Effects of tile drainage, seasonality, and cash crop rotation on edge-of-field nitrogen and phosphorus losses from southern Ontario Watersheds

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Abstract

Effects of tile drainage, seasonality, and cash crop rotation on edge-of-field nitrogen and phosphorus losses from Southern Ontario Watersheds

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Eutrophication is an ongoing global problem and agriculture is an important non-point source of nutrient loading. Specifically, nitrogen (N) and phosphorus (P) losses from agricultural landscapes continue to drive water quality issues. In southern Ontario, agriculture has intensified in recent decades, with major expansions of cash crop production and extensive tile drainage (TD). Through intensive monitoring of 12 tile outlets draining operational fields under the conventional corn-soybean-wheat rotation, this study examined differences in measured and volume-weighted total P, total N, and nitrate-N concentrations and loads over 28 months (October 2020- April 2023) amongst crop covers and between growing (GS; May – September) and non-growing seasons (NGS; October – April).

Nitrogen concentrations (i.e., TN and NO_3-N) in TD eluent were consistently high both between seasons and were found to be significantly highest from winter wheat (WW) fields in the NGS, and corn fields in the GS. Volume-weighted TP concentrations were not significantly different either amongst crop covers or between seasons, although TP losses tended to be highest from the cover crop (CC) fields in the NGS. Differences in N and P losses between years and amongst crop covers were attributed to differences in legacy soil nutrients, the establishment and decomposition of over-winter cover crops, and physical soil properties. The results of this study can inform agricultural management by addressing the urgent need for improved information around the relationship between agricultural practices and nutrient losses, especially in the NGS.

Keywords: Best management practices, Crop rotation, Nitrogen, Over-winter cover crops, Phosphorus, Seasonality, Tile drainage, Water quality

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List of abbreviations:

Al: Aluminum

BD: Bulk density

BMP: Best management practices

C: Carbon

Ca: Calcium

Carbon: nitrogen ratio: C: N

CR: Corn residue

CC: multi-species cover crops

CI: Confidence interval

FC: Field capacity

Fe: Iron

GLWQA: Great lakes water quality agreement

HABs: Harmful algal blooms

HPO_4: Orthophosphate

LMM: Linear mixed model

LOI: Loss on ignition

N: Nitrogen

NASS: U.S. department of agriculture's national agricultural statistics service

NO_3-N: Nitrate-nitrogen

NTD: Non tile drained

NOHFC: Northern Ontario heritage fund corporation

OMAFRA: Ontario ministry of food, agriculture, and rural affairs

P: Phosphorus

PP: Particulate phosphorus

SI: Algae bloom severity index

SOM: Soil organic matter

SRP: Soluble reactive phosphorus

TD: Tile drainage

TDP: Total dissolved phosphorus

TC: Total carbon

TIC: Total inorganic carbon

TLP: Tile loan program

TN: Total nitrogen

TOC: Total organic carbon

TP: Total phosphorus

WQG: Ontario freshwater quality guidelines

WW: Winter wheat

1. Literature review and general introduction

1.1 Nutrient enrichment in the Great lakes

The eutrophication of waterways is an ongoing global issue causing problems within ecosystems, threatening drinking water resources, and causing socioeconomic losses. Elevated concentrations of nitrogen (N) and phosphorus (P) in natural water systems are most frequently associated with eutrophication (Blann et al., 2009; Conley, 1999). It is important to acknowledge that N and P occur naturally throughout the environment including in freshwater systems; however, an overabundance of these two nutrients from anthropogenic sources can lead to extensive algae growth and eutrophication (Dodds & Smith, 2016; Dove & Chapra, 2015). Within the Laurentian Great Lakes, elevated levels of P have been associated with the nuisance growth of macroalgae and toxic cyanobacterial blooms (Dolan & Chapra, 2012). Specifically, concentrations of dissolved fractions of P in some Great Lake tributaries have increased in recent decades (Dolan & Chapra, 2012). Furthermore, research indicates that higher levels of nitrate-nitrogen (NO_3-N) in freshwater systems may lead to the growth of certain algal species such as toxic blue-green algae, or lead to more severe hypoxic conditions (Chaffin et al., 2018; Salk et al., 2018). Overall, understanding the factors that could be contributing to nutrient enrichment of dissolved bioavailable N and P and the eutrophication of waterways is critical to developing strategies to combat these issues.

The transport of P from landscapes to aquatic systems has historically been attributed to erosion and surface flow due to the relative immobility of P in soils and therefore P is often delivered to aquatic systems in particulate form (particulate P or PP; Correll, 1998; Sims et al., 1998). Phosphorus is often described as 'sticky' due to its tendency to sorb to clays or form complexes with soil minerals containing iron (Fe), aluminum (Al), and calcium (Ca); as a result, P is less mobile than other nutrients of concern such as nitrate (NO_3-N; Krzic et al., 2021; Zhang et al., 2015). Although P can bind strongly with soils, the loss of total dissolved P (TDP) via subsurface drainage is an emerging issue being reported throughout the midwestern US and Canada (Gentry et al., 2007; Kinley et al., 2007; Macrae et al., 2007). Once PP or dissolved P enters the aquatic system, P compounds can be chemically or enzymatically hydrolyzed to orthophosphate (HPO_4) which is bioavailable to bacteria, algae, and plants (Correll, 1998). High levels of HPO_4 in freshwater environments can lead to eutrophication and hypoxic conditions which has led many researchers to try to understand the pathways that are contributing to P leaching and methods to prevent P leaching (Djodjic et al., 1999; Dodds & Smith, 2016; Heathwaite & Dils, 2000).

Furthermore, the influx of NO_3-N into aquatic systems from terrestrial landscapes often depends on two factors: soil N concentrations and the volume of drainage or surface flow draining through soil (Cameron et al., 2013). Nitrate only weakly sorbs to soil particles and therefore can be easily mobilized in water (Gentry et al., 1998). When there is an accumulation of NO_3-N in the soil profile that coincides with a fallow wet period there is an increased risk of NO_3-N leaching. This can be a critical issue in agricultural watersheds dominated by annual crops like corn and soybean, as annual crops can leach substantially greater amounts of NO_3-N in comparison to perennial crops (Randall &

Mulla, 2001). As NO_3-N is bioavailable, once it enters aquatic systems it contributes to eutrophication and the severity of algal blooms (Cameron et al., 2013).

Although there is a debate on which nutrient, P or N, should be focused on to reduce the severity and frequency of harmful algal blooms (HABs), all researchers agree that the impacts of nutrient enrichment and HABs on ecosystems present a risk to human and environmental health (Schindler et al., 2008). Drinking water resources around the Great Lakes can be negatively impacted by the frequency and duration of HABs as they can complicate drinking water treatment processes and lead to negative human health effects (e.g., abdominal pain, nausea, vomiting, diarrhea, sore throat, dry cough, headache, blistering of the mouth, atypical pneumonia; Alliance for Great Lakes, 2022; Carmichael & Boyer, 2016; Dove & Chapra, 2015; Michalak et al., 2013). For instance, in 2014 over 400,000 residents in Toledo, Ohio were placed under a “do not drink” advisory for two days due to harmful levels of toxic microcystin in treated drinking water drawn from Lake Erie (Jetoo et al., 2015). Furthermore, the frequency and severity of HABs have been associated with significant reductions in recreational and tourism profits in Michigan, Ohio, and Ontario as well as substantial property value losses (Bunch, 2016). For instance, algal blooms could impose an annual economic loss of $272 million in Canadian communities around the Lake Erie basin of which the tourism sector would lose $110 million (2015 Canadian dollar; Smith et al., 2019). Concerns for drinking water resources and the socio-economic costs of HABs within the Great Lakes have pushed the federal and provincial governments to investigate the factors contributing to HABs.

1.1.1 Historical nutrient enrichment of the Great Lakes

Historically, studies related to eutrophication have focused on reducing P loading as P is the most common limiting nutrient to freshwater algal growth (Mahdiyan et al., 2021; Sims et al., 1998; Zhang et al., 2015). Notably, industrial waste and the use of phosphate detergents in the mid-1900s increased P loading to the Great Lakes which led to water quality concerns. Issues were so severe throughout the 1960s and 1970s that sections of the Great Lakes were declared to be "dead" after hypoxic bottom waters led to the death of both sessile and mobile organisms (Dybas, 2005). In 1972, with amendments in later decades, the Great Lakes Water Quality Agreement (GLWQA) was established between Canada and the United States with the aim to regulate the discharge of pollutants and protect drinking water resources. The GLWQA resulted in improved sewage treatment practices and the elimination of phosphate-based detergents in much of the USA and Ontario (Dove & Chapra, 2015). As a result, P inputs to the Great Lakes from municipal and industrial sources greatly declined between 1972 and the late 1980s (Dove & Chapra, 2015; Mahdiyan et al., 2021). In contrast, limiting N inputs has historically been less of a priority in many freshwater systems, yet there is growing concern over NO_3-N enrichment as it may pose a threat to drinking water quality and human health (Schindler et al., 2008; Ward et al., 2018). For instance, NO_3-N concentrations in Lake Ontario increased by almost 60% from 1970 to 2010 (Dove & Chapra, 2015). Although the GLWQA led to stricter regulations regarding P inputs, N inputs continue to be undermanaged and algal blooms, eutrophication, and related water quality issues have persisted throughout the Great Lakes.

1.1.2 Current trends of nutrient enrichment in the Great Lakes

Despite some improvements in water quality due to the GLWQA, eutrophication symptoms continue in the Great Lakes and their tributaries (Mohamed et al., 2019; Smith et al., 2015). Within recent years (i.e., 2011, 2015), Lake Erie has experienced record-breaking algal blooms since the systematic HAB record program began in 2002 (**Figure 1-1).** As recent as 2015, an algal bloom in Lake Erie spanned over 775 km^2 with greater density and bloom severity index (SI) than previous years (**Figure 1-1**; Stumpf, 2022). Current nutrient concentrations and trajectories vary across the Great Lakes due to each lake's unique features (i.e., depth, proximity to urban centers, and geology). In general, over the past four decades total P (TP) levels have declined in offshore surface waters in most of the Great Lakes. In contrast, concentrations of dissolved forms of P (i.e., soluble reactive P or SRP) have generally increased, specifically in Lake Erie, Lake Ontario, and the tributaries that feed these Great lakes (Daloğlu et al., 2012; Dove & Chapra, 2015; Environment and Climate Change Canada, 2020). For instance, various studies have identified the Maumee River to be a key driver in the bloom intensity within the western Lake Erie Basin due to the exceptionally high TP and dissolved P loading within the tributary (Kast et al., 2021; Michalak et al., 2013; Williamson et al., 2023). Additionally, NO_3-N levels within the Great Lakes have increased (Dove & Chapra, 2015), and increases in NO_3-N have also been reported in agricultural tributaries that drain into Lake Ontario and Lake Erie (DeBues et al., 2019; Eimers & Watmough, 2016; Stets et al., 2015). Notably, Eimers & Watmough (2016), reported that 13 large southern Ontario tributaries (8.4 to 2779 km^2) that drain into Lake Ontario have experienced significant increases in

NO_3-N concentrations. Shifts towards greater dissolved nutrient leaching and concentrations (i.e., the more bioavailable forms of P and N) within the Great Lakes could impact algal productivity and community composition (Daloğlu et al., 2012; Newell et al., 2019). Specifically, increases in dissolved nutrients (i.e., NO_3-N, TDP) may be correlated with land use changes as watersheds throughout the Great Lakes regions have experienced population growth, urbanization, and agricultural expansion (Paerl, 2009).

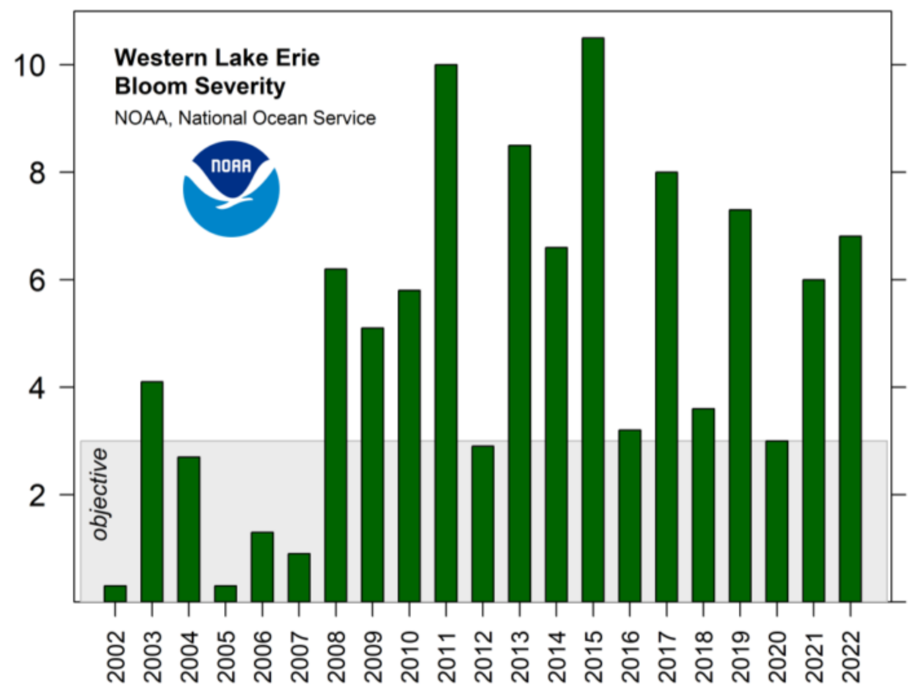

Figure 1-1: Bloom severity index (SI) within the Lake Erie over the past two decades (2002-2022) where the SI is based on the amount of biomass over the peak 30-days (Stumpf, 2022).

1.2 Agriculture's influence on eutrophication

To limit the eutrophication of the Great Lakes, researchers have begun focusing on reducing nonpoint sources of nutrients in addition to point sources (e.g., domestic sewage, industrial waste). Nonpoint sources of nutrients include natural ecosystems, atmospheric deposition, urban activities, and agriculture (Tiessen et al., 2010). Agricultural runoff in tributaries is often recognized as the largest and most influential non-point source of nutrients to surface waters (Conley, 1999; Smith et al., 2015; Williams et al., 2016). Nearly 25% of the Canadian and 7% of the US agricultural production is located within the Great Lakes Basin which may have a significant contribution to nutrient export and eutrophication of the Great Lakes (Carmichael & Boyer, 2016). Researchers are now beginning to understand the complexity and unique nutrient pathways of P and N from agricultural fields to surface waters (Joosse & Baker, 2011; Smith et al., 2015; Withers et al., 2014). However, it remains unclear what methods or management practices on-farm can help to control and reduce nutrient leaching. Various best management practices (BMPs) are employed in agricultural landscapes to improve soil health, reduce erosion, improve soil structure, and limit off-site nutrient losses (Blann et al., 2009; Farmaha et al., 2022; Janovicek et al., 2021; Tiessen et al., 2010). Tile drainage, conservation tillage, and crop rotations including over-winter cover crops are three BMPs that are commonly adopted to benefit soil health and crop productivity; however, these three practices when used in combination may also affect the quantity and quality of water leaching from agricultural landscapes.

1.2.1 Agricultural tile drainage

Subsurface drainage, or tile drainage (TD), is a common land improvement method within poorly drained soils across eastern North America, including Ontario, Quebec, and the Maritimes (Blann et al., 2009). Tile drains consist of perforated plastic pipes which are typically installed between 40 to 100 cm below the surface of agricultural soils that are flat or fine-textured (Van der Veen, 2010). Gravity drainage allows excess soil moisture to flow into the perforated pipes and be expelled via tile drain outlets which ultimately discharge into nearby rivers or ditches. Tile drainage is used to manage seasonal soil saturation by artificially lowering the water table which can improve water infiltration, increase soil aeration, and reduce flooding risks in agricultural landscapes (Blann et al., 2009; Gramlich et al., 2018; King et al., 2015). Tile drainage has been found to extend the growing season (GS), improve crop resistance to wind due to deeper root growth, and overall improve crop yields (Blann et al., 2009; Gramlich et al., 2018; Marmanilo et al., 2021). Although records of TD infrastructure are often incomplete due to a lack of historical record keeping (Eimers et al., 2020), in Ontario there is a known 1.6 million ha of artificially drained agricultural land (Sunohara et al., 2015) and in the midwestern US, there is 19.4 million ha (U.S. Department of Agriculture's National Agricultural Statistics Service (NASS), 2024).

