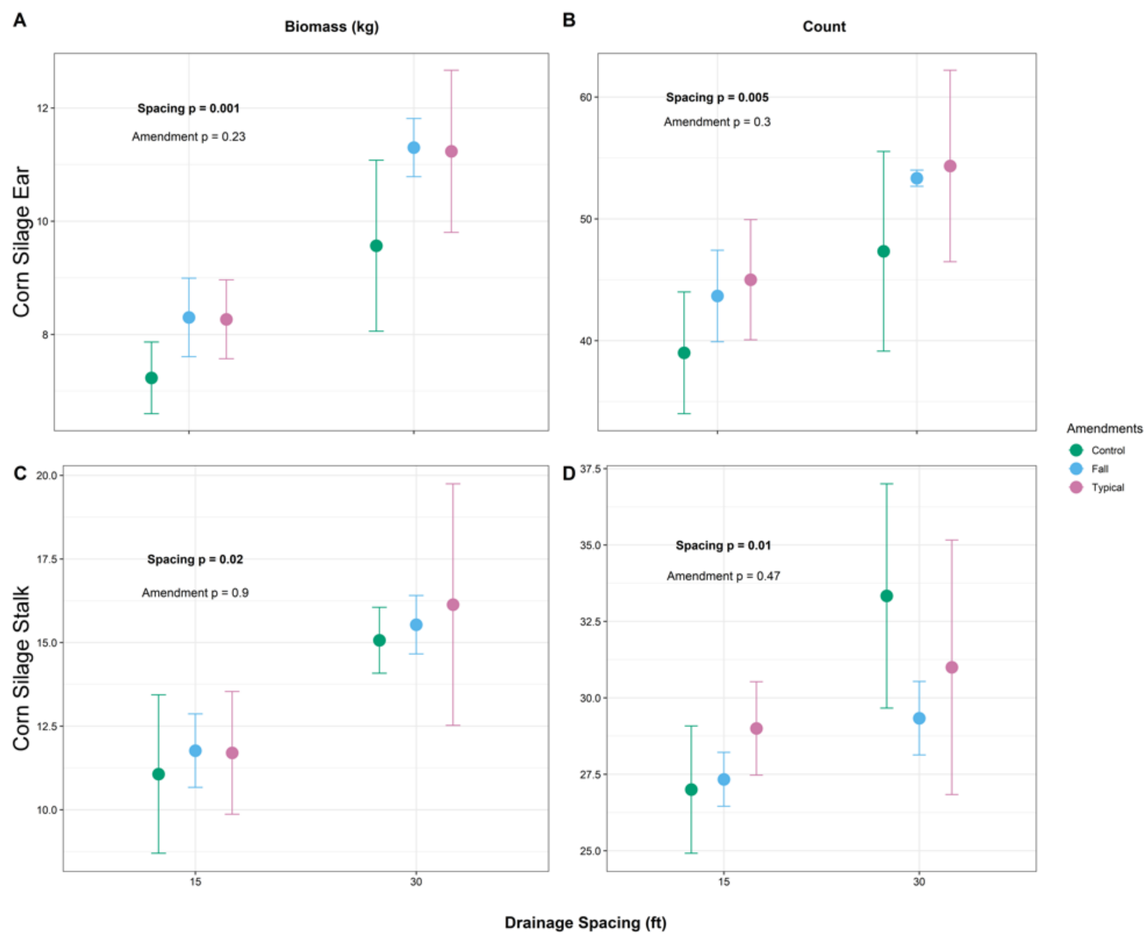

Figure 7. Average ear biomass (A), ear count (B), stalk biomass (C), and stalk count (D) at the Delta site for each tile drainage spacing treatment (15- and 30-ft) just prior to silage corn harvest (Fall 2020). The coloured points represent three amendment application treatments (green-control, blue-fall compost application, and pink-typical (spring) compost application. Significant differences (p > 0.05) are indicated in bold for tile drainage spacing. No significant differences between amendment treatments, at either level of tile drainage spacing. Error bars show ± standard error (SE) of the mean.

4. Discussion

4.1 Plant available nitrogen and electrical conductivity

Overwinter cover type significantly influenced PAN dynamics. In the spring after overwinter cover treatments, NO_3^--N was significantly higher under tarps relative to cover crops or no-tarp conditions in both the regional and experimental trials. These results were expected given the impermeable nature of the polyethylene tarps, which inhibited at least some water flow through the soil profile, likely reducing leaching. Given the net negative charge of soil colloids, anions such as NO_3^- are more likely to be lost to leaching than cations such as NH_4^+. Thus, one of the posited mechanisms for increased NO_3^--N under tarps, the reduction of water flow through the soil, is likely why tarps significantly impacted NO_3^--N and not NH_4^+-N. This finding is consistent with the work of Rylander et al. (2020a) who observed no difference in NH_4^+-N concentration between tarp and no-tarp trials despite observing significant differences in NO_3^--N by treatment type. Results from the experimental trial indicate that impacts from overwinter cover type on PAN may last into the growing season and, in some cases, influence post-harvest NO_3^--N. This result underscores the need to consider overwinter cover in fertility planning for organic growers.

In the experimental trial, soil PAN with tarp cover at UBC Farm and GRF Farm increased between 4-PH sampling in 2020 and 1-TR sampling in 2021. No fertility amendments were applied between these sampling dates, so the increase is likely due to mineralization of N from SOM or previously applied amendments. The relationship between NO_3^--N and overwinter tarping has potentially important agronomic and economic implications for growers. PAN is often a limiting growth factor for early spring crops; the boost of NO_3^--N from tarped soil may be important for growers in planning fertility applications. Relatedly, sources of N often come from off-farm sources, such as compost or organic fertilizer, both with an associated financial cost. Soil sampling to account for residual spring NO_3^--N could enable farmers to reduce fertility inputs for early spring or first succession crops. The estimation of residual NO_3^--N is complicated by several factors. Total NO_3^--N measured in the spring is likely related to post-harvest residual NO_3^--N, meaning that fertility application rate in the previous growing season will impact the amount of NO_3^--N available in the soil after overwinter tarping. More information about these other factors is required before actionable information can be given to farmers that is specific to their operation. Further, soil type, soil moisture, and soil temperature may impact NO_3^--N under overwinter tarps. Despite the variability in these factors, which were represented across the regional farms in this study, the results indicate that overwinter tarping increased spring soil NO_3^--N relative to fallow conditions. This finding is consistent with the work of Rylander et al. (2020a) who found that soil NO_3^--N increased with increasing tarping duration in a study focused on the impact of tarp use and duration on soil and crop properties on three organic vegetable farms in the Northeastern United States.

The difference in NO_3^--N between overwinter treatments was more pronounced in the experimental trial than the regional trial; this may be due to the impact of the cover crops. Cover crops take up soil NO_3^- during their establishment and growth, lowering available soil NO_3^-. In the regional study, most sites did not have established cover crops over the winter or at the time of soil sampling in the spring. Thus, in this study, residual NO_3^--N from the growing season was either leached from the sampling depth (0-15 cm) or held by the soil but not held in plant biomass. This finding illustrates a clear benefit of overwinter tarping when cover cropping is not possible. The PAN provided from cover crops via N fixation or release from decomposition of cover crop biomass can provide a sizeable quantity of crop N requirement (Sullivan et al., 2019). The quantity of PAN available from cover crops is important information for growers in comparing the impact of overwinter cover on spring N dynamics and is assessed in Chapter 3.

The accumulation of NO_3^--N under overwinter tarps is likely related to the elevated measures of EC. EC is an indicator of soil salinity; the ions present in soil solution or loosely held by soil colloids. It is presumable that the mechanism that results in the accumulation of NO_3^--N under tarps also results in the accumulation of other anions over the winter. These anions may be important plant nutrients, but in high quantities, these salts can impede plant growth. EC levels above 1.0 dS m^{-1} are deemed detrimental to crop health (Smith & Doran, 1997). EC has been correlated with yield and is an important indicator of soil health (Smith & Doran, 1997). Accumulation of soil salts has been observed with the use of plasticulture, such as low tunnels, high tunnels or greenhouses, which alter the hydrology of the soil by excluding infiltration of rainwater into the soil (Hu et al., 2012). All EC measurements obtained on both experimental and regional sites were below the 1.0 dS m^{-1} threshold in both years of this study indicating that EC did not increase with the use of overwinter tarping from the first to the second year of study. The long-term impacts of this practice on soil EC need to be investigated especially in salinity-prone regions such as the Lower Fraser Valley (Climate Action Initiative, 2015).

One potential advantage of overwintering tarps may be the early season availability of NO_3^-N. The timing of this available N source for crops is notable on farms that rely on carbon-based (organic) forms of nutrient amendments such as compost and cover crops. Nitrogen mineralization from SOM is a microbially-mediated process and is therefore impacted by soil conditions such as moisture and temperature (Miller & Geisseler, 2018). Nitrogen mineralizes slowly in the low temperatures of early spring, which may result in a deficit for early season crops. Increased NO_3^--N associated with overwinter tarps in this study imply a possible benefit to crops planted in soils where temperatures are limiting N mineralization from organic matter.