Due to the widespread agronomic benefits of TD, the practice is expanding into areas where natural drainage is expected to dominate (Eimers et al. 2020). In the province of Ontario, the Ministry of Food, Agriculture, and Rural Affairs (OMAFRA) encourages tile drainage via financial assistance through the Tile Loan Program (TLP) and the Northern Ontario Heritage Fund Corporation's (NOHFC) regional tile drainage initiative. With the TLP, farmers can receive a loan of up to 75% of the value of the tile drainage work and the regional tile drainage initiative covers up to 50% or up to 1 million dollars of the cost to install TD in northern Ontario communities (NOHFC, 2023; OMAFRA, 2022b). With the financial support of the Ontario government, TD is expanding into agricultural land with lighter textured soils as well as northern communities. An improved understanding of the impacts of TD on nutrient movement is required to prevent unknown negative side effects from this agronomically beneficial management practice as it expands throughout Ontario.

Although TD has clear benefits for agriculture, many studies have documented the significant pathway TD provides for nutrient transport of both N (Blann et al., 2009; Gramlich et al., 2018; Randall & Goss, 2008; Skaggs et al., 1994) and P (Blann et al., 2009; Gentry et al., 2007; Gramlich et al., 2018; King et al., 2015; Sims et al., 1998). While losses of the particulate forms of nutrients (e.g., PP) may be lower in fields that are artificially drained (Tan & Zhang, 2011), losses of soluble nutrients (e.g., TDP, NO_3-N) are often greater from tile-drained fields (Schilling & Zhang, 2004). Although many factors influence the concentrations of N in subsurface discharge (i.e., precipitation events, soil characteristics, fertilizer application) the consensus amongst studies is that NO_3-N levels in subsurface drainage waters often exceed freshwater quality guidelines (3.0 mg L^{-1}; Canadian Council of Ministers on the Environment, 2012) and contribute to elevated NO_3-N concentrations in downstream aquatic systems (Di & Cameron, 2002; Gramlich et al., 2018; Randall & Goss, 2008). Furthermore, the elevated concentrations of HPO_4 in agriculturally dominated watersheds have led many researchers to investigate connections between P losses and subsurface drainage (Grant et al., 1996; Jamieson et al., 2003; King et al., 2015; Sims et al., 1998; Williams et al., 2016). In a review paper by King et al. (2015), it was found that while TP concentrations in subsurface discharge are often highly variable (<0.01 to >8.0 mg L^{-1}) they generally exceed water quality guidelines (0.03 mg L^{-}

[1]; Canadian Council of Ministers of Environment, 2004). Overall, TD can facilitate the movement of nutrients below the rooting zone and thereby expedite their transfer to downstream surface waters leading to eutrophication.

1.2.2 Agricultural tillage practices

The various tillage practices used on agricultural soils can impact their physical, chemical, and biological properties (Lv et al., 2023). Conventional tillage completely turns over the topsoil layer to incorporate crop residue and fertilizers, terminate weeds, and loosen compact topsoil (Hillel & Hatfield, 2005; Tiessen et al., 2010). With long-term use, conventional tillage can increase soil compaction below the plow layer, decrease soil stability, and increase soil erosion (Lv et al., 2023). Conversely, a common BMP that reduces soil disturbance is ‘conservation tillage’ which includes both reduced tillage and no-till (Liu et al., 2019). In contrast to conventional tillage, conservation tillage avoids mechanical disturbances to the soil matrix and leaves at least 30% of the previous crop residue at the soil surface (Hillel & Hatfield, 2005). Ultimately, conservation tillage can lead to higher soil organic matter (SOM) concentrations and increase soil resistance to erosion (Smith, 2015). The aim of ‘reduced tillage’ is to minimize soil disturbance through either tilling at a shallower depth or less frequent tilling (e.g., rotational tillage once every three years). In contrast, ‘no-tillage’ refers to the complete absence of tillage, and crops are planted directly into the residue of the previous crop. Both ‘reduced tillage’ and ‘no-till’ can improve soil conditions and reduce fuel and labor costs (Busari et al., 2015; Smith, 2015). Since 1991, the number of farmers reporting conservation tillage increased by 50%, with 81% of farmland across Canada reporting a reduced till approach in 2016 (Statistics Canada, 2018). However, it is important to note that individual definitions of 'reduced' vs. 'no-tillage' vary, which may affect the accuracy of census reports on tillage practices in Canada. Anecdotal reports suggest that reduced tillage is only possible in conjunction with artificial drainage, as one of the benefits of conventional tillage is enhanced soil drying in the spring and fall (J. Lennox, pers. comm.). Conversations with Northumberland, Ontario farmers indicate that without conventional tillage in the spring, high soil moisture levels in naturally drained fields would delay seeding and fertilizer application in 'reduced-till' or 'no-till' fields. As a result, conservation tillage and tile drainage often go hand-in-hand, with potentially complicated consequences for soil fertility and nutrient leaching (Abid & Lal, 2009; Tiessen et al., 2010).

Despite the various benefits of conservation tillage, some studies have reported that it can increase dissolved nutrient leaching (Liu et al., 2019; Tiessen et al., 2010; Williams et al., 2016; Zhang et al., 2017). Within Lake Erie, dissolved P concentrations increased coincident with the implementation and widespread adoption of no-till practices within its highly agricultural watershed (Joosse & Baker, 2011; Smith et al., 2015). Findings from the Lake Erie Basin may also apply to other freshwater lakes within highly agricultural watersheds. For instance, Tiessen et al. (2010), reported that P exports increased by 42% after the adoption of no-till in a paired watershed study in the Canadian prairies, and most of the increase in P was in the dissolved, bioavailable form. It is speculated that increases in dissolved nutrient concentrations in artificially drained landscapes under conservation tillage may be attributed to the development of preferential flow pathways (i.e., macropores, cracks, fissures, root channels, bio pores, and earthworm burrows; Kleinman et al., 2011). Due to the lack of mechanical mixing of soils under conservation tillage, preferential flow pathways can persist year-round or worsen over the years, especially in fine-textured soils, which can facilitate dissolved or particulate nutrient losses (Busari et al., 2015; Hillel & Hatfield, 2005). Preferential flow pathways can act as conduits that allow nutrients to bypass the soil matrix and flow directly into subsurface drainage pipes (Grant et al., 2019; Tiessen et al., 2010). Various studies have found that preferential flow through macropores has led to significant losses of sediment, PP, and other contaminants in subsurface drainage which are comparable to losses in surface runoff (Blann et al., 2009; Chapman et al., 2003; Grant et al., 1996). To reduce the transport of dissolved and particulate nutrients from agricultural landscapes to water systems it is critical to understand the pathways of sediment and nutrient transfer within artificially drained landscapes. For example, another consequence of conservation tillage is nutrient stratification within the Ah (i.e., topsoil) of agricultural soils (Soil Classification Working Group, 1998). Nutrient stratification can develop in fields under no-till, as the absence of mechanical mixing allows surface broadcast fertilizers and crop residues to concentrate at the soil surface (Crozier et al., 1999; Smith et al., 2017). Higher levels of organic matter and inorganic nutrient concentrations at the soil surface can lead to increased nutrient leaching in surface flow via erosion, and augment losses via preferential flow pathways. One nutrient of particulate concern for stratification under no-till is P due to the common application of largely immobile P fertilizers and the lack of crop residue incorporation leading to increased mineralization within the surface soils (Smith et al., 2017). Unlike P,

NO_3-N is a highly mobile nutrient as it tends to move through the soil matrix with water leading to less pronounced stratification within the topsoil (Tiessen et al., 2010). Overall, the combined impact of conservation tillage on macropore formation and soil stratification, particularly in subsurface-drained agricultural fields, has been shown to increase concentrations of dissolved P (King et al., 2015, 2016; Tiessen et al., 2010; Van Esbroeck et al., 2016; Williams et al., 2016), and NO_3-N (Li et al., 2023) in drainage discharge waters.

1.2.3 Crop rotation

Aside from TD and tillage operations, cropping systems may also influence nutrient leaching from agricultural fields (King et al., 2016; Zhu & Fox, 2003). Crop rotation (as opposed to monoculture cropping) is a BMP whereby different crops are sequentially planted in rotation to help break insect and disease cycles, replace key nutrients (e.g., fixed N from soybeans), and can increase the potential success of conservation tillage in comparison to repeated growth of a single crop such as corn (Government of Ontario, 2009; Jalli et al., 2021; Smith, 2015; Yang & Kay, 2001). Factors such as rooting depth, root density, water use rates, nutrient requirements, and nutrient uptake efficiency vary between crops and could influence nutrient leaching in artificially drained systems (Peterson & Power, 2015). As the nutrient requirements and uptake efficiencies vary between crops within the rotation, N and P leaching could vary through the crop cycle, yet no clear consensus has been made. Some research suggests that crop rotations that include soybean and wheat, have lower NO_3-N losses compared with continuous corn (Nila Rekha et al., 2011), while others have found that rotations that include soybean can increase NO_3-N leaching (Klocke et al., 1999). Inconsistencies between studies are likely due to differences in fertilizer form and application rate, management practices, climate conditions, and soil fertility.

The current standard practice in the Great Lake Basin is a three-year rotation of grain corn, soybean, and winter wheat. Over the past several decades, many farms in Ontario have switched from mixed livestock plus perennial crop systems to focus on annual row crops that have high global demand including corn and soybean. For instance, the area of agricultural land planted to corn tripled between 1961 and 1981 in Ontario, and in 2022 over 60 % (9.4 million metric tonnes) of all corn for grain in Canada was grown in Ontario (Joseph & Keddie, 1981; Smith, 2015; Statistics Canada, 2022). Soybean production in Ontario has also increased by 136% over the past two decades, and in 2022 soybeans were grown on more than three million hectares in Ontario accounting for more than 60% (4.0 million metric tonnes) of Canadian soybean production (Smith, 2015; Statistics Canada, 2017, 2022). A legume such as soybean can ‘fix’ atmospheric dinitrogen gas into ammonium thereby enriching plant available N in soils (Ciampitti et al., 2021). As a result, N-fertilizer is rarely applied to soybean crops and the N ‘credit’ provided by soybean can be used to offset the N-fertilizer requirement of the subsequent crop (e.g., winter wheat; Gentry et al., 2001; Vanotti & Bundy, 1995). However, if the N credit is not adequately considered in fertilizer calculations for the subsequent crop, then N losses could be even greater (Smith, 2015). Winter wheat is typically planted following soybean harvest in Ontario, and like corn and soybean trends, the area planted to winter wheat more than doubled between 1976 and 2011 and 90% of all wheat in Ontario was the winter wheat variety in 2011 (Smith, 2015). Although winter wheat only accounted for 8% (or 2.7 million tonnes) of the total wheat produced in Canada in 2022, the majority (74%) of Canadian winter wheat was produced in Ontario. Recent changes in agricultural land use towards the strict row crop rotation of corn-soybean-winter wheat in Ontario could influence nutrient movement and water quality within this region.

1.2.3.1 Winter cover

A BMP that has quickly increased in popularity within Ontario is the inclusion of over-winter cover crops during the non-growing season (NGS) when otherwise the soil would be barren. Over-winter cover crops are typically planted in the late summer or early fall and can be either non-living (i.e., winter-killed cover crops) or living but dormant (i.e., winter wheat) over the winter. Cover crop mixtures often include a suite of different plants to provide different benefits, including grasses that have deep roots to prevent soil erosion (e.g., rye, oats, sorghum), legumes that are N fixers (e.g., clover, alfalfa, peas), and broadleaf tubers that can break up soil compaction (e.g., turnip, radish; OMAFRA, 2021). While winter wheat is a cash-crop, it is also considered an over-winter living cover crop since it is planted in the fall and is harvested the following summer. Winter wheat can tolerate a wide range of growing conditions and once established can survive harsh winter conditions (Skinner, 2014).

A living crop cover, whether it is a multi-species mix or single species like winter wheat, can improve the physical properties of agricultural soils by providing ground cover to protect and retain sediment, suppress weed growth, and increase water infiltration (Christopher et al., 2021; Haruna et al., 2020). For instance, a review by Haruna et al. (2020), found that winter cover crops could reduce soil losses by as much as 96% and increase water infiltration up to 629%. However, improvements in soil infiltration may in part be due to the increased presence of macropores created by the roots of cover crops. For example, Haruna et al. (2020), found that fields planted to cover crops over the NGS had 33% more macropores in comparison to fields without cover crops. In addition to the impact cover crops can have on physical soil properties, this BMP can also influence soil nutrient conditions and nutrient leaching via subsurface discharge or surface runoff (Christopher et al., 2021; Hanrahan et al., 2021; Haruna et al., 2020). Cover crops can scavenge excess soil nutrients, reducing the risk of nutrient loss over the NGS. For instance, Christopher et al. (2021), found that cover crops had 50% lower soil NO_3-N concentrations in comparison with non-cover crop fields, and this was directly related to the amount of cover crop biomass in 15 agricultural fields in Indiana. While many studies have reported the benefits of cover crops for utilizing excess N in the NGS (Blesh & Drinkwater, 2014; Christopher et al., 2021; Lacey & Armstrong, 2015), there is less certainty regarding the ability of cover crops to utilize excess P, with some reporting reductions in P leaching (Blanco-Canqui et al., 2015; Trentman et al., 2020) and others reporting increased P leaching (Bergström et al., 2015; Ulen, 1997). Furthermore, a study by Hanrahan et al. (2021), which examined cover crops' influence on both N and P leaching, indicated that the two-nutrients responded differently. Hanrahan et al. (2021), found that cover crops reduced monthly tile NO_3-N and TN loads by 1.0-2.6 kg N ha^{-1} from January to June in comparison with on-cover crop TD fields in Columbus, Ohio. However, the influence of cover crops on P leaching in TD agricultural setting was less beneficial as monthly tile TP loads increased by 1.2-31.6 g TP ha^{-1} in comparison with non-cover crop fields. Recent reports have suggested that the inconsistent effect of cover crops on P leaching via TD is likely due to variations in soil, climate, and management factors (Cober et al., 2019; Liu et al., 2019; Trentman et al., 2020). Furthermore, the benefits of over-winter cover crops may be limited if the crops are not well-established prior to winter dormancy. Due to a lack of establishment prior to frost, cover crops can be inefficient at reducing soil erosion and preventing nutrient leaching thus impacting how successful cover crops can be in minimizing nutrient losses (Liu et al., 2019; Zhu & Fox, 2003).

1.3 Seasonal nutrient losses in agricultural watersheds

Seasonality plays an important role in controlling soil moisture and TD discharge volumes in seasonally snow-covered agricultural landscapes like southern Ontario. Soil moisture conditions are often greater in the NGS when limited plant uptake and low evapotranspiration losses are translated into greater TD discharge volumes. As TD increases the hydrological connectivity of agricultural landscapes, nutrient export in the NGS is typically elevated through both higher nutrient concentrations as well as increased volumes of tile discharge water (Bjorneberg et al., 1996; Gaillot et al., 2023; Hirt et al., 2011).

1.3.1 Seasonal influence on soil moisture and hydrology of tile drains

The volume of discharge exported through TD infrastructure is a function of antecedent soil moisture conditions (i.e., the amount of water present in soils prior to the event) and event type (i.e., precipitation type, duration, and intensity; Macrae et al., 2010). In seasonally snow-covered landscapes, tile discharge is typically greatest and most consistent from late fall to spring when living crops are dormant or fields are bare (King et al., 2014; Macrae et al., 2007). For example, Bjorneberg et al. (1996), found that 50-85% of annual tile drainage discharge occurred over the NGS in a study out of Iowa. In contrast, over the GS tile drainage discharge is usually episodic, with tile flow often only initiating during intense storm events (Bjorneberg et al., 1996). For instance, during periods of low antecedent soil moisture (i.e., summer, GS), the storage capacity of soils is greatest, which reduces the hydrological connectivity between soils and surface waters. In comparison, during periods of high antecedent soil moisture (i.e., winter, spring, NGS), when the water table is elevated, the storage capacity of soils is low, which increases the hydrological connectivity between the soils and surface waters (Gramlich et al., 2018; Macrae et al., 2010; Skaggs et al., 1994). For example, Gaillot et al. (2023), reported that the responsiveness of tile flow to precipitation events varied between the NGS and GS due to differences in antecedent moisture conditions in a 5-ha field located in Paris, France. Within this study, there were 106 tile drainage events within a single year with 96% of these events occurring during the NGS. The greater drainage volumes and increased reactivity of TDs over the NGS suggest that the influence of TDs on nutrient movement and eutrophication may be greatest over the NGS.

1.3.2 Seasonal influence of nutrient cycling and movement in TD landscapes

Seasonal or climatic patterns can affect both the amount and concentration of nutrients leached via tile drains. Seasons with greater discharge volumes such as in late autumn, winter, and early spring (i.e., the NGS) when volumetric soil moisture is high, evapotranspiration is low, and effective precipitation is high, resulting in greater TD discharge volumes. Increased tile discharge can be associated with higher nutrient concentrations (e.g., high TP concentrations during event flow) or simply greater nutrient leaching due to the overall increase in volume of TD discharge (e.g., greater cumulative N leaching due to the greater volume of discharge; Bjorneberg et al., 1996; Heathwaite & Dils, 2000; Macrae et al., 2019; Tan et al., 2002). Both NO_3-N and P leaching typically peak over the NGS with Bjorneberg et al. (1996), reporting that 45-85% of annual NO_3-N loads occur over the NGS in Iowa, and Lam et al. (2016), reporting that 98% of annual P export occurred during the NGS in Southern Ontario. However, patterns of N and P leaching over the NGS and the events that drive their losses can vary.

The export of N via TD is often sensitive to the frequency and magnitude of precipitation events, especially when large pools of soil inorganic N are present (Gentry et al., 1998). For example, Gentry et al. (1998), found that most of the annual NO_3-N leaching occurred during high-flow events with 75% of annual NO_3-N leaching occurring over just nine days from corn-soybean fields in Illinois. It is important to note that high-flow events can only produce large NO_3-N losses when there are significant inorganic N pools within the soil matrix. Following a productive GS, when the inorganic N pool is low due to crop uptake, leaching of NO_3-N tends to decline through the subsequent NGS, whereas in poor growing years (e.g., affected by drought, floods, or pests) or after the application of fall N fertilizer, NO_3-N export via TD can increase substantially through the NGS (Di & Cameron, 2002). Nitrogen losses over the NGS have been associated with two main factors (Bjorneberg et al., 1996; Di & Cameron, 2002; Tan et al., 2002). First, unused N within the soil profile from excess/ unused fertilizer or ongoing mineralization of organic matter provides leachable NO_3-N that can be readily mobilized in soil solution (Baker & Johnson, 1981; Tan et al., 2002). Second, due to plant dormancy in the NGS, no active crop roots are present to utilize N or water, and therefore NO_3-N in soil solution is free to percolate out of the rooting zone and into TD discharge (Di & Cameron, 2002; Tan et al., 2002).

Similarly, seasonality and climatic factors (e.g., precipitation events, snow melt, rain-on-snow) have been reported to have a significant influence on P losses in TD (Jamieson et al., 2003; King et al., 2016; Lam et al., 2016; Van Esbroeck et al., 2016). For example, Van Esbroeck et al. (2016), found that 83 to 97% of P export occurred in the NGS and the majority of P losses occurred during event flow conditions in a study of three tile drains in southern Ontario. Phosphorus concentrations in event flow discharge are often a function of multiple factors such as event characteristics (e.g., rain intensity, duration) and P pools in the soil prior to the event (King et al., 2015). For instance, events that occur shortly after P fertilizer application are associated with substantial increases in P in tile eluent in comparison to events with similar characteristics yet no recent history of fertilizer application (Sharpley et al., 2001; Stamm et al., 1998). Furthermore, Vidon & Cuadra (2011), reported that P losses via TD during event conditions were due to enhanced preferential flow activity which allowed P to bypass the soil matrix and directly enter the TD infrastructure more rapidly. Overall, while TD, no-till, and crop rotations including over winter cover are associated with agronomic benefits, these BMPs may have unintended consequences for water quality. Rising dissolved nutrient concentrations in agriculture-dominated watersheds (e.g., Eimers and Watmough 2016; DeBues et al. 2019), and questions around BMP effectiveness, together inspired the current study.

1.4. Study objectives and hypothesis

While there is a large body of work that reports nutrient leaching via tile drainage, there are relatively few studies that assess nutrient losses during the NGS, and most studies focus on either N or P, with very few considering the two nutrients together. Of particular interest is the influence of winter cover crops (living or winter-senesced) on nutrient losses in the NGS, and whether certain crop covers (e.g.,winter wheat and multi species cover crops) help to reduce nutrient leaching during the winter/spring. Full crop rotation studies that include the NGS are not common in the literature, yet they are required to capture variation in TD discharge and water quality due to differences in weather conditions, crop growth, and date of crop establishment that occur year-to-year.

To address these knowledge gaps, this study monitored N and P levels in tile-discharge water and soil samples at 12 tile-drained operational fields under a no-till corn-soybean -WW-CC rotation over 28 months (Oct 2020 – Apr 2023) to better understand the influence of soil conditions, crop type, season, and events on nutrient leaching within southern Ontario. Specifically, the tile drains within this study discharge water into ditches or rivers within the Gages Creek, Ganaraska River and Cobourg Creek watersheds, which directly feed Lake Ontario. Previous studies of these watersheds indicted declines in TP and increases in NO_3-N (see Eimers and Watmough, 2016; DeBues et al., 2019). Additionally, soils from the tiled fields were analyzed for total and labile nutrients (C, N, and P) both in the spring and fall for the duration of the study to assess seasonal variability. Tile water was analyzed for concentrations of N (total and NO_3-N), C (inorganic and organic C), and P (total and dissolved) as well as discharge, in order to assess nutrient export (mass). Thus, the objectives of this study were to (i) compare N and P concentrations in TD leachate between the GS and NGS through a typical crop rotation, (ii) identify the influence of crop cover on nutrient losses in tile drain discharge, and (iii) compare total vs. labile (water-extractable) soil nutrient conditions through the crop rotation. It was hypothesized that:

1. Volume-weighted nutrient (N and P) concentrations and loads within TD discharge would be greater in the NGS than the GS due to greater volume of TD discharge.
2. Fields planted to over-winter cover (WW and CC) would have lower N and P losses in tile discharge compared with corn residue (CR) during the NGS.
3. Total soil nutrient concentrations (N, C,) would be relatively stable throughout the crop rotation whereas the labile soil nutrient fraction (water-extractable, Olsen-P) would be more sensitive to crop cover/residue within the top 30 cm of soil.
4. Phosphorus and C concentrations would be higher in surface soils compared with deeper soils (i.e., nutrient stratification) due to no-tillage and surface application of fertilizer, whereas N would be relatively unaffected due to the more mobility of N.

2. Methods

2.1 Study area and site description

This study was conducted in east central Ontario, Canada within the Gages Creek, Ganaraska River, and Cobourg Brook watersheds. Prior research in these watersheds outlined by Liu et al. (2022), indicated that these watersheds contained 61%, 48%, and 43% row crop agriculture, respectively in 2019. The study watersheds are located within the Dfb climate region, which is described as having warm humid summers and cold snowy winters (Köppen Dfb climate zone). This area has approximately 160 growing days per year from May to October (OMAFRA, 2022b). The 30-year average annual temperature is 7.5 °C (1981-2010), with a monthly maximum of 25 °C in July, and a minimum of -9.7°C in January (Government of Canada, 2023). Precipitation is relatively consistent throughout the year, with a 30-year annual mean of 890 mm (1981-2010), of which 96.5 cm occurs as snowfall between November and March (Government of Canada, 2023). Climate data were retrieved from Environment Canada's Cobourg AUT climate station ID 6151684 (43^{o}57'00" N 78^{o}10'00" W), and when records from the Cobourg AUT station were missing, gaps were filled using climate data retrieved from the Cobourg STP climate station ID 6151689 (43^{o}58'00" N 78^{o}11'00" W). Gap filling accounted for less than 10% of the overall climate record for this study.

From October 2020 through to April 2023, year-round tile outlet sampling (event-based and baseflow) was conducted at 12 tile outlets at a single operational farm to understand differences in TD discharge and nutrient concentrations amongst crop types and between seasons (i.e., GS and NGS). Fields were selected to encompass a range of crops including grain corn, soybean, WW, and a multi-species non-cash CC, and an entire crop rotation was evaluated at all 12 fields (**Figure 2-1)**. Tiles were monitored for both instantaneous discharge and nutrient concentrations through three non-growing seasons (NGS1, NGS2, NGS3) and two growing seasons (GS1, GS2) where the NGS refers to samples collected from October to April, and the GS refers to samples collected from May to September, inclusive.

All fields in the study have been under no-till management since 1998, and tile drains were installed between 1980 and 2002 and thus ranged in age from two to four decades at the time of monitoring. Tile drains were installed with an average depth of 75-90 cm and a spacing of 12-15 m. The drainage area associated with each outlet ranged in size from 0.06 to 0.65 km^2 **(Table 2-1).** Contributing tile area delineations were made based on historical records of tile maps shared by the operational farmer. In some cases, tiles drained a subarea of a larger field (e.g., H7A2, N. House, S. Lakes) or drained subareas of multiple fields in the case of the one composite tile used to assess TD discharge throughout the study period (i.e., Mystery**; Figure 2-1).** Soils within the study area are predominantly Luvisols, with flat or gently sloped landscapes and an average texture of silty clay loam (**Table 2-1**; OMAFRA, 2023; Soil Classification Working Group, 1998).

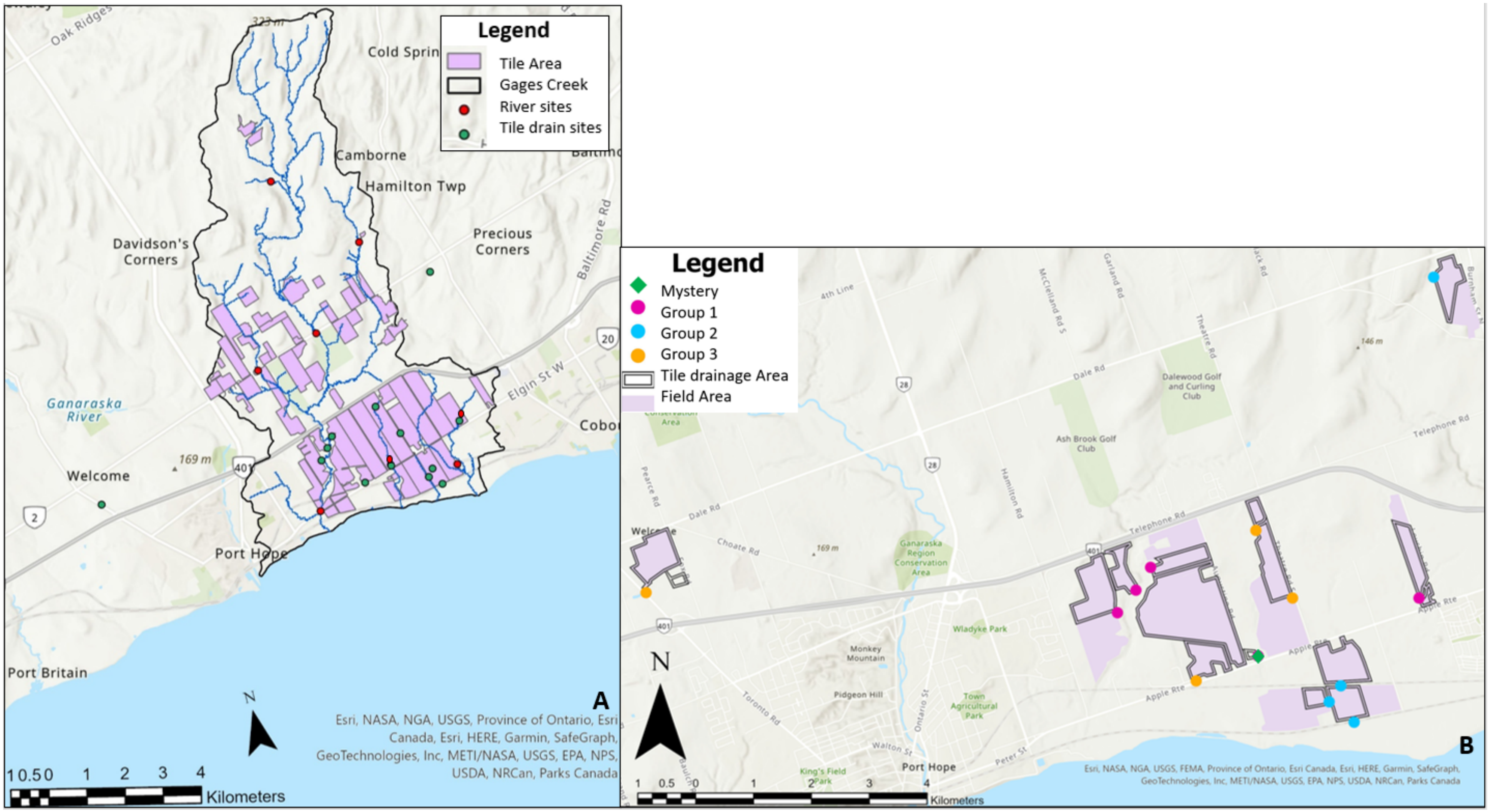

Figure 2-1: Locations of study tile outlets (green), and river sampling stations (red) relative to Lake Ontario and the Gages Creek watershed (A). Fields following the same crop rotation are shown in groups, where Group 1 (pink) includes Gravel, Hubicki's, N. House & Lovshin, and Group 2 (blue) includes S. Lake, Beers, Carr's & Burnham), and Group 3 (yellow) includes Welcome, Jason's, H7A1 & H7B, The Mystery TD outlet (composite tile) is indicated with a green diamond. The map was created in Arch GIS Pro and the tile layer was retrieved from Ontario Geohub (2019).

Table 2-1: Study fields ordered from north to south and their respective texture, tile area, slope, SOM, and bulk density (BD).

Sites	**Soil Texture** [a]	**Tiled field Area (km^2)**	**Slope (%)** [a]	**BD (g/cm^3)**	**pH$_{H_2O}$**
Burnham [b,c]	Sandy loam	0.34	5.0	0.99	5.2
H7A2 [b,c]	Silty clay loam	0.06	3.5	1.0	5.4
N. House	Silty clay loam	0.24	3.5	1.2	7.4
Hubicki's [b,c]	Silt loam	0.14	3.5	1.2	5.4
Welcome	Sandy loam	0.32	3.5	1.2	6.9
Lovshin [c]	Silt loam	0.27	3.5	1.1	6.7
Gravel [b,c]	Silty clay loam	0.61	3.5	1.2	6.3
H7B [c]	Silty clay loam	0.65	3.5	1.0	5.8
Jason's [b,c]	Silt loam	0.18	3.5	N/A	6.0
Carrs [b,c]	Silty clay loam	0.28	3.5	0.89	5.3
S. Lakes	Silty clay loam	0.42	3.5	1.2	6.3
Beers [c]	Silty clay loam	0.32	3.5	0.94	7.5

a) Texture and slope values obtained from the Soil Survey Complex database (OMAFRA, 2019).
b) Fields with soil moisture and temperature monitoring stations.
c) Fields that received buried bags (BB) and plant root simulator (PRS) probes during two incubation periods.

By working with a single farm operator, management was kept consistent, and all fields had the same seeding, fertilizer type and application rates, and cover crop mixtures. Fertilizer was surface broadcasted and application rates varied based on crop type as outlined in **Table 2-2.** The timing and rates of fertilizer application were consistent over the monitoring period, apart from the fall of 2022 when no fertilizer was applied to any of the fields due to high cost (J. Lennox, pers comm). Furthermore, the spring-planted crops, including soybean and corn, were seeded in May throughout the monitoring period, and soybean crops were harvested in late August whereas corn was harvested typically by mid-November depending on weather conditions. Fall-planted crops, including WW and the CC mixture were seeded in late August (CC) to mid-October (WW). Wheat was harvested in late August of the following year whereas CC species that survived the winter were terminated in early May with glyphosate. Over-winter CC included in the multi-species mixture changed over the three NGSs, however, in all years the aim was to include at least one cold grass, one cold broadleaf, one warm grass, and one warm broadleaf (J. Lennox, pers. comm). In winter 2020 (i.e., NGS1), the mix included fava beans, berseem clover, hairy vetch, oats, rye, buckwheat, turnip, and daikon radish. In winter 2021 (i.e., NGS2), the cover crop mix included oats, rye, turnip, daikon radish, berseem clover, sunflowers, buckwheat, hairy vetch, sorghum, fava beans, and peas. Lastly, in winter 2022 (i.e., NGS3), the cover crop mix was comprised of oats, rye, buckwheat, turnip, daikon radish, crimson clover, sunflower, peas, and sorghum.