While many factors must be considered when determining farm-specific optimal timing for tarp removal in the spring, the length of time between tarp removal and planting is an important consideration. Once tarps are removed the soil is exposed to rainfall and potential leaching of NO_3^-, reducing the NO_3^- available for plant uptake. Further, the density and modality of planting will impact the capture of NO_3^- by plants; transplants with developed roots systems may be able to utilize residual NO_3^- more quickly than direct-seeded crops. However, management decisions based on spring available NO_3^- must be balanced against other farm management considerations. Several grower participants in the regional trial remarked that winter tarped ground was more ideal for direct seeded crops because unlike cover cropped areas, the beds were relatively free of debris and decomposing biomass. The conditions of the previously tarped soil were more favorable for the operation of a push seeder that enabled desirable plant spacing and germination rates.

The only significant difference on PAN between nutrient treatments was observed at GRF in 2020. PAN in the C+F treatment was substantially elevated compared to HC, LC, and CON at the 3-MS sampling date. This is likely due the timing of nutrient application rate; at GRF in 2020 treatments were applied at the time of planting while in all other instances nutrients were applied 9-22 days before planting. Several other studies have identified the asynchrony between PAN mineralization and crop requirement to be the source of variation in soil PAN and N recovery by organic vegetable crops (Berry et al., 2003; Pinto et al., 2016). In a two-year study of differing compost rates on soil NO_3^--N and N, carryover found that soil NO_3^--N concentrations were a function of the compost application rate, generally increasing with increasing compost application (Olsen et al., 2015). While such a clear trend was not observed here, differences in methodologies and application rates between studies may be the cause. Differences in PAN were observed between years both in total PAN and the trend over the growing season. These differences highlight some of the difficulties in accurately calculating application rates for diversified farms, several of which are relevant in this study. N enters organic growing systems through several avenues. In this study, N sources outside of the treatments included N fixation (e.g.

legumes), cover crop decomposition, and SOM mineralization. These additional sources of N make it difficult to tease apart the impact of N from the treatment sources on PAN and yield.

Crop species likely impacted the increase in PAN between 2020 and 2021 on both farms. *Biei* and *Teggia* beans were grown in 2021, both of which fix atmospheric N through their associations with *Rhizobium* bacteria. It is assumed that biological N fixation added to the pool of PAN throughout the season. This is evidenced by increased PAN in the CON plots in 2021 as compared with 2020 despite neither compost nor fertilizer inputs to CON in either year. Further, post-harvest PAN was greater on both farms in 2021, another indication that more PAN was being added to the system over the course of the season. N fixation by the bean crops may also explain the difference in trends between 2020 and 2021 at UBC Farm. PAN at 3-MS and 4-PH P was greater in 2021 than 2020. This trend, however, is not as clear at GRF Farm. While it is assumed that legumes will fix atmospheric N, fixation depends also on the presence of *Rhizobium* bacteria in the soil and other soil conditions including the presence of mineralized N (Murphy et al., 2017). These factors highlight the difficulty in assessing individual fertility strategies with N fixing crops.

The methodologies used to calculate nutrient application rate may have influenced both growing season PAN and post-harvest PAN measurements. Application rates were calculated based on crop requirement; however, only N estimated to be released from compost and feather meal was credited. N dynamics were likely influenced by decomposing cover crops and mineralizing SOM over the growing season. Depending on the ratio of legume to cereals in the cover crop mix and the timing of termination, cover crop biomass may immobilize or mineralize N over the growing season (Sullivan et al., 2019). Given the legacy nutrient applications and high SOM, especially at UBC Farm, it is assumed that N from SOM mineralized during this research but was unaccounted for in amendment quantity calculations. These factors lend themselves to the over application of compost and feather meal as the N credit is likely underestimated. To increase the precision in targeting crop removal N, an agronomic model could be used in the future. This model would credit N mineralization from SOM, cover crops, compost, and fertilizer to determine the quantity of N to be supplied by the nutrient treatments that would meet, but not greatly exceed, crop requirement.

High post-harvest PAN represents both an environmental threat and an economic inefficiency for growers. In 2020 at both UBC and GRF, average observed 4-PH PAN in all nutrient treatments was below 20 mg NO_3^--N kg^{-1} soil. This is below the threshold of 25 mg NO_3^--N kg^{-1} (corresponding to 100 kg NO_3^--N ha^{-1}) outlined by the BC Ministry of Environment's Agricultural Environmental Management Code of Practice above which may require follow-up soil testing (Government of British Columbia, 2019). This protocol aims to reduce the instance of NO_3^- leaching and subsequent environmental impacts. Substantial amounts of N were left over after the growing season in 2021. At UBC Farm in 2021, all nutrient strategies but not the control averaged above 25 mg PAN kg^{-1} soil. At GRF Farm in 2021, all nutrient strategies and the control averaged above 25 mg PAN kg^{-1} soil. These results indicate that N was overapplied in the spring. Norgaard (2020) also observed high post-harvest PAN values on organic vegetable farms in BC. Precipitation rates in South Coastal BC are more than adequate to leach all the remaining NO_3^- prior to the onset of the following spring (Odhiambo et al., 2012). Most NO_3^- leaching occurs over the winter, making the reduction in post-harvest N a priority to minimize N losses (Berry et al., 2002). This underscores the value of winter cover in organic vegetable systems, especially following a N fixing cash crop. Winter cover crops must have well established root systes prior to heavy winter precipitation to effectively scavenge PAN from the soil (Berry et al., 2002). In South Coastal BC, Odhiambo et al. (2012) found that winter cereal cover crops scavenged more than 3-fold the N when planted in the third week of August as compared to the third week of September.

At UBC Farm, PAN differences by overwinter treatment remain pronounced in all nutrient amendment strategies at 1-TR, 2-PL, and 3-MS in 2021 when there was ample PAN in the system. This is in contrast with 2020, when by the 3-MS sampling date PAN was close to zero in all treatment types. It appears that differences in PAN between overwinter cover type persisted longer into the season when total PAN was greater. Notably, only the HC treatment maintained differences in PAN between overwinter cover type at the 4-PH sample in 2021. This may be because N continued to mineralize out of the compost later into the season in this high application whereas in the LC and C+F N had mineralized prior to the end of season. However, these trends were not observed at GRF Farm. In both 2020 and 2021, the C+F treatment had the highest post-harvest PAN, although C+F was statistically greater than HC, LC, and CON in 2020 only. At GRF at the 2-MS 2020 sampling time, C+F PAN was notably higher than all the other treatments at that time. This is possibly because the N from the feather meal mineralized quickly but was not needed by the crops in the quantity released resulting in high measures of soil PAN. At GRF in 2020, treatments were applied on the date of planting which differs from UBC Farm and GRF in 2021. This shift in application timing may also relate to the increased PAN measured at 3-MS in 2020.

4.2 Volumetric water content (VWC)

Under tarp VWC was equal to or greater than cover crop or fallow treatments at the time of tarp removal. This is consistent with the findings of Rylander et al. (2020a) who observed that at the time of tarp removal (April - July), soil water was significantly higher under tarps compared with no-tarp treatments in five out of ten on-farm trial sites. They also found soil water insignificantly increased in three trials, and in the two remaining experiments, soil moisture was equivalent. The impact of tarping on soil moisture depended on farm location and soil type (Rylander et al., 2020a). In studies conducted during the growing season, it has been observed that the use of black plastic tarps modulates VWC and prevents large swings in soil water content associated with rainfall events (Lounsbury et al., 2020). A similar effect was observed at UBC Farm during the winters of 2019/2020 and 2020/2021. During this season of heavy precipitation and low temperatures, lower VWC was recorded underneath the tarps, suggesting that the tarps kept rainfall from infiltrating into the soil.

The relationship between soil moisture and soil workability underlies the importance of its measurement with respect to overwinter soil cover type. While optimum soil moisture for tillage is dependent on both soil texture and SOM content, the results of this study show that the type of overwinter cover influences spring soil moisture. Further, when comparing the impact of tarps to cover crops, the timing of tarp removal is likely to have a significant effect on soil moisture. Data from UBC Farm indicate that there was a critical management window in mid-March, during which the VWC of tarped areas stayed relatively constant, while VWC of cover cropped areas began to decline. It is possible that this change was caused in part by increasing spring temperatures and daylight hours, both stimulating evaporation and plant growth in the cover crop plots moving water from the soil into the air and plant biomass. At UBC Farm, tarps should have been removed approximately four weeks earlier if the growers' intention was to minimize soil water content. While this finding is specific to the soil and climate conditions at UBC Farm, there are likely similar VWC management windows that can be used to make tarp removal decisions to meet specific objectives (e.g., to conserve or reduce soil water content). These results would be augmented by the calculation of soil workability thresholds given SOM and soil textures of the participating farms. Threshold values could help growers identify whether tarping increases soil workability windows in the spring. With expected increased in precipitation due to climate change, it is possible that these management windows will shift. Relative to cover crops, tarps require less time and effort to move fields in and out of production in high soil water conditions. This advantage may become more evident in unpredictable and wet shoulder seasons.