Table 2-2: Fields and their respective crop rotation and fertilizer application. NGS fertilizer application occurred between August and November, whereas GS fertilizer application occurred in early May. Within the GS, C indicates corn, S indicates soybean and W indicates wheat. In the NGS CC indicates cover crop, CR indicates corn residue and WW indicates winter wheat.

Field and Area (m^2)		**NGS1**		**GS1**		**NGS2**		**GS2**		**NGS3**	
		Crop	Fertilizer	Crop	Fertilizer	Crop	Fertilizer	Crop	Fertilizer	Crop	Fertilizer
Jason's *H7B* *Welcome* *H7A2*	178,068 650,807 319,713 56,724	CR		S		WW	168 kg/ha potash 61 kg/ha K MAG 91 kg/ha MAP 47L/ha 6-24-6 starter	W		CC	None
Hubicki's *Gravel* *Lovshin* *N. House*	137,598 611,579 267,102 243,402	WW	168 kg/ha potash 61 kg/ha K MAG 91 kg/ha MAP 47L/ha 6-24-6 starter	W		CC	168 kg/ha potash 61 kg/ha K MAG	C	17 kg/ha MAP	CR	
Carr's *Burnham* *Beers* *S. Lakes*	283,290 339,948 323,760 416,841	CC	168 kg/ha potash 61 kg/ha K MAG	C	17 kg/ha MAP	CR		S		WW	

2.2. Data collection

2.2.1 Tile drainage discharge and sample collection

Instantaneous flow measurements (L sec^{-1}) were recorded at 12 individual tile outlets during each sample collection day (η=59 days) using a stopwatch and a 1000 mL graduated cylinder (**Appendix A; Figure 6-5**). During periods of intense flow such as during spring melt, a 15 L bucket was used in place of the graduated cylinder. However, at times throughout the study period, the instantaneous flow at the individual tiles was not recorded or was impossible to measure (e.g., saturated periods when tile pipes were completely submerged in drainage ditches/ rivers). In addition, a single composite tile pipe, which discharges to Mystery Creek, was instrumented with a FloWav FW-33 logger with a Stingray ultrasonic sensor in October 2021 to continuously measure water depth (cm) within the tile at 15-minute intervals. Using the Manning equation, water depth was converted to (m^3 sec^{-1}). The diameter of the tile outlet pipe was 31 cm, allowing for a maximum discharge of approximately 0.082 m^3 sec^{-1}.

A line graph (**Appendix A; Figure 6-5**) was used to evaluate the temporal coherence of flow across the 12 individual tiles and the Mystery composite TD outlet and confirmed that measurements at Mystery could be used to prorate flow at the other tiles. As all fields experienced similar precipitation and temperature conditions due to their proximity, all fields exhibited increased discharge during event conditions during the NGS and lower discharge during the GS despite having different response sizes (i.e., some tiles had greater discharge volumes than others likely due to differences in tileshed area and topography). This study assumed that tile discharge volume was proportional to the tileshed area, and the Mystery FloWav logger was used to pro-rate flow at the other 12 tile drains based on drainage area. As the FloWav logger was installed a year after this study was initiated, tile discharge from October 2020 to October 2021 was estimated using a discharge relationship developed from level loggers (Heron Instruments Inc.) installed at two nearby rivers (i.e., Mystery Creek and Gage west) which continuously measured stream water level every 15 mins from September 2018 – April 2023 **(Appendix A; Figure 6-2, 6-3, 6-4, 6-9).** These level loggers were used in a previous assessment of river depth, temperature, and nutrient concentrations described by Liu et al. (2022). A complete record of tile drain discharge at Mystery and additional discharge relationships between the two rivers and Mystery can be found in **(Appendix A; Figure 6-1).**

Each tile outlet was sampled year-round from October 2020 to April 2023, with a focus on events including rain, rain-on-snow, and spring melt, however, baseflow samples were also collected. Tile water samples were collected in acid-washed 500 mL Nalgene polyethylene bottles after pre-rinsing three times with tile water. Samples for TP and TDP were collected directly into borosilicate glass digestion vials and TDP samples were filtered (0.45 μm) in the field to avoid particulate formation during sample storage. All samples were stored in a dark, insulated container for transport to the Environmental Geoscience Laboratory at Trent University. Samples were refrigerated at 4 °C and were generally analyzed within 14 days of collection. In addition, *in-situ* measurements of pH, temperature, and conductivity of tile water were recorded during each field visit using an

Oakton PCTSTestr. Additionally, water samples were collected from eight river sites within the Gage Creek watershed as part of a separate study (**Figure 2-1. A)** and the resulting water chemistry can be found in **Appendix B; Table 6-3.**

2.2.2 Soil monitoring and sample collection

As tile drains influence soil moisture and temperature, they may also influence nutrient turnover in soils. As part of a separate study, soil microclimate monitoring stations were established at a sub set (six) of the TD fields as outlined in **Table 2-1** and six non-tile drained (NTD) fields (see **Appendix D; Figure 6-9).** Some of the soil climate data collected from the TD fields are included here for context. Soil climate measurements were recorded using either a Decagon Device (EM 50 ECH_2O) datalogger or a HOBO Micro station (H21-USB) datalogger. The data loggers were connected to soil temperature probes (ECH_2O EC-TM, HOBO bit temperature smart sensor S-Smx-M005) and soil moisture probes (HOBO soil moisture smart sensor S-TMB-M0xx) installed at 15 cm below the soil surface and were programmed to record a measurement of soil temperature and moisture every hour from October 2021 to April 2023, inclusive. Probes were installed to a depth of 15 cm to reflect conditions in the rooting zone of the dominant crops. Soil microclimate monitoring stations were located ~15 m from the nearest tile outlet in relatively flat, shade-free areas along the edge of fields to avoid disturbance from farm machinery. Data were downloaded from loggers approximately every three months. Additional soil microclimate data for the six NTD fields are reported in **Appendix D; Figure 6-10.**

At nine of the TD fields, including the six fields outfitted with soil monitoring stations, and the six NTD fields, two *in situ* incubation methods were used to estimate nutrient cycling at the seasonal time scale including plant root simulator (PRS) probes (PRS^{TM} probes, Western Ag Innovations, Inc., Saskatoon, SK) and buried bags (BB; **Table 2-1**). The PRS probes contain an ion exchange resin membrane which provides a dynamic measure of ion flux within the soils which can respond to changes in soil moisture, soil temperature, and microbial activity (Western AG, 2023). Buried bags can be used to estimate net mineralization *in situ* in response to soil temperature, microbial activity, and quality of incubated soil material (Hanselman et al., 2004; Isaac & Timmer, 2006; Sullivan et al., 2020). The PRS probes and BBs were installed in a subset of fields at a depth of 15 cm over two incubation periods, including Winter 2021 (27 November 2021 to 5 April 2022, 130 days), and Summer 2022 (21 June 2022 to 9 August 2022, 50 days). To install the PRS probes and BBs, a small soil pit (15 cm deep, 20 cm wide) was excavated and the PRS probes were placed vertically into undisturbed soil on the side of the soil pit at a depth of 15 cm, whereas the BB were placed at the bottom of the pit. The excavated soil from the pit was replaced and any surface residue or vegetation was replaced. Special care was taken to avoid creating cracks or macropores from the disruption of digging the soil pit. The first incubation period was selected to encompass the NGS (specifically NGS2) and spanned from post-harvest to spring melt. The summer incubation period was selected to encompass the GS (specifically GS2) and spanned from established crop growth to shortly before crop harvest.

The subset of six tiled fields and the six NTD fields received four PRS probes per incubation period, two deployed about 5m from the soil monitoring stations and two deployed about 50m from the soil monitoring station, toward the field's center. The two PRS probe installations were selected to capture soil conditions near the TDs and in the field. Prior to laboratory analysis at Western AG, the PRS probes were cleaned with B-Pure water to remove any residual soil and stored in sealed plastic bags at 4^{o}C until shipped to Western Ag Innovations Inc. on ice for analysis. Additional PRS probes were installed at six NTD fields as reported in **Appendix D; Figure 6-13, 6-14.**

Four BBs were deployed at the same time and locations as the PRS probes. The BBs were prepared by filling a polyethylene bag with 100 g of field moist soil which was sieved (5 mm) to remove roots and any plant debris. The soil used to fill the BB was collected at a CR and CC field in November 2021 for the winter incubation and in May 2022 for the summer incubation. Soils under two different crop rotation phases were used in buried bag incubations to capture a range of initial nutrient conditions (i.e. corn was expected to leach a high level of N whereas CC mixtures contain N_2 fixers). Pre- and post-incubation soil samples were refrigerated (4^{o}C) before being dried at 105^{o}C within 3 days of collection and sieved (2mm) prior to analysis. Results from the BB incubations from the nine TD and six NTD fields can be found in **Appendix D; Table 6-6, Figure 6-11, 6-12.**

Additionally, soil samples at the 12 TD fields were collected in the spring (April 2021 and April 2022) and fall (October 2021 and October 2022) to evaluate soil nutrient conditions and to characterize soil properties. At each of the 12 agricultural fields 300 g of soil was collected at two depths, including ‘surface’ (0 - 5 cm) and ‘deep’ (15 - 20 cm), at three locations within 15-30 m of the tile outlet and stored separately in Ziploc bags for a total of six soil samples per field per sample period. Additionally, bulk-density (117.8 cm^3) samples were collected in the spring of 2021 and 2022. These samples were taken from undisturbed soils approximately 30 m from the tile outlet. Soil samples were oven-dried (105^oC) for 24 hours and sieved (2 mm) prior to chemical analysis. Results of the analysis of soil samples collected at the six NTD fields can be found in **Appendix D; Table 6-4, 6-5.**

2.3 Laboratory chemical analysis

Tile water samples were analyzed for several chemical parameters including total carbon (organic and inorganic) and total nitrogen (TN) using combustion catalytic oxidation via the Shimadzu TOC-V_{CPH} with a TN module; NO_3-N using ion chromatography via the Dionex ICS-1100 and TP/ TDP via colorimetry using the Lambda XLS benchtop UV-Vis spectrophotometer. Tile water samples were prepared for TOC-TN analysis by transferring unfiltered sample aliquots into 20 mL Shimadzu autosampler borosilicate glass vials. To prevent the off-gassing of samples as they waited for analysis, vials were filled to the rim, and sealed with parafilm. The Shimadzu TOC-V_{CPH} detection limit was 0.05 mg L^{-1}. Tile water samples were prepared for ion chromatography by first filtering through an InnoSep™ SF25N 0.45 μm nylon syringe filter from Canadian Life Science Inc. into 5mL Dionex autosampler vials. Again, parafilm was used to prevent the off-gassing of the solution prior to analysis. Lastly, tile water was prepared for colorimetric analysis of TP and TDP by first digesting in 11N sulfuric acid and ammonium persulfate, and then autoclaving at 121°C for 50 minutes. Phosphorus was measured by colorimetry following the Murphy-Riley method (Murphy & Riley, 1962) and recorded values were blank-corrected. The analytical detection limit of this method was ~ 5 µg L^{-1}. Standards including a multi anion mixture (i.e., F^-, Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-}), a 1000 ppm PO_4^{3-}, and a 100 ppm TOC, TC, TIC, and TN standard were analyzed to confirm the accuracy and precision of all the above-mentioned methods.

Similarly, soil water extracts were prepared for analysis of water-soluble TC, TIC, TOC, and TN via the Shimadzu TOC-V_{CPH} with a TN module and water-soluble NO_3-N via Ion Chromatography by shaking a 1:8 ratio of soil to β-pure H_2O in a 50 mL FroggaBio centrifuge tubes for 18 hours. The shaken slurries were then centrifuged at 3000 RPM for 20 minutes before being filtered (0.45 µm nylon syringe filter). The filtered soil water extracts were then transferred to either 20 mL Shimadzu autosampler borosilicate glass vials or 5 mL Dionex autosampler vials prior to analysis. Within this study the labile fractions of C, and N were assessed through the determination of water-extractable TC, TN, and NO_3-N; however, it should be noted that other methods may be appropriate for examining labile fractions for agronomic performance; for example, potassium permanganate oxidizable C can be used to assess active carbon (Culman et al., 2013; Svedin et al., 2023). This study was not designed to understand agronomic performance, instead, the labile fraction of nutrients was examined as a possible indicator of nutrient concentrations in tile drainage discharge, and therefore a water extraction was effective for this purpose.

Furthermore, soil samples were prepared for the determination of P concentrations following the Olsen P method (Olsen et al., 1954). The Olsen P method provides a measure of ‘plant-available’ P and is recommended by OMAFRA for the circumneutral soils that characterize this region of southern Ontario (OMAFRA, 2020). Soil samples were prepared by first mixing a 1:4 ratio of soil to 0.5 M $NaHCO_3$ solution with a pH of 8.5 for 18 hours in 50 mL FroggaBio centrifuge tubes. The slurries were then centrifuged at 3000 RMP for 20 minutes and aliquots of the samples were vacuum filtered using Whatman no. 42 filter papers. The filter extracts were then treated with 2 drops of ρ-nitrophenol and were acidified with 0.25 M sulfuric acid. Filtered soil extracts then underwent cold digestion for up to 74 hours before undergoing colorimetric analysis using the Lambda XLS benchtop UV-Vis spectrophotometer. All sample values were blank-corrected and compared to a standard curve ranging from 10 μg L^{-1} to 750 μg L^{-1}.

Additional soil characterizations were conducted following standard methods and procedures. Soil pH was determined using a 1:1 ratio of oven-dried (105^{o}C) soil to β-pure which was mixed for 15 minutes in 15 mL sample tubes and then left to stand for 45 minutes. Soil pH was measured in the resulting slurry with an Oakton 510 series benchtop meter. Oven-dried soil samples were also analyzed for total carbon and total nitrogen on a Vario EL cube. Between 20 – 40 mg of composite soil samples collected at two different times (Spring and Fall 2021 and 2022) from each field were analyzed to determine the percent N, and C, and acetanilide was used as the standard. Furthermore, the loss on ignition (LOI) of the soil samples was determined by ashing two grams of oven-dried soil at 550^{o}C for five hours. Ashed soil samples were then analyzed for texture via a Horiba Partica LA-960V2 laser scattering particle size distribution analyzer. Additionally, soil texture was confirmed using oven-dried soil samples via the hydrometer method whereby 50 g of soil was mixed with 100 mL of 5% dispersion solution (Calgon) and then diluted to 1000 mL. Lastly, to assess the accuracy of soil texture values, results from the Horiba Partica LA-960V2 and hydrometer method were compared to values reported in the soil survey complex of Ontario (OMAFRA, 2019).

2.4 Analysis and statistical approach

Tile discharge measured (raw) nutrient concentrations, volume-weighted concentrations, and soil moisture/ temperature were compared by season (NGS1, GS1, NGS2, GS2, and NGS3) and by crop cover: corn, soybean, wheat, corn residue (CR), winter wheat (WW), and over-winter cover crop (CC). The NGS was based on the period from crop harvest through to spring (October – April, inclusive) and the GS included samples collected from planting to harvesting (May to September). The crop cover was based on the crop planted or residue present on the fields at the time of sampling. Soil quality and conditions were summarized based on the sampling period (spring or fall). The spring period is defined as prior to fertilizer application and crop seeding. The fall period is defined as just after crops were harvested; and as such the timing of soil sampling differed between crops. For example, soybeans were harvested in early October whereas corn was harvested in mid-November.

The 12 TD fields within this study followed a strict and consistent crop rotation throughout the 28-month study period. As such the fields within this study can be divided into three groups based on their crop rotation as outlined in **Table 2-2.** Importantly three of the four fields within each study group were located close to one another (see **Figure 2-1)**, however, one field within each Group was located apart from the rest (i.e., Welcome, Burnham, & Lovshin; see **Appendix D; Figure 6-9).** These more distant fields are important to note, as otherwise there could be some concern over spatial bias within the crop rotational groups.

Fluxes of N and P (mass) were calculated by multiplying the nutrient concentration in tile discharge water (TN, NO_3-N, TP) by the volume of tile outlet discharge for the respective tile drain. These nutrient masses were then summed by season to obtain mass nutrient loss by season and then divided by the volume of discharge over the same period to estimate seasonal volume-weighted concentrations. The effects of season (GS versus NGS) and the influence of crop cover on measured and volume-weighted concentrations were evaluated using a linear mixed model (LMM) in GraphPad Prism 8.0 (Graph pad prism 2022). The mixed model allowed for a compound symmetry covariance matrix and was not impacted by the absence of missing values. This test is similar to a two-way analysis of variance (ANOVA), with crop cover and year as factors. A probability level of 0.05 was used to evaluate statistical significance. Furthermore, a Tukey multiple comparison post hoc test was used to identify significant ($\rho \leq 0.05$) differences in nutrient leaching between crops/ crop residues/ over winter cover crops in the GSs and NGSs.

To test the hypothesis that labile nutrient concentrations are sensitive to crop rotation, an ANOVA was used to compare differences in total vs. labile soil concentrations. Analysis was conducted seasonally (spring and fall) with fields being compared to one another by soil depths (5 and 15 cm). As the data were non-parametric the Mann-Whitney U test was used, and all analyses were conducted using GraphPad Prism 8.0 (GraphPad Prism 2022). Furthermore, PRS results were analyzed by crop cover for two time periods (Winter 2021, Summer 2022). Again, an ANOVA was used to compare PRS probe results by crop cover. Similarly, to address the hypothesis that nutrient concentrations would be greater in surface soils compared with deeper soils, soil properties (total N and C via combustion, TN, TC, NO_3-N via water extraction, and TP via Olsen P) at 0-5 cm were compared to those at 15-20 cm via a multi-pairwise t-test at $p \leq 0.05$ significance level.

3. Results and discussion

3.1 Climate, precipitation, discharge, and soil microclimate

Climate conditions during the 28-month period of study were generally similar to long-term (30-year) averages for the region, with some exceptions (**Table 3-1).** Both growing seasons (GS 1 & 2) had typical temperature conditions, whereas GS2 was wetter than normal (540 mm). In contrast, the first two non-growing seasons (NGS1 & 2) were colder than average, and NGS1 was also comparably dry (390 mm). The final NGS (NGS3) had an average temperature but was relatively wet (540 mm) compared to the long-term mean (460 mm; **Table 3-1).**

Table 3-1: Mean temperature, total precipitation, and tile drain discharge for the five study seasons compared to the long-term (30-year) climate normals. The numbers in parentheses represent the minimum and maximum temperatures, the % precipitation as snow, the fraction of precipitation manifested as TD (yield), and the numbers in square brackets represent the 95% confidence interval (CI). Climate data was retrieved from Environment Canada's Cobourg AUT climate station ID 6151684 (43°57'00" N 78°10'00" W).

	Mean Air Temperature (°C)	**Total Precipitation (mm)**	**Mystery Discharge (mm)**
NGS1	2.1 (-19 to 21)	390 (21% snow)	184 (0.48)
GS1	17 (0 to 30)	380	45 (0.12)
NGS2	1.4 (-23 to 22)	400 (23% snow)	283 (0.71)
GS2	17 (1.2 to 29)	540	37 (0.07)
NGS3	2.4 (-27 to 23)	540 (26% snow)	223 (0.41)
30-year NGS normal	2.5: CI [2.4, 2.6]	460: CI [406, 514]	N/A
30-year GS normal	17: CI [16.8, 17.2]	380: CI [348, 412]	N/A

From December to March, precipitation was typically snow or frozen (i.e., freezing rain). Across the three NGSs, the percentage of precipitation falling as snow ranged from 21 – 26 % which contributed to varying snowpack depths throughout the study period **(Figure 3-1, 3-2).** Despite the long duration of a snowpack in NGS1 (21/11/2020 to 31/3/2021, 130 days), the relatively thin pack depth in that year (Average: 2 cm, Max: 12 cm) likely limited its influence on soil thermal conditions. In comparison, the snowpack lasted a similar length of time in NGS2 (28/11/2021- 22/3/2022, 115 days), but was generally thicker (Average: 5 cm, Max: 17 cm). Lastly, snowpack depth and duration were more variable in NGS3, which led to extended periods of non-snow-covered conditions within the December to March window (**Figure 3-1**). Despite greater snow depths throughout NGS3 (Average: 11 cm, Max: 33 cm) in comparison to NGS1 &2, there was also increased soil exposure due to the prolonged (max consecutive days without snow cover: 23 days) non-snow-covered periods (see **Figure 3-1, 3-2).** Previous work by Lam et al. (2016), showed that the presence of a snowpack helped to minimize soil frost and allowed for greater infiltration of snowmelt water which minimized overland flow and erosion in the spring. A thin snowpack or the absence of snow cover over agricultural fields can expose soils to colder air temperatures, resulting in deeper or more frequent soil freezing and freeze-thaw events (Freppaz et al., 2007; Green et al., 2022). Although soils were occasionally snow-free in NGS3, soil temperatures remained above 0ºC in this year, whereas there were numerous dates when soil temperature dropped below freezing in NGS2 (see **Figure 4-3**). More frequent freeze-thaw events may have implications on organic matter decomposition (e.g., crop material and residue breakdown) or the presence of macropores (e.g., cracks or fissures). Freeze-thaw cycles over the NGS can influence the forms of nutrients present within the soil matrix leading to increased mineralization of organic nitrogen and greater concentrations of NO_3-N within the soil matrix (Freppaz et al., 2007; Green et al., 2022). Furthermore, freeze-thaw cycles allow for an increase in dissolved P over the NGS due to the breakdown of organic material (i.e., crop residues) and fertilizers (Freppaz et al., 2007). Lastly, variations in soil temperature due to repeated freezing and thawing cycles within the NGS may create preferential flow paths in the topsoil which can have implications on nutrient concentrations and TD discharge volumes (King et al., 2015). These changes in nutrient form coupled with greater volumes of discharge over the NGS can lead to greater fluxes of bioavailable nutrients in tile discharge.

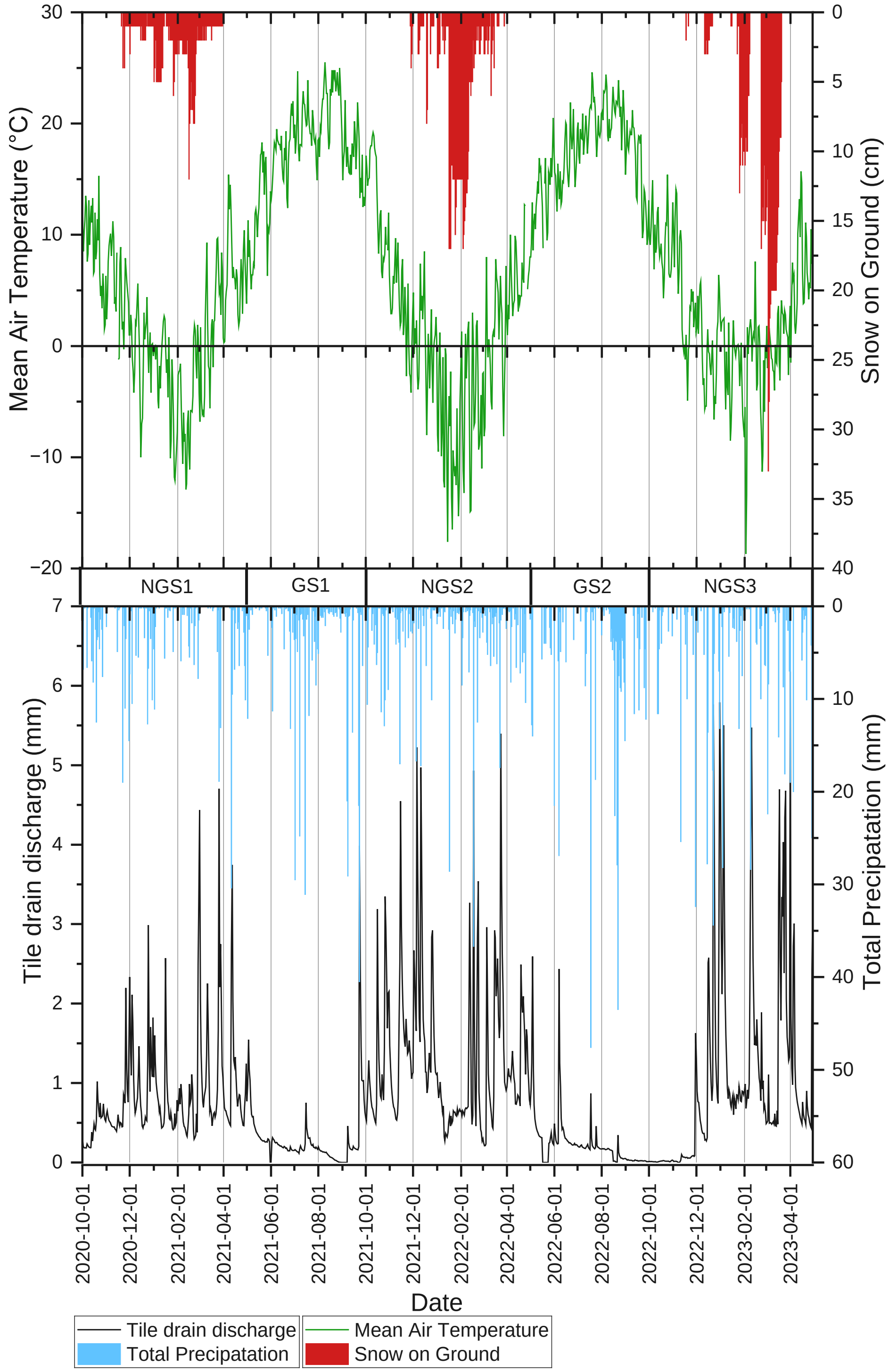

Figure 3-1: Daily (Oct 2020 – April 2023, inclusive) total precipitation, air temperature, snowpack depth, and tile drainage discharge volume at Mystery TD based on season (NGS and GS) Climate data are from the Cobourg AUT climate station ID 6151684.

Figure 3-2: Observations of the snowpack at Jason's field in a) NGS2 (February 10, 2022) and b) NGS3 (February 9, 2023)

3.1.1 Tile drain discharge

Tile drain discharge was highly seasonal, with field observations indicating that most of the 12 tiles flowed continuously throughout the three NGSs, whereas most tile drains ceased to flow for a prolonged time during the GSs. These field observations were reflected in the Mystery tile drain discharge record shown in **Table 3-1** and **Figure 3-1.** Discharge from the Mystery tile outlet was greatest during the NGS, ranging from 184 mm in NGS1 to 283 mm in NGS2, which are equivalent to 48-71% of precipitation in those same periods (**Table 3-1**). In comparison, tile runoff during the growing season was only 45 mm in GS1 and 37 mm in GS2, which are equivalent to 7-12% of incoming precipitation in those same periods (**Table 3-1)**. These findings are similar to those reported by King et al. (2016), who found that tile discharge over the NGS ranged from 198 to 436 mm which was equivalent to 39-87% of precipitation, whereas, within the GS there was 42-104 mm of discharge which was equivalent to only 9-21% of precipitation over an eight-year study of three tile drains in Ohio. The increase in tile discharge during the NGS is likely the result of reduced crop uptake, lower evapotranspiration, predominantly wet antecedent conditions (i.e., high water table), and precipitation characteristics (e.g., form, intensity, timing, duration; Bjorneberg et al., 1996; Gramlich et al., 2018; Macrae et al., 2010). Numerous studies have documented that TD discharge responds rapidly to precipitation events during the NGS (Gentry et al., 2007; Macrae et al., 2010; Smith, 2015), whereas precipitation events in the GS generally generate a much smaller response (Bjorneberg et al., 1996; Gaillot et al., 2023). For instance, Gaillot et al. (2023), found that 54-81% of rainfall events > 0.6 mm during the NGS generated tile drainage discharge above baseflow conditions, however, during the GS only 3% of rain events >8.8 mm generated a tile response. The strong seasonal difference in TD discharge volume influences the timing of nutrient export and emphasizes the value of having BMPs that are targeted to the NGS.

3.1.2 Soil microclimate conditions

Temporal patterns in soil moisture at a depth of 15 cm were highly coherent across all fields, increasing or declining in unison in response to changes in season and precipitation (**Figure 3-3)**. For example, during the springs of both 2022 and 2023, soil moisture spiked likely due to snow melt and increased effective precipitation, but as crop uptake and evapotranspiration rates increased, the volumetric water content of the soil declined. For instance, the average volumetric water content at the tiled fields at a depth of 15 cm was 0.34 m^3m^{-3} on March 4, 2022, but declined steadily to 0.24 m^3m^{-3} by June 6, 2022 (**Figure 3-3).** Furthermore, soil moisture was highly responsive to precipitation events, especially throughout the GS when rapid spikes in soil moisture were observed following precipitation events. For example, on July 18, 2022, soil moisture rose from 0.18 to 0.26 m^3m^{-3}, in response to a precipitation event of 48 mm (**Figure 3-3).** Furthermore, a precipitation event of 44 mm on August 22, 2022, caused the soil moisture to rise from 0.17 to 0.28 m^3m^{-3} (**Figure 3-3).** The results from the current study align with those reported by Lam et al. (2016), who found that soil moisture demonstrated both seasonal and interannual variability, with soil moisture typically lowest during the GS but similar at other times of year at two sandy loam TD agricultural fields in Southern Ontario. It should be noted that soil moisture is also sensitive to changes in air/ soil temperature and volumetric moisture measurements during the NGS are unlikely to be completely accurate due to subzero air/ soil temperatures. For example, soil moisture plummeted between January and March 2022 (NGS2) suggesting a rapid drying event (**Figure 3-3).** However, the soil moisture probes are incapable of accurately recording moisture conditions at subzero temperatures as they are unable to detect the difference between frozen soils and dry soils (Onset HOBOware, 2022). Soil moisture data collected during the NGS must therefore be treated with caution.

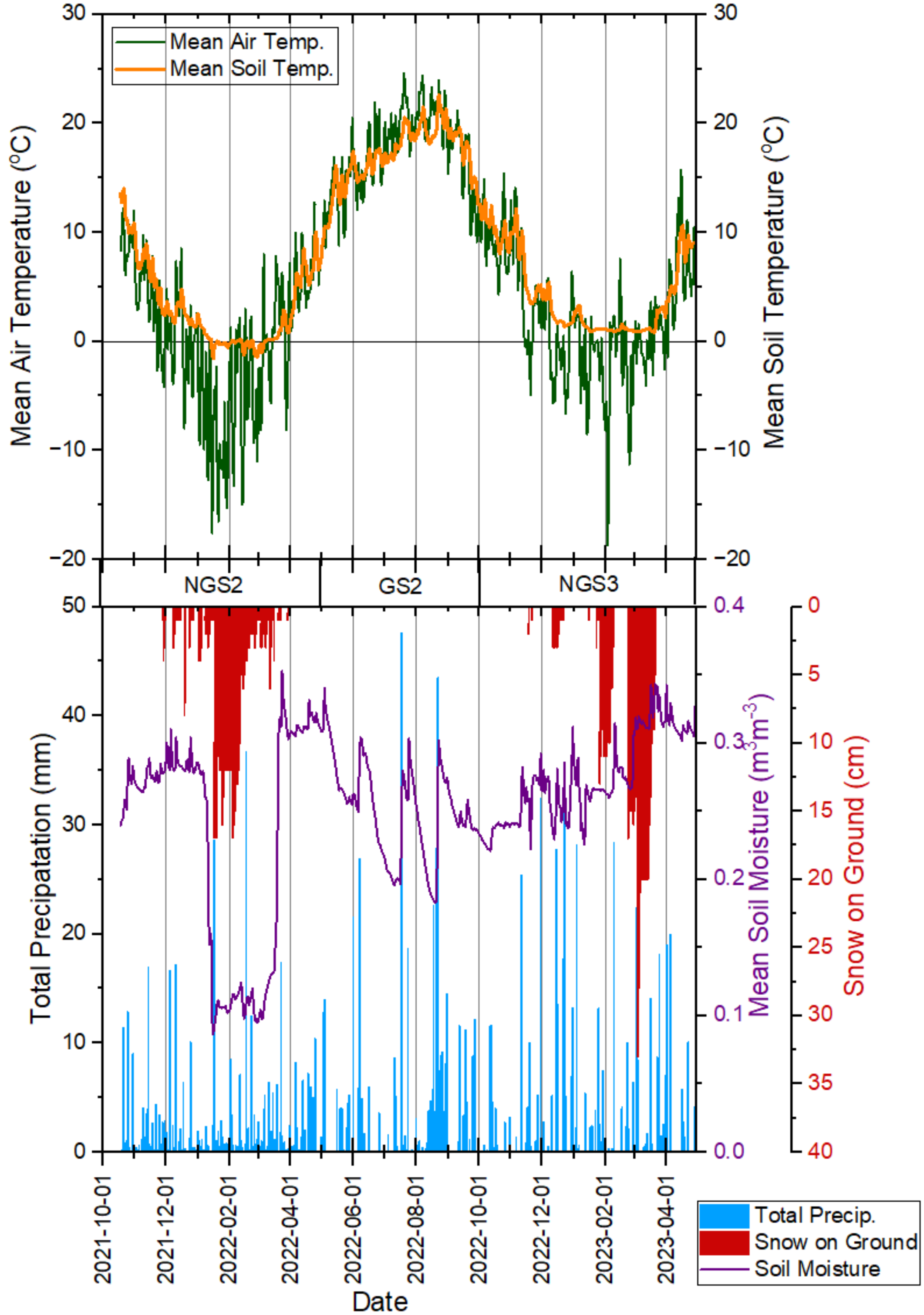

Figure 3-3: Daily soil moisture, total precipitation, soil and air temperature throughout NGS2, GS2, and NGS3, which correspond to: October 2021-April 2022, May 2022-October 2022, and October 2022-April 2023. Climate data are from the Cobourg AUT climate station ID 6151684.