The ideal timing of tarp removal is also dependent on the growers' approach to spring bed preparation. While in many cases annual growers perform some form of tillage prior to planting a cash crop, some growers use tarps to reduce or eliminate the tillage required to transition into the growing season. In these cases, particularly on course textured soils, it may be the growers' intention to hold water in the soil with the use of tarps until the time of planting. The results from both regional trial and UBC Farm indicate soil covered with tarps retained more water later into the spring relative to fallow or cover cropped ground. In this trial tarp removal dates ranged from April 13 to 27, 2020 and March 29 to May 3, 2021.

Several on-farm factors not measured in this study are likely to influence under tarp spring soil moisture. Tarp size, bed design topography, and soil type are all likely to influence the way that water may enter the soil under the tarp. Tarps with a higher area to perimeter ratio likely provide more reliable soil coverage because there is more soil area that is not near a tarp edge from which water may wick under the tarp by capillary action or run under the tarp by gravity. In some cases, small-scale growers in this study were managing tarps on a bed-by-bed basis using tarps as small as 1.5 × 7.6 m. The water dynamics underneath such a tarp are likely to be different than that of some of the larger tarps utilized by growers, an example from this study being 3.7 × 30.5 m.

No clear relationship was observed in this study between spring VWC and nutrient amendment treatment. Soil VWC can fluctuate greatly with rainfall; a single snapshot in the spring does not give a clear picture of the influence of the nutrient treatment at GRF Farm. Soil texture may be responsible for some of the differences observed between UBC Farm and GRF Farm. Nutrient treatment was significant in explaining differences in VWC over the course of the study at UBC Farm. Differences between treatments were more pronounced during the off-season compared with the growing season. Interestingly, VWC in the C+F trended the lowest from November 2019-April 2020 when overwinter cover was removed. This was prior to the nutrient application in April of 2020 so it is likely this difference occurred due to a factor outside of the applied treatments. Nutrient amendment strategies are also expected to impact soil carbon in the long term. Differences in soil carbon may also impact VWC. Legacy compost applications have created high SOM conditions at UBC Farm across all plots. Total C at UBC Farm ranged from 5.7% in the CON plots to 6.5% in the HC and LC plots in 2021. These values are much greater than the <2% total C that is typical of a Podzolic, coastal Douglas-fir soil (Luttmerding, 1981). Since the establishment of the original nutrient amendment trial at UBC Farm in 2015, these fields have received varying levels of compost and fertilizer applications. These amendment strategies may be one of the drivers behind the differences between treatment total C. Water retention is impacted by SOM, especially in a course textured soil like that of UBC Farm. As there is a low clay content in this soil, SOM is likely to be the driver of water holding capacity.

Results from the Delta site indicate that tile drainage has a clear impact on early-season soil moisture. Given our limited ability to travel to the site, we were unable to track changes in soil moisture throughout the spring season and thus are not able to assess how these differences would translate into an increased number of workable days. Nor were we able to evaluate the interaction between these changes in soil moisture and the availability of N.

4.3 Yield

While no significant differences in crop yield were observed at UBC Farm in either year or at GRF Farm in 2020, there are a variety factors that may contribute to these results. Beet, fennel, and bean crops were harvested in August-September 2020 and 2021 at least five months after tarp removal. There are many farm management decisions that influence crop yield occurring between overwinter cover and harvest, including irrigation method and quantity, nutrient amendment strategy, pest presence, and disease presence. After tarp removal, nutrients were applied to both previously tarped and cover cropped plots that did not account for the differences in early season NO_3^--N observed between overwinter treatments. This amendment application may have masked any yield differences that could have been caused by differences in NO_3^- resulting from over winter treatments. Nitrogen fixation by legume crops may have further contributed to a masking effect by supplying additional NO_3^-. Crop yields of short-season spring crops, such as cutting greens, radishes, or lettuce, may be differently affected by overwinter cover type because of the reduced time between overwinter treatment and harvest. Further, there may be differences in yield per unit of labor associated with overwinter soil cover type not captured by this study. At GRF in 2021, bean yield from the cover crop treatment was significantly higher than the tarp treatment. This difference is likely due to factors other than overwinter cover type, namely germination issues associated with extreme heat events occurring in the summer of 2021.

While tillage practices in the experimental trial were reflective of typical methods on organic farms, Rylander et al. (2020b) found that the use of tarps was important to yield for no-till and reduced-till systems. The use of tarps in their study significantly increased yield across all types of tillage. Importantly, Rylander et al. (2020b) observed a significant interaction between tarp and tillage treatments, yield of reduced-till and no-till trials were only comparable to conventional till when tarps were used for at least three weeks in the late winter or early spring. When tarps were not used in reduced and no-till systems, beet yield was significantly less than the conventional till; this is likely because of the observed reduction in weed pressure with the use of tarps (Rylander et al., 2020b). This finding is supported by the work of Lounsbury et al. (2020) who similarly found that the use tarps as a termination method for overwinter cover crop suppressed weeds and increased organic no-till cabbage yield. The results from these studies indicate that tarping may facilitate the productive use of reduced tillage management. This can be considered a climate change adaptation tool because of the challenges associated with shoulder season tillage due to increased precipitation and the potential detriment to soil health from excess or improperly timed tillage.

Nutrient amendment treatment did not significantly impact yield in this study. This finding has both logistical and financial implications for growers. Compost is often a costly input for growers and can be laborious to apply to fields; lower application rates correlate with lower fertility expenses for growers. This threshold is likely to be mediated by other soil properties including SOM, pH, and available nutrients. UBC Farm in particular has very high SOC, well above the ~2% SOC threshold above which yield increases level off (Oldfield et al., 2019). Additionally, this finding must be tempered by the understanding that additional sources of nutrients were being supplied beyond the treatment applications. Decomposing cover crops, soil organic matter, and N fixation by the bean crops all likely supplied yield limiting nutrients such as PAN. The impact of the nutrient treatments would be clearer if the methodology for calculating application rate were refined to include these addition sources of N and other nutrients. The timing of nutrient application relative to crop need could also influence crop yield. Evanylo et al. (2008) found no significant differences in organic bell pepper or pumpkin yield based on organic nutrient amendment strategy but did see differences in corn yield. Evanylo et al. (2008) attributed the differences observed in corn yield to the asynchrony between N mineralization from compost and the timing of corn N requirement. At our Delta site experiment, we also did not observe yield differences for silage corn between fall-applied low PAN compost and spring-applied high PAN compost suggesting that this might be an important alternative to consider for farmers seeking greater flexibility in response to shifting precipitation patterns. However, given that we also did not observe significant differences with the control and were not able to evaluate the potential for N losses during the winter or follow these treatments for a second season we cannot recommend this approach at this time.

5. Future Research Directions

Future research should employ agronomic models for estimating PAN release. Several datasets and methodologies could be improved to facilitate our understanding of PAN dynamics. To this end, soil tests should be developed for farm systems that rely primarily on carbon-based amendments and organic fertilizers. Of particular interest are the findings of increased soil NO_3^--N with the use of overwinter tarps. In conversations with growers, it became clear that one barrier to integration of this knowledge into on-farm decision making is the lack of tenable farm-scale options for NO_3^--N testing. The measurement of PAN in both trials was conducted using time sensitive lab methods which are not commercially available to growers at this time. Further, samples must be extracted while fresh (within 72 hours), creating another logistical barrier to farmers wishing to use soil NO_3^--N levels to adjust spring fertility applications. The improved accuracy of spring amendments has the potential to positively impact economic and environmental outcomes for growers. More specific and accurate yield estimate for organic annual vegetable crops would improve the precision of nutrient amendment studies. Most of the existing data to quantify vegetable yield comes from conventional large-scale systems. Ideally estimated yield would be given on a 100 bed-foot basis to calculate scale appropriate amendment quantities. With the focus on N movement on organic farms, a deeper understanding of biological mediation in the N cycle may help to illuminate factors underlying N release and inform management practices.

Based on commentary of growers and recently published research (Rylander et al., 2020a; 2020b), there is potential for tarping and cover cropping to be used in concert. In circumstances where the primary barrier to cover cropping is high spring soil moisture and not fall planting timing, tarps can be used to minimize or eliminate spring tillage and terminate cover crops. This approach has the potential to be used as a climate change adaptation technique by facilitating living overwinter cover and decreasing spring soil disturbance. Systems-level investigation into the specifics of tarp installation timing and duration would provide information required to substantiate recommendations for growers.

With respect to VWC, the identification of soil workability thresholds relative to VWC associated with overwinter cover and nutrient amendment strategies is required to provide recommendations to growers. To develop the dataset necessary for this connection, VWC throughout the spring should be measured under different management strategies on different soil textures in differing geographic regions. Pedo-transfer functions have been developed to determine soil workability functions (Paul et al., 2020), however, more investigation is needed into high SOM and low clay soils. Accurate thresholds for soil moisture to determine tillage timing will only go so far for adoption of these numbers into actionable on-farm management. Growers are not generally using technology to determine VWC in the field, so work must be done to connect in-field metrics to VWC. Funding for on-farm weather stations or portable VWC devices would likely improve the adoption of recommendations to come out of further study of soil moisture thresholds to tillage.

Many growers who participated in this study expressed one of their primary concerns about the use of silage tarps being the lack of available plastic recycling. This concern was not isolated to silage tarps as many farm inputs are plastic products, such as irrigation, plastic mulch, greenhouses, and harvest containers. The fate of these plastic products speaks directly to the sustainability of their use. Organizations such as Cleanfarms (Etobicoke, ON) are currently working to recycle agricultural plastics; however, there is currently no options to recycle silage tarps in BC. Some mechanisms exist for growers to acquire silage tarps second hand from dairy or nursery operations, but in the regions of this study, there are no options for recycling beyond their lifespan as on-farm ground cover.

6. Conclusion

Overwinter soil cover and nutrient amendment strategy both strongly influence the ecological and economic outcomes of organic farms. To validate the findings of two replicated studies across the geographic variation of Southern BC, 12 additional farms in three agricultural regions were included in this project. This study showed that tarps significantly influenced spring soil nitrate (NO_3^--N), electrical conductivity (EC), and soil volumetric water content (VWC) relative to cover crops or fallow ground. Trends observed at University of British Columbia (UBC) and Green Fire (GRF) Farms held true in the regional experiment despite differences in climates and soil types. NO_3^--N was elevated under tarps in every region. EC did not increase between the first and second year of study in the tarp treatment, indicating that salts were not building up in the soil with the use of over winter tarps. VWC dynamics were more complex; results from UBC Farm, located on a coarse textured loamy sand to sandy loam soil, indicated that tarps may keep the coarse soil drier over the winter but wetter into the spring than cover crops. While the timing for this switch in VWC between overwinter cover types was observed to be mid-March at UBC Farm, this management important window of shifting soil moisture will likely vary with soil type and climate. No differences in yield between overwinter cover types were observed in this study; however, an analysis of the impact of tarps on labour requirements for ground preparation and weed management may reveal a more complex picture. Tarps show potential to be a valuable tool for small-scale organic growers in circumstances when adequate winter protection cannot be provided by cover crops. Based on conversations with growers involved in this study and beyond, tarps are valued by growers for their ability to reduce tillage in organic vegetable systems. This is an important strategic advantage to traditional cover cropping in a changing climate.

The results from the nutrient amendment experiment at UBC and GRF Farms were less clear with few differences observed between the high compost (HC), low compost (LC), and compost + fertilizer treatments (C+F) and no differences at the Delta site for compost timing were observed. It was expected that PAN would decrease with decreasing compost application throughout the growing season. However, no clear trend was observed over the course of the growing season between PAN and nutrient amendment strategy. These results highlight the difficulty of estimating N dynamics in organic systems. A more accurate calculation of amendment treatment application rate relative to additional sources of N may reveal a clearer relationship between compost application in PAN. The data collected in 2021 when a N-fixing legume crop was grown illustrates how additional N can have a modulating effect on PAN. Interestingly, while there was no statistically significant effect of interaction of overwinter cover type and nutrient amendment type on PAN, another trend was observed under high N conditions. In 2021 at UBC Farm, when PAN was relatively high throughout the growing season, the initial relative difference between tarp and cover crop PAN levels remained throughout the season. The longevity of this relationship was apparent in the measure of post-harvest PAN. Post-harvest PAN was concerningly high and represented a significant risk of leaching. Residual N also represents a significant economic value to the growers, reiterating the need for effective overwinter cover that preserves this resource for the following growing season and protects it from loss to the detriment to the surrounding environment. No consistent impact to EC by nutrient amendment strategy was observed. Few conclusive findings can be drawn from the spring VWC data collected at the regional sites in this experiment. Continuous measurement of VWC at sites with differing soil texture and SOM may show interesting effects of nutrient amendment strategies. Relative crop yield was not reliably impacted by nutrient amendment strategy. This information can be contextualized by differences in economic cost of amendment strategies; however, the lack of differences could be due to abundant PAN across strategies. Management implications for growers

In South Coastal BC, cover crops must be established in late summer to achieve adequate root development to scavenge residual N, however, harvest of many vegetable crops persists late into the fall. Asynchrony between cover crop planting date and timing of vegetable harvest is exacerbated by predictions of the climate change. With predicted increases in the fall and spring precipitation, it becomes more difficult for famers to move fields in and out of production. The benefits of cover cropping must be weighed against the soil degrading practices of improperly timed tillage relative to soil moisture, and the potential loss of income if crops are terminated early to accommodate cover crop establishment. This project observed that the use of tarps changed both NO_3^--N and VWC dynamics relative to cover crops. Tarps preserved residual NO_3^--N potentially impacting the amendment strategy following an overwinter tarp. Growers may be able to reduce spring N applications following overwinter tarping having potentially positive economic impacts. However, grower accessible PAN testing would improve the confidence of growers to rely on such information. Further study is required to provide adequate quantification of these tarps on spring NO_3^--N before producer action can be expected.

On a course textured soil in South Coastal BC, silage tarps reduced overwinter VWC relative to cover crops until mid-March when VWC under the tarps measured higher than the cover crops. This finding indicates that there is likely a window in the early spring when tarps should be removed if the management goal is to minimize soil moisture. This finding is particularly important for systems that require spring tillage or for systems on course textured soils that may want to preserve soil water into the late spring.

In this project, no differences were observed between a high (15% mineralization) and low (30% mineralization) compost application. This suggests that growers may be able to opt for a more conservative compost application rate without experiencing a reduction in yield. However, this finding would be strengthened if application rates were calculated using an agronomic model that accounted for nitrogen (N) mineralization from cover crops, soil organic matter (SOM), and biological N fixation. While no significant interactions were observed between nutrient amendment strategies with farm and year, trends indicate the impact of overwinter cover had impacts on NO_3^--N that lasted into growing season when NO_3^--N levels remained high.

7. References

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8. Appendix

Appendix A – Experimental design

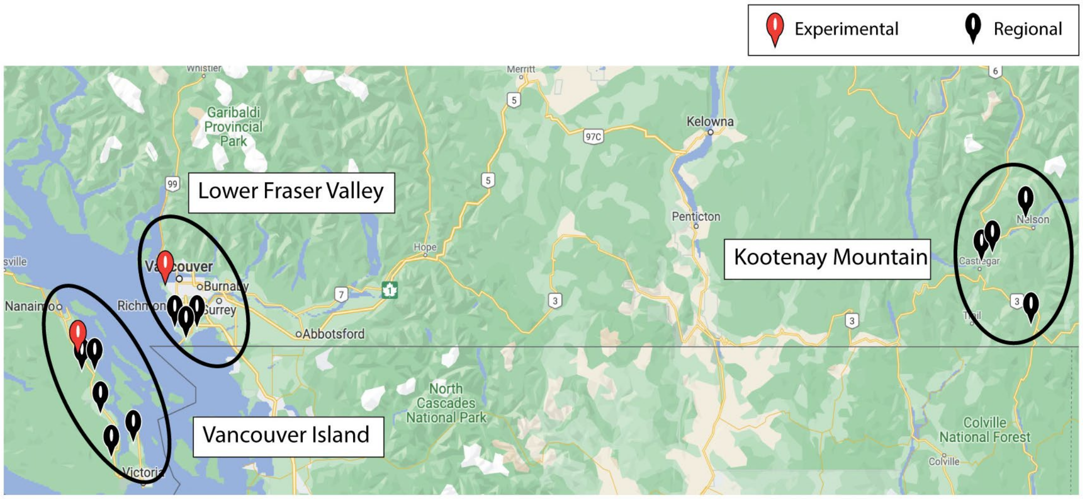

Figure 8. Study site locations in BC for experimental and regional farms in three regions: Lower Fraser Valley (LFV), Vancouver Island (VI), and Kootenay Mountain (KM).