In addition to soil moisture conditions, soil temperature conditions at a depth of 15 cm were recorded at the fields and the results indicated that the soil temperature was highly coherent with air temperature conditions (**Figure 3-3).** Throughout the NGSs, fluctuations in air temperature were much larger than in soil, which demonstrates the role of the snowpack (**Figure 3-3)**. Within the current study, soil temperatures within the two NGSs were marginally warmer than the air temperatures (**Figure 3-3)**. Specifically, in NGS2, the average air temperature was 1.4^{o}C, and a snowpack, ranging from 5 to 17 cm, was present from mid-January to mid-February (**Figure 3-3).** Despite the presence of a snowpack, the soil temperature temporarily dropped below zero between February and March 2022 (**Figure 3-3)**. In comparison, NGS3 experienced slightly warmer air temperatures with an average air temperature of 2.4^{o}C and a snowpack greater than 10 cm from mid-January to early February and from the end of February to mid-March (**Figure 3-3).** Unlike NGS2, NGS3 did not experience subzero soil temperatures likely due to both warmer air temperatures and greater snowpack depth (**Figure 3-3)**. The coherence in soil and air temperature has been observed by others, especially at shallow depths such as 15cm and during non-snow-covered periods (Jin et al., 2008; Zheng et al., 1993). The presence of snow cover over the winter months can insulate soils from extreme air temperatures, and thus soil temperatures even at a shallow depth are less reflective of air temperatures within snow-covered periods (Jin et al., 2008; Lam et al., 2016). For example, Jin et al. (2008), found that soil temperatures mirrored air temperatures at shallow depths (0-30 cm) at fields in Minnesota apart from during snow-covered periods when soil temperature was up to 9^{o}C warmer than minimum air temperatures due to the insulating effect of the snowpack. Due to the short duration and limited depth of the snowpacks in NGS2 and NGS3, the soils may not have experienced a substantial insulating effect as generally it's agreed upon that between 30 to 40 cm of snow is needed to provide an insulating effect (Zhang, 2005). The snowpacks across the three NGSs within this study rarely exceeded 30 cm which may explain why the soil temperature and air temperature are so similar within the NGS.

3.2 Tile drainage water quality

Measurements of C compounds (i.e., TC, TIC, and TOC) and *in-situ* conditions (i.e., temperature, pH, conductivity) indicate several similarities across the 12 TD sites despite variations in crop cover throughout the study period. For example, the temperature of tile water was generally lower than air temperature in the growing season and warmer than air temperature in the non-growing season months. Inorganic C accounted for on average 93% of total C in tile water with average concentrations of TIC ranging from 57 to 71 mg L^{-1} across the 12 TDs over the 28-month study period (**Table 3-2**). High TIC is consistent with the neutral to slightly alkaline pH (7.8- 8.0) of tile water samples, and the range in conductivity of TD samples (540 to 680 µS cm^{-1}) was within the normal range for freshwater (Environment and Climate Change Canada (ECCC), 2017; **Table 3-2)**. Although TOC made up only a small percentage of TC, TOC concentrations consistently spiked during event-flow conditions, both in the NGS and the GS (**Appendix B; Figure 6-7).** For example, a rain-on-snow event of 7.8 mm on February 27, 2021, resulted in flow at the Mystery TD increasing from 0.49 L sec^{-1} at 9:00 am to 8.5 L sec^{-1} at 6:30 pm **(Figure 3-1).** Peak TOC concentrations in TD eluent during this NGS event ranged from 7.1 to 26 mg L^{-1}, which is much greater than the range in average TOC over the study period (3.7 to 8.4 mg L^{-1}; **Table 3-2, Appendix B; Figure 6-7).** Furthermore, a rain event of 19 mm on

June 16/17, 2022, led to a minor increase in Mystery TD from 0.37 L sec^{-1} at 1:00 am on June 16 to 0.43 L sec^{-1} at 8:30 am on June 17 **(Figure 3-1).** The peak TOC concentration during this GS event ranged from 14 to 17 mg L^{-1} (**Appendix B; Figure 6-7).** Spikes in TOC during event flow conditions suggest that preferential flow pathways are contributing to by-pass-flow (Schilling et al., 2023). Preferential flow paths (macropores) allow nutrients that are enriched in surface soils (i.e., high SOM, C) to be transferred relatively conservatively into TD rapidly after the onset of event conditions.

Table 3-2: Supplementary and *in situ* tile water chemistry across the 28-month study period. Values are reported as means +/- standard deviation, except for pH, which is the median, and temperature which is reported as a range.

Field	**Temperature (°C)**	**pH**	**Conductivity (µS/cm)**	**TC (mg/L)**	**TIC (mg/L)**	**TOC (mg/L)**
Welcome	1.8 - 18	7.8	670 ± 120	62 ± 13	57 ± 13	5.8 ± 3.8
Hubicki's	1.7 - 16	7.9	640 ±110	67 ± 18	64 ± 18	5.3 ± 4.7
Gravel	2.0 - 16	7.9	660 ± 150	68 ± 17	64 ± 18	5.9 ± 4.8
Jason's	2.5 - 17	7.9	650 ± 120	76 ± 19	69 ± 19	8.4 ± 6.3
N. House	2.5 - 18	7.9	590 ± 110	63 ± 15	61 ± 15	4.4 ± 3.8
H7B	1.4 - 16	7.9	630 ± 110	69 ± 16	64 ± 16	6.0 ± 4.6
H7A	0.8 - 17	8.0	650 ± 150	66 ± 13	62 ± 14	5.6 ± 4.7
Beers	2.9 - 11	7.8	600 ± 50	74 ± 15	71 ± 15	5.2 ± 4.2
S. Lake	2.4 - 11	7.8	590 ± 50	69 ± 21	67 ± 21	3.7 ± 3.4
Carr's	3.2 - 19	7.7	590 ± 70	66 ± 16	62 ± 17	5.3 ± 4.2
Lovshin	2.1 - 14	8.0	680 ± 190	64 ± 19	60 ± 19	5.8 ± 4.4
Burnham	1.9 - 17	7.8	540 ± 120	63 ± 20	61 ± 21	3.9 ± 4.7

3.3 Concentrations of N and P in tile water

Tile water concentrations of N and P differed based on crop and/or crop cover, as well as discharge conditions (i.e., event vs. baseflow) throughout the study. Nitrogen concentrations (TN and NO_3-N) indicated a connection with crop cover, specifically in the

NGS, but were relatively insensitive to flow conditions or season. In contrast, P concentrations (TP and TDP) were not consistently related to crop cover and were instead sensitive to hydrology and observed physical soil conditions (i.e., macropores), such that TP concentrations in TD discharge were generally higher under event flow compared with baseflow. These observations are described further below.

3.3.1 Seasonal measured and volume-weighted nitrogen concentrations in TD discharge

Over the study period, measured concentrations of TN and NO_3-N exceeded the freshwater quality guideline of 3 mg L^{-1} in 58 % (i.e., 290 of 500 samples) and 39 % (i.e., 193 of 492 samples) of the samples collected for TN and NO_3-N, respectively. Total N and NO_3-N concentrations at the 12 sites varied greatly across the entire 28-month period (0.1 to 16 mg L^{-1}), and there was no clear seasonal pattern across the five study periods. For instance, measured TN concentrations in the 12 TDs ranged from 0.01 to 11 mg L^{-1} in NGS1, from 0.01 to 7.4 mg L^{-1} in GS1, from 0.01 to 9.8 mg L^{-1} in NGS2, from 0.01 to 11 mg L^{-1} in GS2 and from 0.01 to 14 mg L^{-1} in NGS3 (**Figure 3-4**). Likewise, measured NO_3-N concentrations across the 12 TDs ranged from 0.01 to 7.0 mg L^{-1} in NGS1, from 0.01 to 6.8 mg L^{-1} in GS1, from 0.01 to 9.9 mg L^{-1} in NGS2, from 0.01 to 9.2 mg L^{-1} in GS2, and from 0.01 to 7.6 mg L^{-1} in NGS3 (**Figure 3-5)**. Maximum measured concentrations of TN and NO_3-N found within this study were considerably lower than those reported by King et al. (2016), who measured TN and NO_3-N concentrations as high as 81 mg L^{-1} and 71 mg L^{-1}, respectively in three tile drains in Ohio under a corn-soybean rotation. However, in the King et al. (2016) report, tile water aliquots were collected every six hours, with concentrations greater than 40 mg L^{-1} being very uncommon. Instead, the majority of samples ranged from 0 to 20 mg L^{-1} which matches findings from the current study (King et al., 2016; **Figure 3-4, 3-5).** The increased sampling frequency likely allowed King et al. (2016), to capture greater variability in N leaching in comparison to the weekly to biweekly sample collection method outlined in the current study. Nevertheless, the range in measured N concentrations from both the current study and King et al. (2016), are comparable and would contribute to downstream eutrophication.

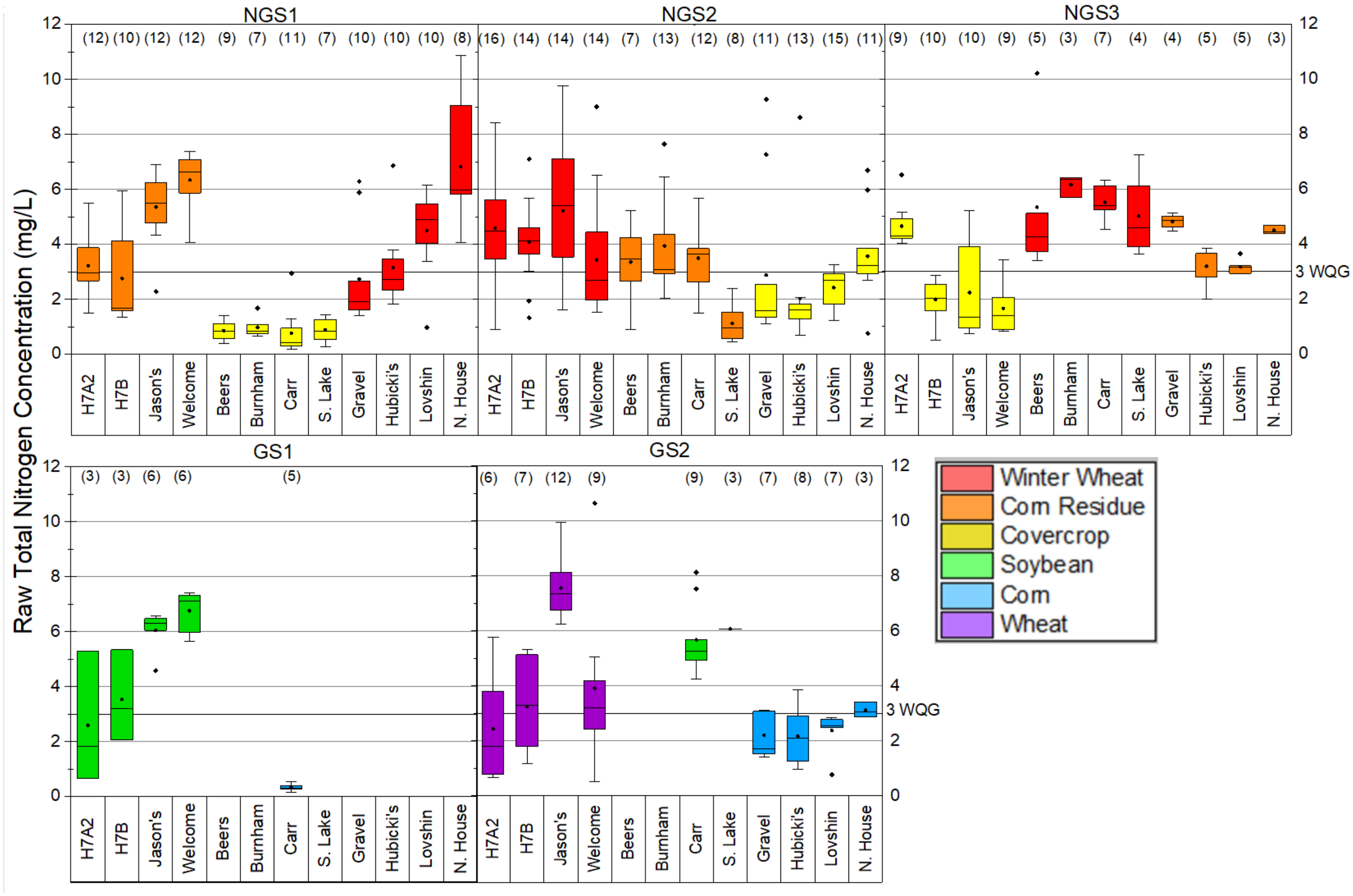

Figure 3-4: Seasonal boxplot of measured TN concentrations (mg L^{-1}) at the 12 tiled fields. Boxes indicate the 25th-75th percentile concentrations, and the median is indicated by the central line. Whiskers indicate the upper and lower extents of the interquartile range multiplied by 1.5. Statistical outliers that exceed the whiskers are indicated by the dots. Numbers in brackets represent sample size (η) at each tile drain for the different seasons. The Provincial Water Quality Objective (WQG) is 3 mg L^{-1}.

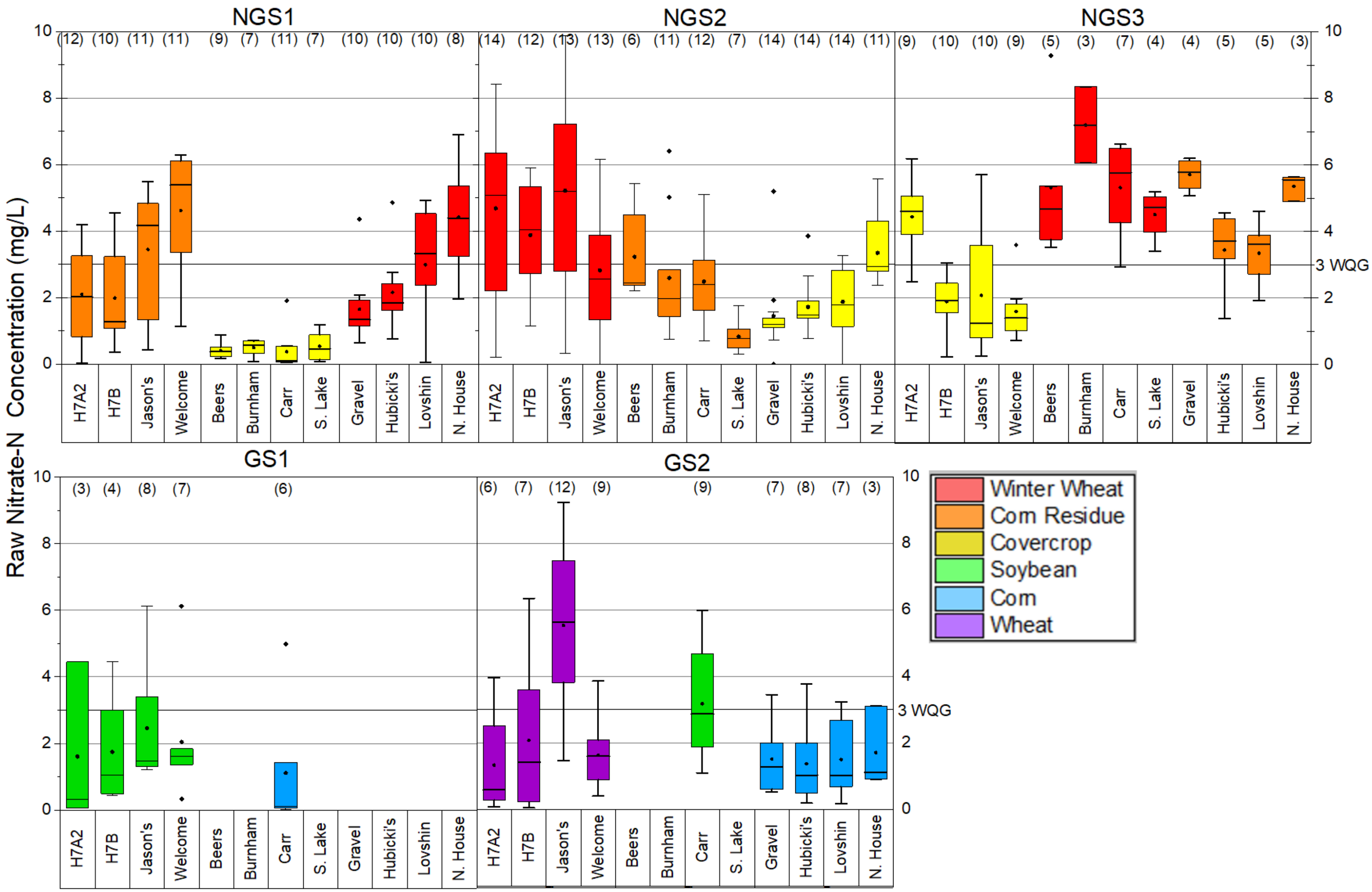

Figure 3-5: Seasonal boxplot of measured NO_3-N concentrations (mg L^{-1}) at the study tile drains. The WQG is 3 mg L^{-1}.