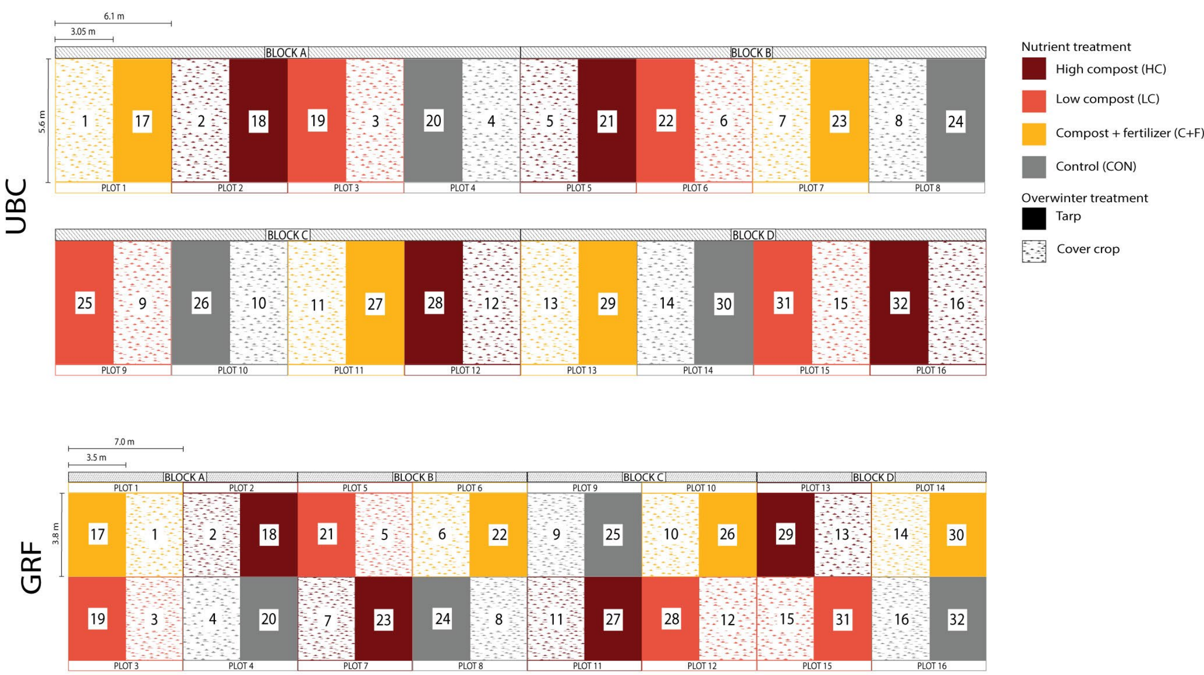

Figure 9. Layout of University of British Columbia Farm (UBC; top) and Green Fire Farm (GRF; bottom) study sites.

Table 2. Plot sizes and dates of installation and removal by unique site identifier (ID) and region (REG; Lower Fraser Valley [LFV], Vancouver Island [VI], Kootenay Mountain [KM]). Dates of tarp installation correspond to soil sampling dates on regional farms. Dates of tarp installation correspond to soil sampling on regional farms and 1-TR sampling on experimental farms.

REG	ID	Plot (m)	Tarp dimensions (m)	Date of tarp install. 2019	Date of tarp removal 2020	Date of tarp install. 2020	Date of tarp removal 2021
LFV	UBC	3.1 x 11.2	3.1 x 5.6	Oct-16	Apr-21	Oct-16	April 26
	40	9.1 x 18.2	9.1 x 9.1	Oct-15	Apr-13	Oct-29	April 6
	246	3.0 x 9.2	3.0 x 4.6	Nov-22	Apr-20	Nov-11	April 6
	35	3.7 x 60.1	3.7 x 30.5	Mar-5	Apr-20	Oct-7	April 6
VI	GRF	3.8 x 7.0	3.8 x 3.5	Oct-29	Apr-27	Oct-8	May 3
	54	10.4 x 31.1	5.2 x 31.1	Oct-29	Apr-15	Oct-15	April 28
	242	3.0 x 40.2	3.0 x 20.1	Dec-5	Apr-17	Dec-1	March 29
	243	1.5 x 15.2	1.5 x 7.6	Oct-29	Apr-15	Sep-30	March 29
	244	2.1 x 18.2	2.1 x 9.1	Oct-11	Apr-17	Sep-17	April 28
	245	9.0 x 66.0	4.5 x 33.0	Oct-11	Apr-15	Dec-29	March 29
KM	237	2.7 x 15.2	2.7 x 7.6	Nov-11	Apr-24	Sep-15	April 14
	238	2.4 x 30.5	1.2 x 30.5	Nov-11	Apr-24	Nov-2	April 14
	239	6.0 x 27.4	3.0 x 27.4	Nov-11	Apr-24	Nov-15	April 21
	240	2.4 x 30.5	1.2 x 30.5	Nov-11	Apr-24	Oct-30	April 14

Table 3. Soil series, drainage, winter cover, and crop type information for regional and experimental farm sites by unique site identifier (ID) and region (REG; Lower Fraser Valley [LFV], Vancouver Island [VI], Kootenay Mountain [KM]).

REG	ID	Soil series	Drainage	No-tarp cover 2019/20	No-tarp cover 2020/21	Crop 2020	Crop 2021
LFV	UBC	Bose	Moderately well	Cover crop	Cover crop	Beets, fennel	Beans
	40	Spetifore, Guichon	Poor	Cover crop	Crop residue	Corn	--
	246	Ladner	Poor	Cover crop	Cover crop	Lettuce	--
	35	Crescent	Poor	Bare	Cover crop	Potatoes	--
VI	GRF	Fairbridge	Imperfect	Cover crop	Cover crop	Beets, fennel	Beans
	54	Tolmie, Fairbridge	Poor -imperfect	Cover crop	Crop residue	Beets	--
	242	Mill Bay	Moderately well - imperfect	Bare/ residue	Cover crop	Cover crop	--
	243	Somenos	Well	Bare	Cover crop	Potatoes	--
	244	Fairbridge	Imperfect	Bare	Bare	Beets	--
	245	Tagnar	Poor	Cover crop	Crop residue	Carrots	--
KM	237	Burtontown	Well	Bare	Bare	Carrots	--
	238	Avis	Well - poor	Crop residue	Crop residue	Cabbage	--
	239	Gillis	Well	Bare	Cover crop	Bok choi	--
	240	Avis	Well - poor	Crop residue	Crop residue	Beets	--

– Climate data

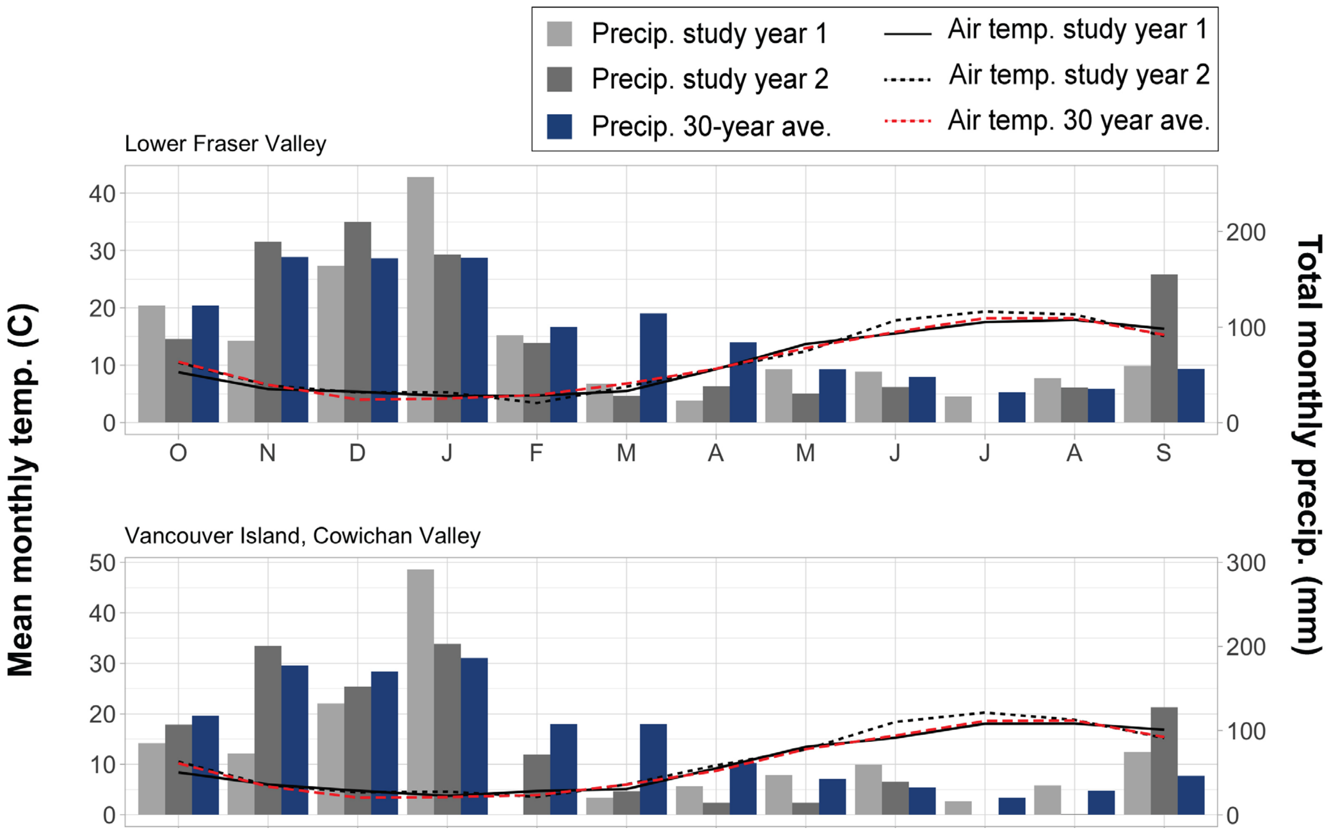

Figure 10. Average monthly temperature (°C) and total monthly precipitation (mm) for the experimental farm regions: Lower Fraser Valley (YVR station) and Vancouver Island (North Cowichan station). Information shown for study year 1 (October 2019-September 2020), study year 2 (October 2020-September 2021), and 30-year average (1991-2020).