Due to considerable differences in tile discharge volume between seasons (**Figure 3-1**) and amongst the 12 tiles, volume-weighted concentrations of TN and NO_3-N were calculated. Similar to the individual observations, volume-weighted seasonal concentrations of TN and NO_3-N did not follow a consistent pattern across the five study seasons. Seasonal volume-weighted mean concentrations of TN from the 12 TDs ranged from 0.9 to 7.1 mg L^{-1} in NGS1, from 0.3 to 7.1 mg L^{-1} in GS1, 1.2 to 5.3 mg L^{-1} in NGS2, 2.0 to 7.7 mg L^{-1} in GS2, and 0.9 to 6.2 mg L^{-1} in NGS3 **(Figure 3-6).** Likewise, seasonal volume-weighted mean concentrations of NO_3-N at the 12 TD ranged from 0.3 to 4.8 mg L^{-1} in NGS1, from 0.1 to 3.6 mg L^{-1} in GS1, 1.1 to 5.3 mg L^{-1} in NGS2, 0.4 to 3.8 mg L^{-1} in GS2, and 0.7 to 6.1 mg L^{-1} in NGS3 **(Figure 3-6).** Volume-weighted concentrations of N in TD in the current study were similar to those reported by King et al. (2016), who found that mean annual flow-weighted concentrations of TN and NO_3-N were 14 and 13 mg L^{-1} respectively for a seven-year study of three experimental fields in Ohio under a corn-soybean crop rotation. Interestingly, the proportion of NO_3-N as TN differed seasonally, with NO_3-N accounting for on average 79 % (range: 43 to 100 %) of TN in the NGS, whereas NO_3-N only made up on average 44 % (range: 8.5 to 77 %) of the TN in the GS **(Figure 3-6).** Thus, although volume-weighted N concentrations were similar across seasons, there was more bioavailable N (as NO_3-N) in the NGS. The greater portion of NO_3-N as TN in the NGS could be reflective of decreased NO_3-N uptake by plants, macropore flow, and freeze-thaw cycles (Gramlich et al., 2018; Gentry et al., 1998). The greater proportion of NO_3-N in the NGS highlights the importance of nutrient losses in the dormant season for contributing to downstream nutrient enrichment of agricultural streams and the water bodies they flow into.

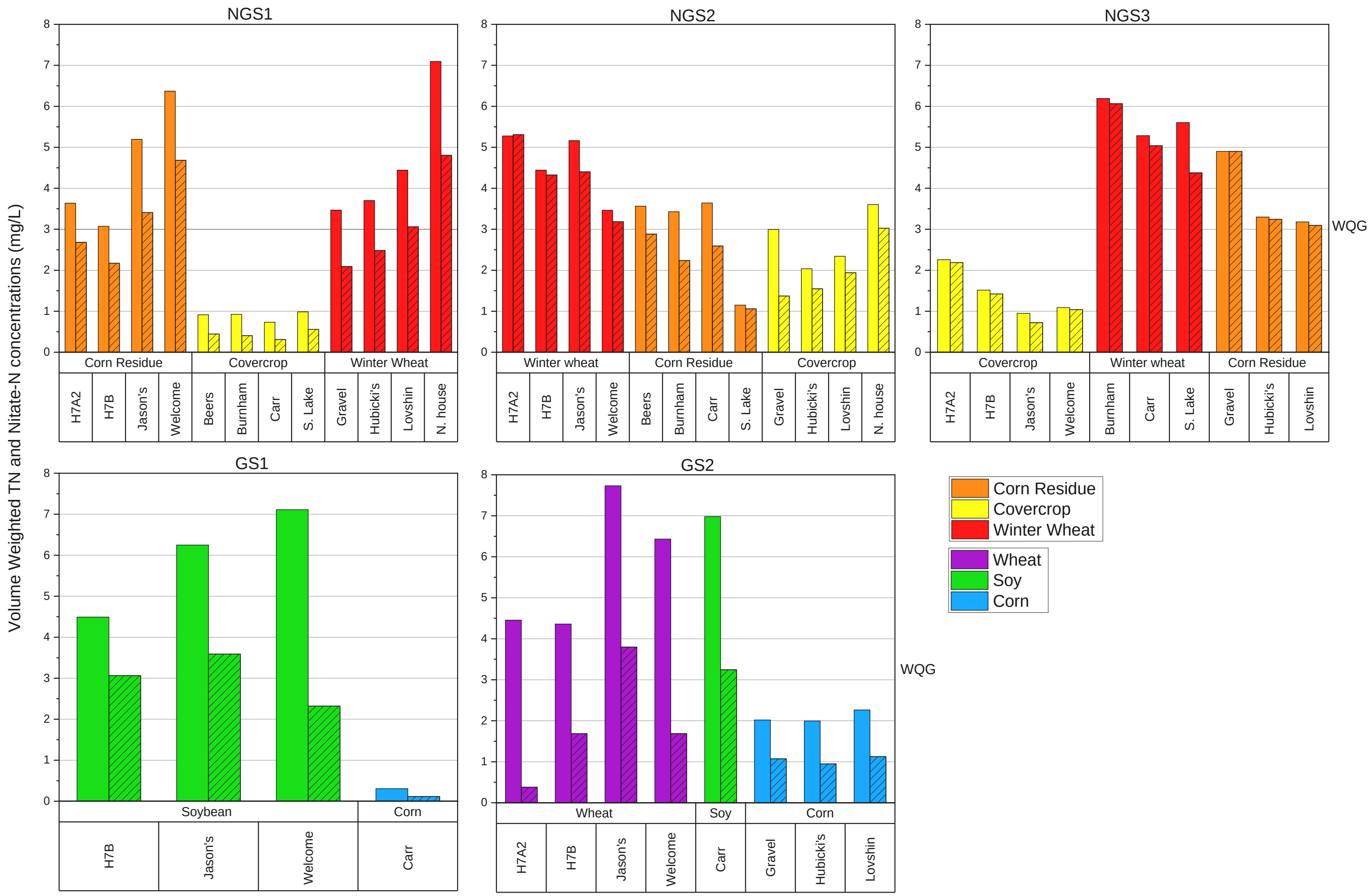

Figure 3-6: Seasonal volume-weighted TN and NO_3-N concentrations based on crop rotation where only fields with at least three measurements of tile water in a season are reported; hashed bars represent NO_3-N.

Although N concentrations in TD eluent (measured and volume-weighted) were similarly high between seasons and amongst the three years **(Figure 3-4, 3-5, 3-6)** the volume of discharge was more than eight times greater in the NGS compared with the GS. Therefore, seasonal variability in N mass flux was primarily due to differences in the volume of discharge rather than concentration (**Figure 3-7, 3-8).** This finding is similar to other studies which found that N export in tile drains correlated mainly with the volume of discharge (Bjorneberg et al., 1996; Gentry et al., 1998). For instance, Gentry et al. (1998), found that a single high-flow day contributed to the export of 148 kg N from a single TD in central Illinois. Likewise, within the current study, a single 40 mm rain event on April 11/12, 2021, led to Mystery TD increasing in discharge from 0.60 L sec^{-1} (3:00 am, on April 11) to 6.9 L sec^{-1} (1:00 am, April 12; **Figure 3-1).** As a result, it was estimated that more than 15 kg N was exported from a single TD on this date. The loss of 15 kg N from a single TD in NGS1 is much greater than the mean mass fluxes reported in **Figure 3-7** & **Figure 3-8,** which indicates the influence of events on N losses. Furthermore, a 28 mm rain-on-snow event on February 9, 2023, to an approximately 19 cm snowpack resulted in Mystery TD increasing in discharge from 1.1 L sec^{-1} (4:45 am, February 9) to 17 L sec^{-1} (5:15 am, February 10; **Figure 3-1).** As a result, it was estimated that up to 13 kg N was exported during this single event. These findings suggest that major rain events in early spring and rain-on-snow events may be a substantial contributor to N export.

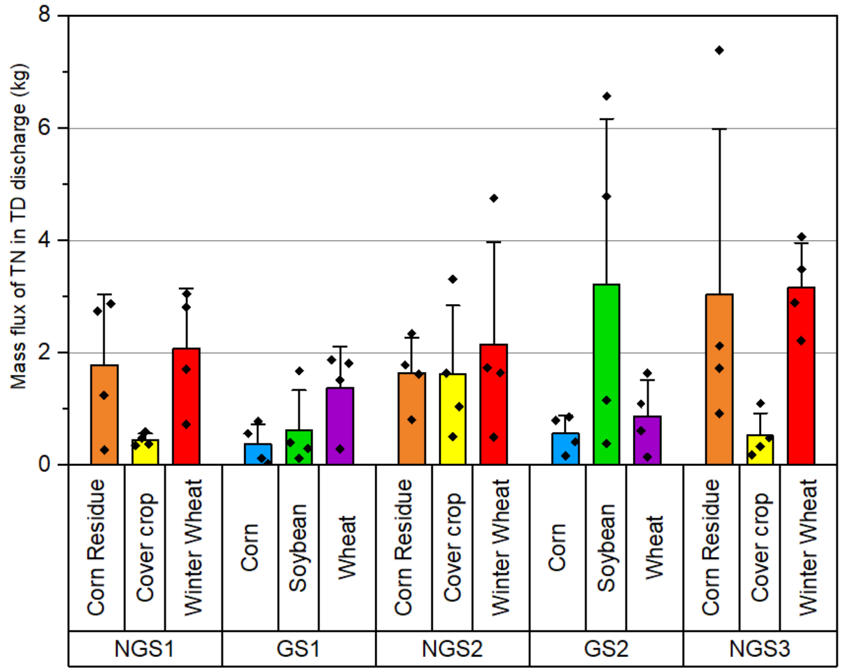

Figure 3-7: Mean mass flux of TN normalized by dividing the sum of TN (kg) by the number of events sampled in each season (η). Black diamonds represent mean field-specific TN mass flux.

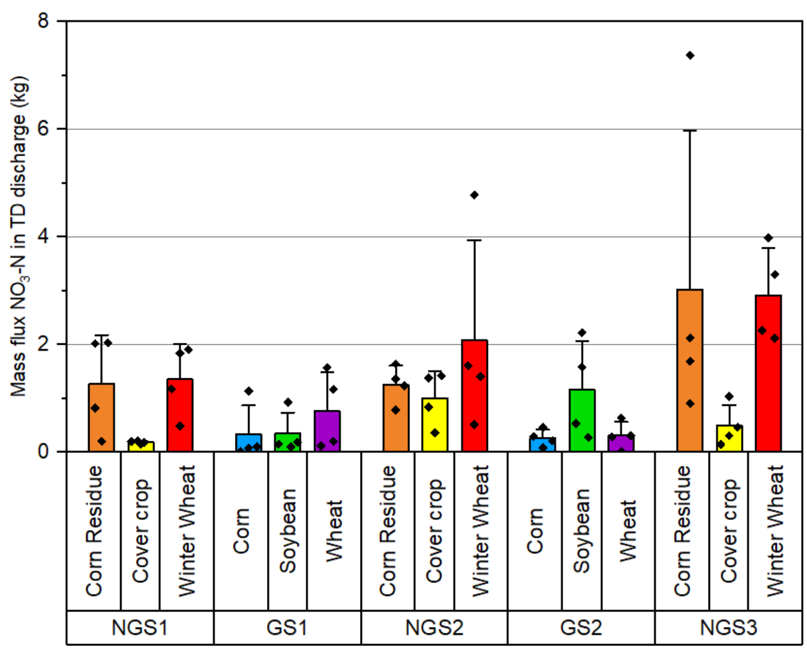

Figure 3-8: Mean mass flux of NO_3-N normalized by dividing the sum of NO_3-N (kg) by the number of events samples in each season (η). Black diamonds represent mean field-specific NO_3-N mass flux.

3.3.1.1 Crop rotational influence on volume-weighted N concentrations.

Using an LMM, the effects of year and crop on nutrient leaching were examined to determine whether interannual differences in climate or management are playing a role. Within the GS, the LMM indicated that both year (ρ = 0.0436) and crop (ρ = 0.0021) had an influence on TN concentrations, whereas only crop (ρ = 0.0010) had an influence on NO_3-N concentrations **(Table 3-3, 3-4**). A post-hoc test indicated that volume-weighted TN concentrations were significantly higher at the soybean and wheat fields in comparison to the corn fields respectively in both GS1 & 2 **(Table 3-4).** Furthermore, the post-hoc test indicated that volume weighted NO_3-N concentrations were significantly greater from the soybean and wheat fields in GS1 **(Table 3-4).** In comparison, King et al. (2016), found that in a study of three TDs in Ohio following a corn-soybean rotation, N concentrations were significantly greater from corn fields in comparison to soybean fields within the GS. Interestingly, the corn fields in King et al. (2016) received a split application of N fertilizer and were seeded into soybean residue which may have contributed to increased N leaching from those fields. Furthermore, precipitation conditions during the two GSs varied considerably, as GS1 received 380 mm of rain whereas GS2 was significantly wetter than normal with 540 mm of rain (**Table 3-1**). Due to greater rainfall in GS2, tiles flowed more frequently during early spring (May-June) allowing for a greater number of samples to be collected from all 12 TDs (i.e., η= 39 in GS1 vs. 88 in GS2). The greater number of samples collected in GS2 allows for possibly a more robust statistical comparison of N concentrations in TD eluent; however, the limited amount of TD discharge in both GS1 & 2 highlights the importance of the NGS as the primary period of nutrient mass loss (**Figure**

3-1). Despite differences in weather between GS1 & 2, the LMM indicated that there was no interaction between year and crop in the GS; however, this was not the case for the NGS, when there was a year vs crop interaction for both TN ($\rho = 0.0062$) and NO_3-N ($\rho = 0.0086$; **Table 3-3, 3-4).** The significant interaction indicates that the effect of crop cover on N leaching differs between years. A post hoc test indicated that volume-weighted TN concentrations were significantly greater at WW and CR fields in comparison to CC fields in NGS1 &3; however, there was no significant difference across the three crop rotations in NGS2 despite higher mean concentrations at the WW fields **(Table 3-4).** Furthermore, volume-weighted NO_3-N concentrations were significantly higher at the WW fields in comparison to the CC fields during NGS1, 2 & 3 **(Table 3-4).** While differences in volume-weighted N concentrations were less consistent between the WW and CR fields, WW fields had significantly ($p \leq 0.05$) higher NO_3-N concentrations compared with CR during NGS2 and higher TN during NGS3 **(Table 3-4).** As such, this study suggests that WW, despite being a BMP, is associated with elevated N leaching, and losses are comparable to those from CR. Whereas multi-species CC fields were found to contribute significantly ($p \leq 0.05$) lower volume-weighted N concentrations across both NGS1 and NGS3 (**Table 2.3-3** and **2.3-5**). Factors that may be contributing to differences in N leaching across crops will be explored in detail in *section 4.6* such as fertilizer application rates and timing, legacy soil nutrients, over-winter cover crop development, and physical soil conditions.