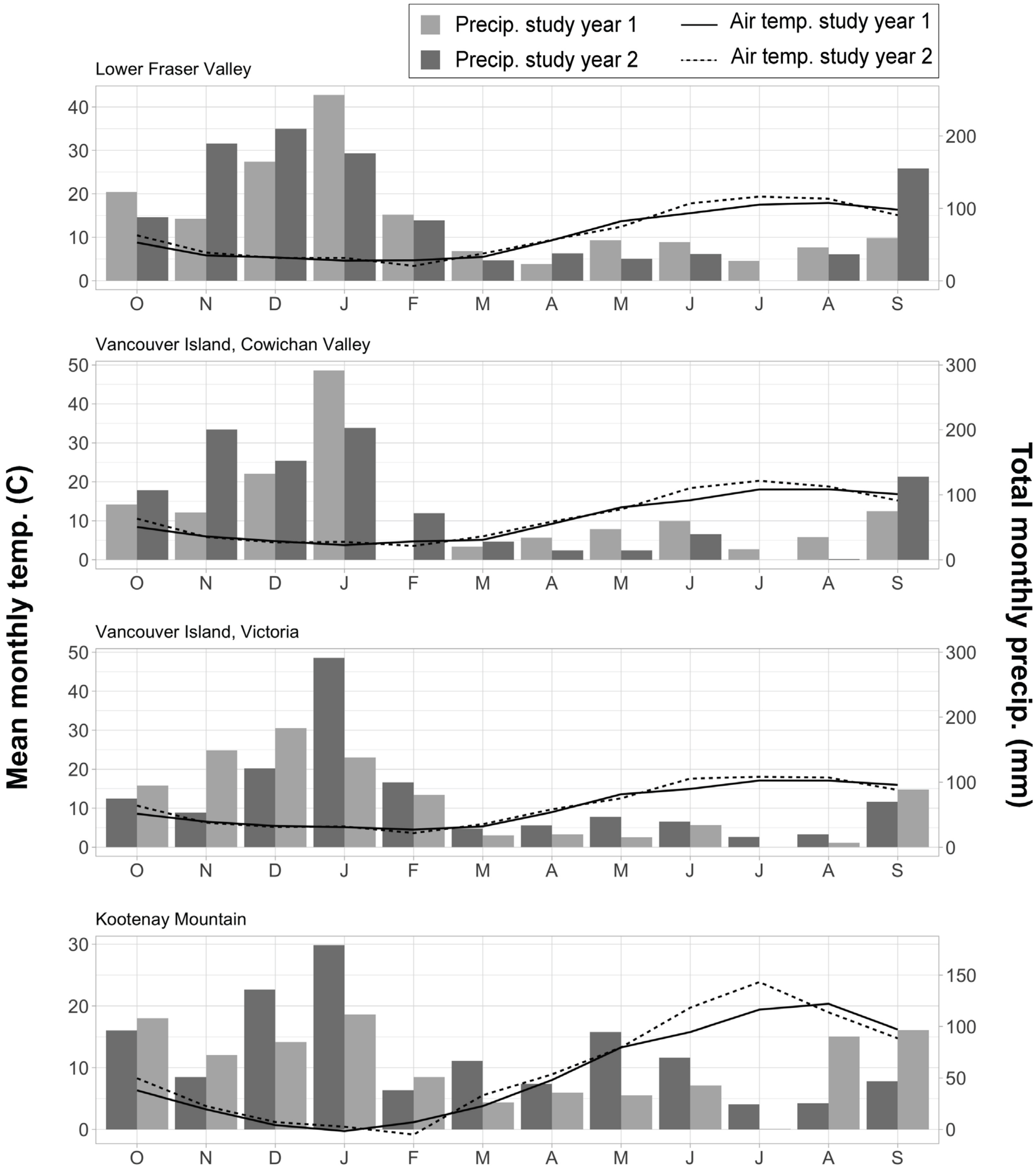

Figure 11. Average monthly temperature (°C) and total monthly precipitation (mm) for relevant geographical regions: Lower Fraser Valley (YVR station), Vancouver Island (North Cowichan station, YYJ station), and Kootenay Mountain (Nelson NE station). Information shown for study year 1 (October 2019-September 2020) and study year 2 (October 2020-September 2021).

Table 4. Spring 2020 soil properties by region (REG) and farm site identifier (ID) including texture (% sand, silt, clay), organic matter (OM), electrical conductivity (EC), and pH. Values are averaged within farm site, regional farms (n=2), UBC Farm (n=32), GRF Farm (n=32). Standard error of the mean is reported in parentheses. Texture n=2 exect at GRF Farm n=1.

REG	ID	Texture	Sand	Silt	Clay	OM	EC	pH
			%	%	%	%	dS m^{-1}	--
LFV	UBC	Sandy loam	71.3 (0.6)	23.9 (0.5)	4.8 (0.1)	7.8 (0.2)	0.30 (0.02)	6.4 (0.0)
	35	Silty clay loam	4.7 (0.7)	65.5 (1.5)	30.0 (1.0)	1.6 (0.3)	0.45 (0.08)	6.0 (0.1)
	40	Loam	48.0 (3.0)	39.5 (2.5)	13.0 (0.0)	2.9 (0.9)	0.24 (0.02)	5.7 (0.2)
	246	Silt loam	26.5 (3.5)	56.5 (2.5)	17.5 (0.5)	5.3 (0.6)	0.25 (0.03)	6.5 (0.1)
VI	GRF	Silty clay loam	17.6	53.7	28.7	4.8 (0.2)	0.22 (0.01)	6.1 (0.1)
	54	Clay loam	29.5 (0.5)	43.0 (1.0)	28.0 (1.0)	10.8 (0.2)	0.29 (0.07)	6.0 (0.0)
	242	Silt loam	42.0 (5.0)	46.5 (3.5)	11.5 (1.5)	8.0 (1.7)	0.37 (0.04)	6.1 (0.0)
	243	Sandy loam	57.5 (1.5)	35.5 (0.5)	7.1 (0.7)	7.7 (0.2)	0.29 (0.08)	6.5 (0.0)
	244	Silt loam	17.5 (0.5)	55.0 (2.0)	27.5 (1.5)	7.5 (0.3)	0.27 (0.05)	5.9 (0.1)
	245	Loam	40.0 (0.0)	47.0 (0.0)	13.0 (0.0)	9.5 (0.2)	0.35 (0.07)	5.8 (0.0)
KM	237	Silt loam	24.5 (1.5)	55.5 (1.5)	20.0 (3.0)	8.4 (1.7)	0.30 (0.13)	6.4 (0.3)
	238	Silt loam	26.5 (1.5)	57.0 (1.0)	16.5 (0.5)	15.3 (1.0)	0.27 (0.03)	5.3 (0.2)
	239	Sandy loam	60.0 (0.0)	32.0 (0.0)	7.7 (0.0)	7.4 (0.1)	0.32 (0.02)	7.0 (0.1)
	240	Silt loam	28.5 (0.5)	57.5 (0.5)	14.0 (0.0)	3.8 (0.1)	0.29 (0.03)	6.5 (0.1)

Table 5. Spring 2021 soil properties by region (REG) and farm site identifier (ID) including bulk density, total nitrogen (N), total carbon (C), electrical conductivity (EC), and pH. Values are averaged within farm site, regional farms (n=2), UBC Farm (n=32), GRF Farm (n=32). KM Total N and total C not reported due to logistical constraints.

REG	ID	Bulk density	Total N	Total C	EC	pH
		g cm^{-3}	%	%	dS m^{-1}	--
LFV	UBC	1.11 (0.02)	0.39 (0.01)	6.15 (0.10)	0.22 (0.02)	6.0 (0.0)
	35	1.29 (0.05)	0.20 (0.02)	2.10 (0.10)	0.31 (0.10)	5.6 (0.0)
	40	1.43 (0.14)	0.16 (0.05)	1.85 (0.55)	0.15 (0.03)	5.1 (0.2)
	246	0.95 (0.13)	0.28 (0.02)	3.75 (0.45)	0.27 (0.12)	6.2 (0.1)
VI	GRF	1.21 (0.02)	0.16 (0.01)	3.03 (0.08)	0.16 (0.01)	6.3 (0.0)
	54	0.95 (0.01)	0.64 (0.02)	6.25 (0.05)	0.19 (0.03)	5.4 (0.0)
	242	1.13 (0.06)	0.33 (0.01)	5.55 (0.25)	0.29 (0.10)	5.8 (0.1)
	243	1.00 (0.03)	0.38 (0.02)	5.45 (0.25)	0.24 (0.09)	6.3 (0.2)
	244	1.04 (0.04)	0.30 (0.02)	4.65 (0.55)	0.30 (0.00)	5.6 (0.0)
	245	0.90 (0.01)	0.53 (0.06)	8.40 (0.20)	0.71 (0.08)	5.3 (0.2)
KM	237	0.89 (0.10)	--	--	0.49 (0.17)	6.1 (0.1)
	238	0.62 (0.00)	--	--	0.45 (0.02)	4.9 (0.1)
	239	0.73 (0.02)	--	--	0.28 (0.10)	6.9 (0.0)
	240	1.14 (0.04)	--	--	0.23 (0.04)	6.2 (0.5)

Table 6. Compost properties for University of British Columbia (UBC) and Green Fire Farm (GRF) Farm in 2020 and 2021 used to calculate nutrient applications organic matter (OM), total nitrogen (N), total carbon (C), ammonium (NH_4^+-N), nitrate (NO_3^--N), C:N, total phoshorus (P), and pH.

2020								
Farm	Date	OM	Total N	NH_4^+-N	NO_3^--N	C:N	Total P	pH
		%	%	ug/kg	ug/kg	--	%	--
UBC	April 4	51.41	2.2	868.26	420.00	13.1	0.74	7.67
GRF	April 27	60.88	1.6	1052.94	60.20	19:1	0.32	6.47

2021					
Farm	Date	Total C	Total N	NH_4^+-N	NO_3^--N
		%	%	mg/kg	mg/kg
UBC	April 26	31	2.1	700	35
GRF	May 3	24	1.2	43	41

Table 7. Nutrient treatment application rates and dates for University of British Columbia (UBC) and Green Fire (GRF) Farms. Nutrient treatments are high compost (HC), low compost (LC), and compost + fertilizer (C+F). Treatments were applied at the plot level. Compost weights were measured wet.

Year	Farm	Date	Treatment	Compost application rate (kg)	Fertilizer application rate (kg)
2020	May 15	UBC	HC	240.9	--
			LC	141.2	--
			C+F	39.1	4.0
	June 8	GRF	HC	197.0	--
			LC	118.2	--
			C+F	35.4	2.1
2021	May 12	UBC	HC	194.3	--
			LC	113.8	--
			C+F	11.5	2.9
	May 17	GRF	HC	158.9	--
			LC	95.3	--
			C+F	16.6	2.2

Table 8. ANOVA results by outcome variable for regional (REG) and experimental trial (University of British Columbia [UBC] Farm, Green Fire [GRF] Farm) with overwinter cover type, region, and cover x region interaction as fixed effects. Outcome variables include spring nitrate (NO_3^--N 1-TR), electrical conductivity (EC), spring volumetric water content (VWC), relative yield, plant available nitrogen (PAN growing season; experimental farms only), post-harvest plant available nitrogen (PAN PH-4; experimental farms only), and 2-year volumetric water content (VWC; UBC only).

Models *Experimental study*: Y~Cover, random=~1|(Block, Plot, Subplot) *Regional study*: Y~Cover*Region, random=~1|(Farm_id)						
Y=NO_3^--N (1-TR)			numDF	denDF	F-value	P-value
2020	UBC	Cover	1	14	40.66	<0.001
	GRF	Cover	1	15	42.40	<0.001
	REG	Cover	1	11	5.21	0.04
		Region	2	11	0.27	0.77
		Cover*Region	2	11	0.02	0.98
2021	UBC	Cover	1	15	137.43	<0.01
	GRF	Cover	1	15	124.66	<0.001
	REG	Cover	1	11	7.48	0.02
		Region	2	11	1.38	0.29
		Cover*Region	2	11	1.11	0.36
Y=EC			numDF	denDF	F-value	P-value
2020	UBC	Cover	1	14	67.59	<0.001
	GRF	Cover	1	15	44.43	<0.001
	REG	Cover	1	11	6.48	0.03
		Region	2	11	0.39	0.69
		Cover*Region	2	11	0.27	0.77
2021	UBC	Cover	1	15	73.67	<0.001
	GRF	Cover	1	15	9.06	<0.01
	REG	Cover	1	11	5.70	0.04
		Region	2	11	0.54	0.60
		Cover*Region	2	11	1.92	0.19
Y=VWC			numDF	denDF	F-value	P-value
2020	UBC	Cover	1	15	9.94	<0.01
	GRF	Cover	1	15	0.61	0.45
	REG	Cover	1	8	95.41	<0.01
		Region	1	8	0.16	0.70
		Cover*Region	1	8	3.37	0.10
2021	UBC	Cover	1	15	0.81	0.38
	GRF	Cover	1	15	43.63	<0.001
	REG	Cover	1	11	3.86	0.08
		Region	2	11	3.40	0.07
		Cover*Region	2	11	0.23	0.80

Y=Relative yield			numDF	denDF	F-value	P-value
2020	UBC	Cover	31	49	0.55	0.96
	GRF	Cover	31	49	0.65	0.90
2021	UBC	Cover	31	17	0.28	1.00
	GRF	Cover	31	15	5.03	0.04
Model: Y~Cover, random=~1|(block, plot)						
Y=PAN (growing season)			numDF	denDF	F-value	P-value
2020	UBC	Cover	1	111	4.37	0.04
	GRF	Cover	1	111	19.62	<0.001
2021	UBC	Cover	1	111	3.97	0.05
	GRF	Cover	1	111	0.25	0.61
Model: Y~Cover, random=~1|(block, plot)						
Y=PAN (4-PH)			numDF	denDF	F-value	P-value
2020	UBC	Cover	1	47	1.63	0.21
	GRF	Cover	1	47	0.82	0.37
2021	UBC	Cover	1	47	4.31	0.04
	GRF	Cover	1	47	0.18	0.67
Model: Y~Cover+Season*Year, random~date|(block)						

Y=VWC (2-year UBC)			Chisq	Df	Pr(>Chisq)
2019-2021	UBC	Cover	0.63	1	0.43
		Season	443.73	2	<0.001
		Year	134.85	1	<0.001
		Season*Year	144.86	2	<0.001
Model: Y~Cover, random~date|(subplot)					
Y=VWC (winter)			denDF	F-value	P-value
2019/20	UBC	Cover	30	1.47	0.23
2020/21	UBC	Cover	30	1.44	0.24

Table 9. ANOVA results by outcome variable for University of British Columbia (UBC) Farm and Green Fire (GRF) Farm with nutrient amendment strategy (Nutrient), overwinter cover type (Cover), and Nutrient x Cover interaction as fixed effects. Outcome variables include electrical conductivity (EC), spring volumetric water content (VWC), relative yield, plant available nitrogen (PAN), post-harvest plant available nitrogen (PAN PH-4),and 2-year volumetric water content (VWC; UBC only).

Model: Y~Nutrient*Cover, random=~1|(Block, Plot)						
Y=EC			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	9	0.58	0.64
		Cover	1	11	54.47	<0.001
		Nutrient *Cover	3	11	0.10	0.96
	GRF	Nutrient	3	9	0.33	0.81
		Cover	1	12	37.22	<0.001
		Nutrient*Cover	3	12	0.21	0.89
2021	UBC	Nutrient	3	9	5.83	0.02
		Cover	1	12	138.50	<0.001
		Nutrient *Cover	3	12	4.61	0.02
	GRF	Nutrient	3	9	0.01	0.99
		Cover	1	12	9.02	0.01
		Nutrient *Cover	3	12	1.94	0.18
Y=VWC			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	9	2.85	0.10
		Cover	1	12	10.84	0.01
		Nutrient*Cover	3	12	0.76	0.54
	GRF	Nutrient	3	9	0.72	0.56
		Cover	1	12	1.01	0.33
		Nutrient*Cover	3	12	2.28	0.13
2021	UBC	Nutrient	3	9	0.16	0.92
		Cover	1	12	0.62	0.45
		Nutrient*Cover	3	12	1.08	0.40
	GRF	Nutrient	3	9	0.75	0.55
		Cover	1	12	42.76	<0.001
		Nutrient*Cover	3	12	0.90	0.47

Y=Relative yield			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	9	15.06	<0.01
		Cover	1	12	1.62	0.23
		Nutrient*Cover	3	12	0.32	0.81
	GRF	Nutrient	3	9	13.27	0.04
		Cover	1	12	0.00	0.95
		Nutrient*Cover	3	12	0.58	0.64
2021	UBC	Nutrient	3	9	0.52	0.68
		Cover	1	12	0.19	0.67
		Nutrient*Cover	3	12	0.47	0.71
	GRF	Nutrient	3	9	1.36	0.31
		Cover	1	12	4.19	0.06
		Nutrient*Cover	3	12	0.16	0.92
Model: Y~Nutrient*Cover, random=~date|(Block)						
Y=PAN (growing season)			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	117	1.70	0.17
		Cover	1	117	4.36	0.04
		Nutrient*Cover	3	117	0.17	0.91
	GRF	Nutrient	3	117	7.99	<0.001
		Cover	1	117	4.12	0.04
		Nutrient*Cover	3	117	0.21	0.80
2021	UBC	Nutrient	3	117	8.53	<0.001
		Cover	1	117	20.38	<0.001
		Nutrient*Cover	3	117	0.33	0.80
	GRF	Nutrient	3	117	1.16	0.33
		Cover	1	117	0.25	0.62
		Nutrient*Cover	3	117	0.76	0.52
Model: Y~ Nutrient, random=~1|(Block, Plot)						
Y=PAN (4-PH)			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	9	4.33	0.04
	GRF	Nutrient	3	9	1.64	0.25
2021	UBC	Nutrient	3	9	8.77	<0.01
	GRF	Nutrient	3	9	0.85	0.50
Model: Y~ Nutrient*Cover, random=~1|(Block, Plot)						
Y=PAN (4-PH)			numDF	denDF	F-value	P-value
2020	UBC	Nutrient	3	9	5.40	0.02
		Cover	1	12	4.84	0.05
		Nutrient*Cover	3	12	0.90	0.47
	GRF	Nutrient	3	9	12.40	<0.01
		Cover	1	12	5.12	0.04
		Nutrient*Cover	3	12	1.46	0.27
2021	UBC	Nutrient	3	9	3.35	0.07
		Cover	1	12	3.88	0.07
		Nutrient*Cover	3	12	1.23	0.34

	GRF	Nutrient	3	9	1.56	0.27
		Cover	1	12	0.92	0.36
		Nutrient*Cover	3	12	0.34	0.79
Model: Y~ Cover+Season*Year, random=~date|(Block)						
Y=VWC (2-year UBC)			Chisq	Df		Pr(>Chisq)
2019-2021	UBC	Nutrient	22.78	3		<0.001
		Season	447.57	2		<0.001
		Year	135.71	1		<0.001
		Season*Year	145.84	2		<0.001

Table 10. Tukey post hoc test results for electrical conductivity (EC) at University of British Columbia (UBC) Farm in 2021. All pairwise comparisons shown for nutrient x cover treatment combinations because of the significant interaction between fixed effects (P=0.02). Nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost + fertilizer (C+F); cover treatments: cover crop (CC) and tarp (T).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=EC		contrasts	estimate	SE	df	t-ratio	P-value
2021	UBC	CON CC – HC CC	-16.14	6.42	9	-2.52	0.30
		CON CC - C+F CC	-4.58	6.42	9	-0.71	0.99
		CON CC – LC CC	-14.77	6.42	9	-2.30	0.38
		CON CC – CON T	-0.57	6.42	9	-0.10	1.00
		CON CC – HC T	-9.84	6.42	9	-1.53	0.78
		CON CC - C+F T	-7.82	6.42	9	-1.22	0.91
		CON CC – LC T	-18.06	6.42	9	-2.81	0.20
		HC CC – C+F CC	11.56	6.42	9	1.80	0.63
		HC CC - C+F CC	1.37	6.42	9	0.21	1.00
		HC CC – LC CC	15.57	6.42	9	2.43	0.33
		HC CC – CON T	6.31	6.42	9	1.07	0.95
		HC CC – C+F T	8.33	6.42	9	1.30	0.88
		HC CC – LC T	-1.91	6.42	9	-0.30	1.00
		C+F CC – LC CC	-10.19	6.42	9	-1.59	0.75
		C+F CC – CON T	4.01	6.42	9	0.63	1.00
		C+F CC – HC T	-5.26	6.42	9	-0.82	0.98
		C+F CC – C+F T	-3.23	6.42	9	-0.55	1.00
		C+F CC – LC T	-13.48	6.42	9	-2.10	0.48
		LC CC – CON T	14.20	6.42	9	2.21	0.42
		LC CC – HC T	4.93	6.42	9	0.77	0.99
		LC CC – C+F T	6.96	6.42	9	1.08	0.95
		LC CC – LC T	-3.29	6.42	9	-0.56	1.00

		CON T – NC T	-9.27	6.42	9	1.44	0.82
		CON T – C+F T	-7.24	6.42	9	-1.13	0.93
		CON T – LC T	-17.49	6.42	9	-2.73	0.23
		HC T – C+F T	2.02	6.42	9	0.32	1.00
		HC T – LC T	-8.22	6.42	9	-1.28	0.89
		C+F T – LC T	-10.24	6.42	9	-1.60	0.74

Table 11. Tukey post hoc test results for growing season plant available nitrogen (PAN) at Green Fire (GRF) Farm in 2020. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=PAN (growing season)		contrasts	estimate	SE	df	t-ratio	P-value
2020	GRF	CON - HC	-2.77	2.53	117	-1.10	0.69
		CON - LC	-1.79	2.53	117	-0.71	0.89
		CON - C+F	-11.36	2.53	117	-4.50	<0.01
		HC - LC	0.98	2.53	117	0.39	0.98
		HC - C+F	-8.60	2.53	117	-3.40	<0.01
		LC - C+F	-9.57	2.53	117	-3.79	<0.01

Table 12. Tukey post hoc test results for growing season plant available nitrogen (PAN) at University of British Columbia (UBC) Farm in 2021. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=PAN (growing season)		contrasts	estimate	SE	df	t-ratio	P-value
2021	UBC	CON - HC	-23.30	4.89	117	-5.77	<0.001
		CON - LC	-16.47	4.89	117	-2.32	<0.01
		CON - C+F	-18.31	4.89	117	-5.46	<0.01
		HC - LC	6.83	4.89	117	3.45	0.51
		HC - C+F	4.98	4.89	117	0.30	0.73
		LC - C+F	-1.85	4.89	117	-3.15	0.98

Table 13. Tukey post hoc test results for post-harvest plant available nitrogen (PAN 4-PH) at University of British Columbia (UBC) Farm in 2020. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=PAN (4-PH)		contrasts	estimate	SE	df	t-ratio	P-value
2020	UBC	CON - HC	-2.75	0.95	9	-2.89	0.07
		CON - LC	-1.94	0.95	9	-2.04	0.24
		CON - C+F	-3.15	0.95	9	-3.31	0.04
		HC - LC	0.81	0.95	9	0.85	0.83
		HC - C+F	-0.40	0.95	9	-0.42	0.97
		LC - C+F	-1.21	0.95	9	-1.28	0.60

Table 14. Tukey post hoc test results for post-harvest plant available nitrogen (PAN 4-PH) at Green Fire (GRF) Farm in 2020. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=PAN (4-PH)		contrasts	estimate	SE	df	t-ratio	P-value
2020	GRF	CON - HC	-0.30	1.51	9	-0.20	0.99
		CON - LC	-1.50	1.51	9	-1.00	0.76
		CON - C+F	-6.78	1.51	9	-4.50	<0.01
		HC - LC	-1.20	1.51	9	-0.79	0.86
		HC - C+F	-6.48	1.51	9	-4.30	<0.01
		LC - C+F	-5.28	1.51	9	-3.50	0.03

Table 15. Tukey post hoc test results for 2-year volumetric water content (VWC) at University of British Columbia (UBC) Farm from November 2019 – October 2021. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y= VWC (2-year UBC)		contrasts	estimate	SE	df	t-ratio	P-value
2019-2021	GRF	CON - HC	-0.01	0.01	17	-1.75	0.33
		CON - LC	-0.02	0.01	17	-2.94	0.04
		CON - C+F	0.01	0.01	17	1.45	0.49
		HC - LC	-0.01	0.01	17	-1.23	0.62
		HC - C+F	0.02	0.01	17	3.21	0.02
		LC - C+F	0.03	0.01	17	4.44	<0.01

Table 16. Tukey post hoc test results for relative yield at University of British Columbia (UBC) Farm in 2020. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=relative yield		contrasts	estimate	SE	df	t-ratio	P-value
2020	UBC	CON - HC	-33.66	5.84	9	-5.77	<0.01
		CON - C+F	-13.51	5.84	9	-2.32	0.17
		CON - LC	-31.89	5.84	9	-5.46	<0.01
		HC - C+F	20.15	5.84	9	3.45	0.03
		HC - LC	1.77	5.84	9	0.30	0.99
		C+F - LC	-18.38	5.84	9	-3.15	0.05

Table 17. Tukey post hoc test results for relative yield at Green Fire (GRF) Farm in 2020. All pairwise comparisons shown for nutrient treatments: control (CON), high compost (HC), low compost (LC), and compost (LC), and compost + fertilizer (C+F).

emmeans(pairwise ~ Nutrient, p.adjust = "tukey")							
Y=relative yield		contrasts	estimate	SE	df	t-ratio	P-value
2020	GRF	CON - HC	-12.70	4.87	9	2.61	0.11
		CON - C+F	-5.91	4.87	9	-1.21	0.63
		CON - LC	-16.13	4.87	9	-3.31	0.04
		HC - C+F	6.79	4.87	9	1.39	0.53
		HC - LC	-3.42	4.87	9	-0.70	0.89
		C+F - LC	-10.22	4.87	9	-2.10	0.23