Table 3-3: The statistical significance (ρ-values) of study year and crop effect on N concentrations in TD discharge determined using a LMM where NS indicates not significant.

Season	Nutrient	Year Effect	Crop effect	Interaction (Year X Crop effect)
NGS	TN	NS	<0.0001	0.0062
	NO_3-N	0.0194	<0.0001	0.0086
GS	TN	0.0436	0.0021	NS
	NO_3-N	NS	0.0010	NS

Table 3-4: Mean seasonal volume-weighted TN and NO_3-N concentrations (mg L^{-1}) by crop cover where significant differences in volume-weighted nutrient concentrations amongst crop covers and season were determined using a LMM with a post hoc Tukey multiple comparison test. Values are reported as means +/- standard deviation. Within the GS, C indicates corn, S indicates soybean and W indicates wheat. In the NGS, CC indicates cover crop mixture, CR indicates corn residue and WW indicates winter wheat.

Season	Nutrient	CR	CC	WW	C	S	W
NGS1	TN	4.6 ± 1.5 $_a$	0.9 ± 0.1$_b$	5.0 ± 1.7 $_a$	N/A		
	NO_3-N	3.2 ± 1.1 $_a$	0.4 ± 0.1$_b$	3.4 ± 1.2 $_a$			
GS1	TN	N/A			1.2 ± 1.1 $_a$	5.5 ± 1.4$_b$	4.8 ± 1.6 $_b$
	NO_3-N				1.8 ± 3.1 $_a$	3.1 ± 0.5$_b$	2.7 ± 1.9$_b$
NGS2	TN	2.9 ± 1.2 $_a$	3.1 ± 0.9 $_a$	4.6 ± 0.8 $_a$	N/A		
	NO_3-N	2.2 ± 0.8 $_a$	2.3 ± 1.0$_a$	4.3 ± 0.9 $_b$			
GS2	TN	N/A			2.9 ± 1.3 $_a$	5.6 ± 1.3 $_b$	5.7 ± 1.6 $_b$
	NO_3-N				1.1 ± 0.1 $_a$	2.5 ± 0.7 $_a$	1.9 ± 1.4 $_a$
NGS3	TN	3.9 ± 0.8 $_a$	1.5 ± 0.6$_b$	5.6 ± 0.4 $_c$	N/A		
	NO_3-N	3.8 ± 0.8 $_a$	1.3 ±0.6 $_b$	5.1 ± 0.7 $_a$			

*Values with different subscript letters in the same row represent a significant difference (ρ ≤0.05).

3.3.2 Seasonal and volume weighted phosphorus concentrations in TD discharge

An important objective of this study was to contrast N and P losses in tile drainage, as the two nutrients are often considered separately (Dinnes et al., 2002; Gentry et al., 1998; Heathwaite & Dils, 2000; King et al., 2015). Although both nutrients are added in agricultural fertilizer, their behavior in soils and losses to tile leachate can be very different due to their different solubilities (Gramlich et al., 2018). Phosphorus is an essential macronutrient for agricultural production; however, the movement of P within soils to surface waters is a long-standing problem in agriculture-dominated watersheds (Blann et al., 2009; Gramlich et al., 2018; King et al., 2015; Sims et al., 1998). Within the current study, measured TP concentrations in tile drain discharge exceeded the Ontario freshwater quality objective of 30 $\mu g\ L^{-1}$ in 29 % (i.e., 97 of 333 samples) of the total samples collected over the 28-month study period, with most exceedances occurring in the NGS (i.e., 79 of the 97 samples; Canadian Council of Ministers of Environment, 2004). Occasional TDP measurements (η = 148) in tile outlet samples indicated that TP was primarily comprised of dissolved P which is common for TD eluent (**Appendix B; Table 6-2**). For example, King et al. (2016), found that 86% of TP within tile discharge water was dissolved.

Measured TP concentrations at the 12 sites indicated greater within site variability compared with among site variability, which was evident for the N compounds (i.e., TN, NO_3-N), as concentrations across the 28-month study period ranged from a low of 5 $\mu g\ L^{-1}$ to a high of 650 $\mu g\ L^{-1}$. Measured TP concentrations across the 12 TDs ranged from 5 to 220 $\mu g\ L^{-1}$ in NGS1, from 5 to 140 $\mu g\ L^{-1}$ in GS1, from 5 to 600 $\mu g\ L^{-1}$ in NGS2, 6 to 100 μg L^{-1} in GS2, and from 5 to 650 μg L^{-1} in NGS3 (**Figure 3-9**). The results from the current study were similar to values reported by Van Esbroeck et al. (2016), who found that TP concentrations in tile drain effluent typically ranged from 10 to 350 μg L^{-1}; however, during periods of high discharge (e.g., storm discharge, spring melt) TP concentrations could be as great as 2170 μg L^{-1}. Furthermore, volume-weighted TP concentrations across all 12 tile outlets ranged from 14 to 68 μg L^{-1} in NGS1, from 13 to 36 μg L^{-1} in GS, from 118 to 160 μg L^{-1} in NGS2, from 15 to 63 μg L^{-1} in GS2 and from 16 to 62 μg L^{-1}in NGS3 (**Figure 3-10).** The volume-weighted TP concentrations measured in this study are slightly less than those found by Algoazany et al. (2007), who reported volume-weighted TP concentrations ranging from 86 to 194 μg L^{-1} in four tile drains under a corn-soybean rotation across a six-year period in Illinois which were sampled automatically based on flow volumes. The increased frequency of sample collection and storm-targeted approach of Algoazany et al. (2007), likely explains the greater variability in P concentrations in comparison with the weekly to biweekly sample frequency of the current study. Nevertheless, the volume weighted concentrations from both the current study and Algoazany et al. (2007) are comparable.

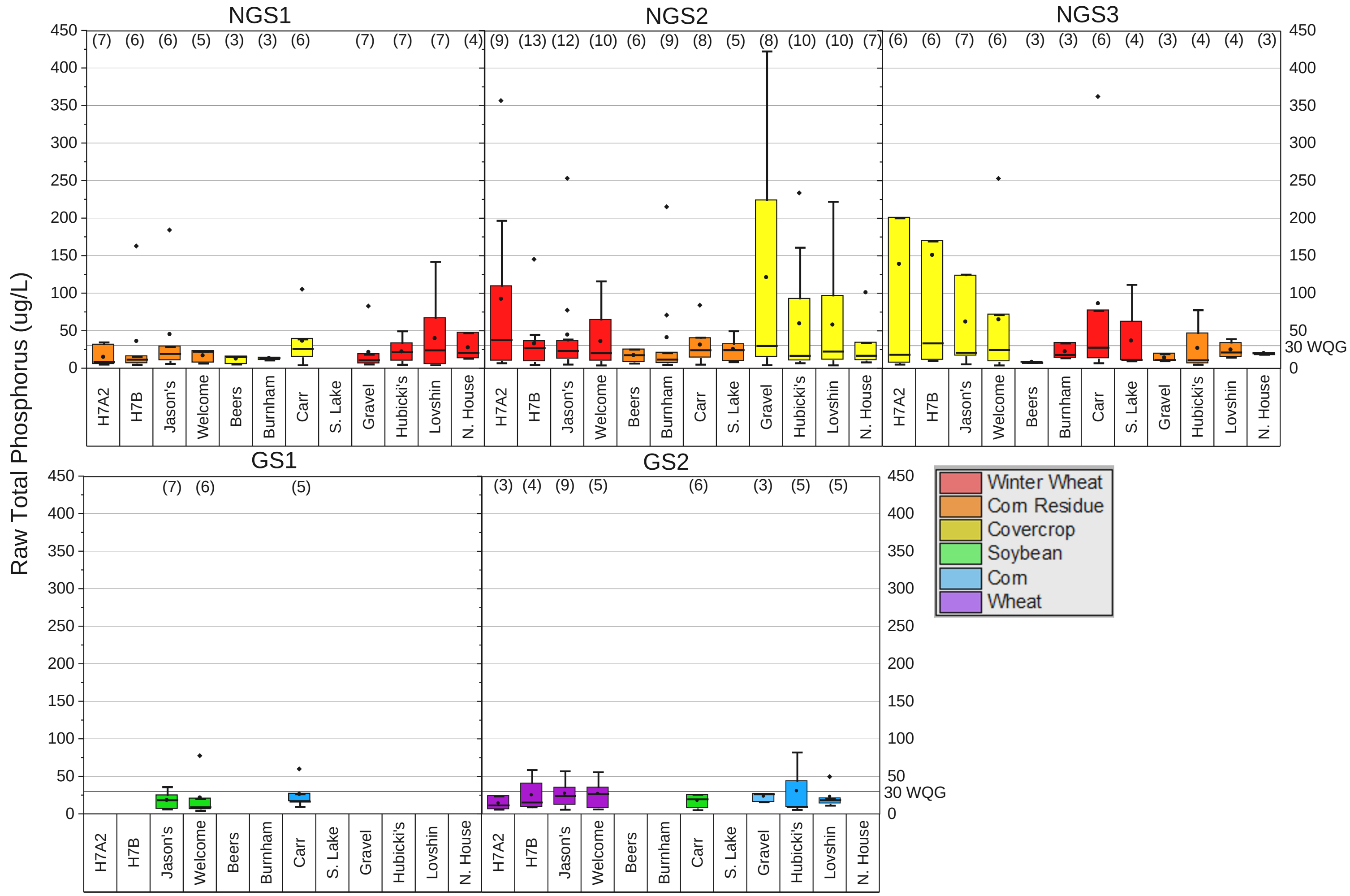

Figure 3-9: Box plots of measured TP by season and crop rotation where numbers in paratheses indicate sample number. Only fields with a sample size (η) ≥ 3 are plotted. The WQG is 30 μg L^{-1}.

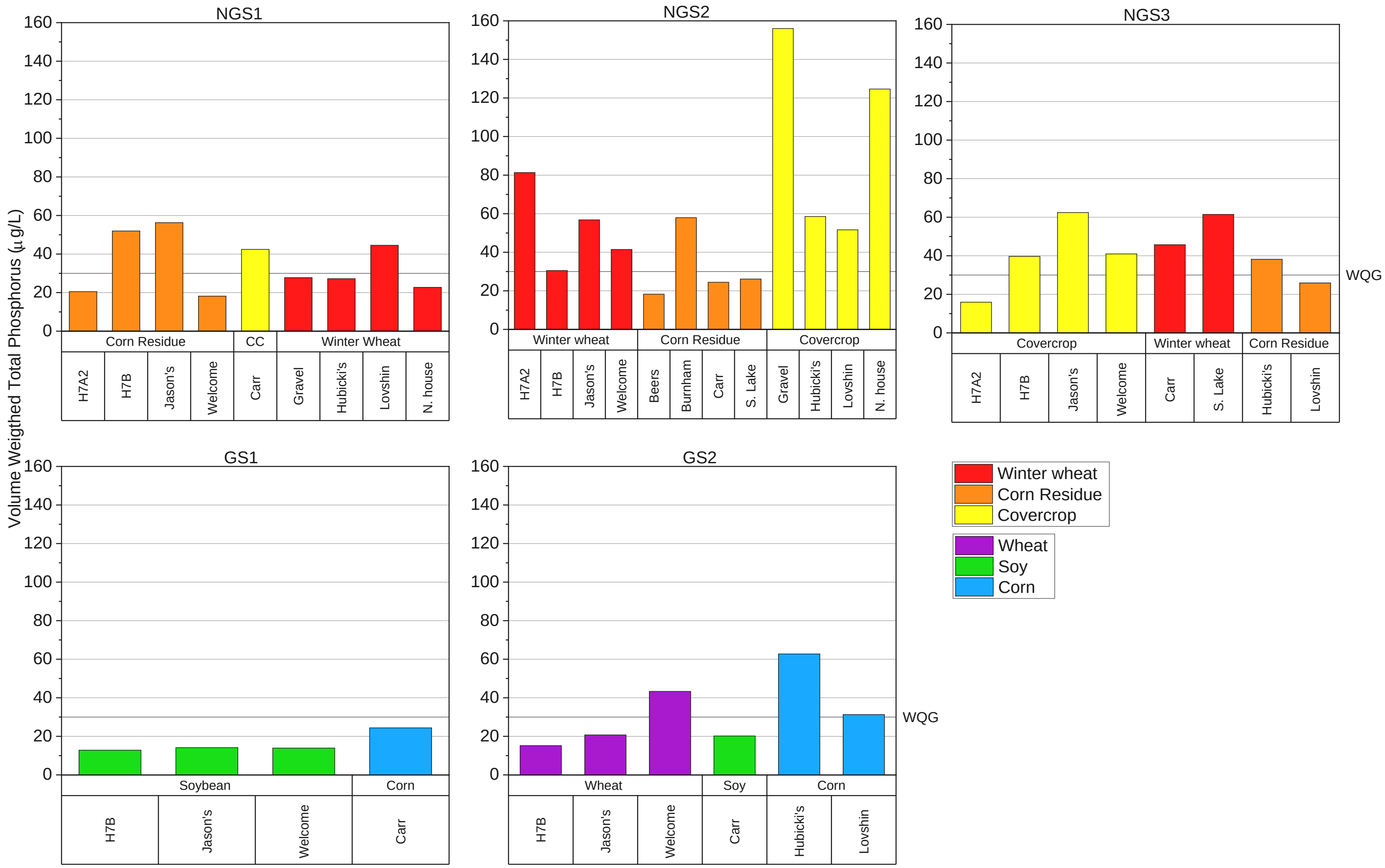

Figure 3-10: Seasonal volume-weighted TP concentrations based on crop rotation where only fields with a sample size (i.e., # of samples collected within a season) greater than 3 per season are plotted. The WQG is 30 µg L $^{-1}$.

Seasonal observations indicated that TP concentrations were generally higher in the NGS than the GS and were especially high during precipitation events, snow melt, and rain-on-snow. Along with increased frequency of event flow conditions, overall, the NGS experienced more than eight times greater volume of TD discharge in comparison with the GS. Therefore, P export was greatest in the NGS due to high P concentrations during event flow and the greater volume of discharge **(Figure 3-11**). The large difference in mass flux of P between the NGSs and the GSs demonstrates the clear seasonal difference in P losses **(Figure 3-11**). For instance, on March 6, 2022, a snow melt event occurred after average air temperatures rose 8^{o}C after a prolonged period of subzero air temperatures (**Figure 3-1**). The snowpack on the fields (up to 30 cm) was almost entirely melted due to the warm air temperatures, and TD discharge at the Mystery TD increased from 3.7 L/sec at 5:45 am to 82 L/sec at 11:30 am, which is the maximum rate of discharge that can occur from the Mystery TD due to the diameter of the pipe **(Figure 3-1, see Appendix A; Figure 6-6).** Measured TP concentrations during the snow melt event were at least 4-times higher than the water quality objective, ranging from 130 to 600 μg L^{-1} and contributing to the export of up to 770 g P from a single TD in just one day. Although tile flow was much lower in the GS, events that were captured during the GS exhibited a similar pattern of rapidly rising TP. For example, a 22 mm rain event on September 22, 2021, led to a modest increase in discharge at Mystery TD (0.22 L sec^{-1} at 6:30 am to 0.33 L sec^{-1} at 5:15 pm), whereas TP concentrations ranged from 37 to 130 μg L^{-1} and this single event was associated with up to 1.9 g TP export from individual TDs **(Figure 3-1).** Similar to N, the majority of TP export occurred during the NGS due to the significantly greater volume of TD discharge in the dormant season (**Figure 3-1; Appendix B; Figure 3-11**). This finding is common among literature as a review by King et al. (2015), reported that most P losses occur during periods of elevated flow within the NGS. For instance, Van Esbroeck et al. (2016), reported that 67- 98% of annual TP losses occurred within the NGS at three working farm fields with a corn-soy-winter wheat rotation in Ontario. The large difference in mass export of P between the March 6 NGS event and the Sept 22 GS event demonstrates the clear seasonal difference in event flow P leaching and highlights the importance of monitoring NGS events when considering the impact of TD on nutrient losses in agricultural watersheds.

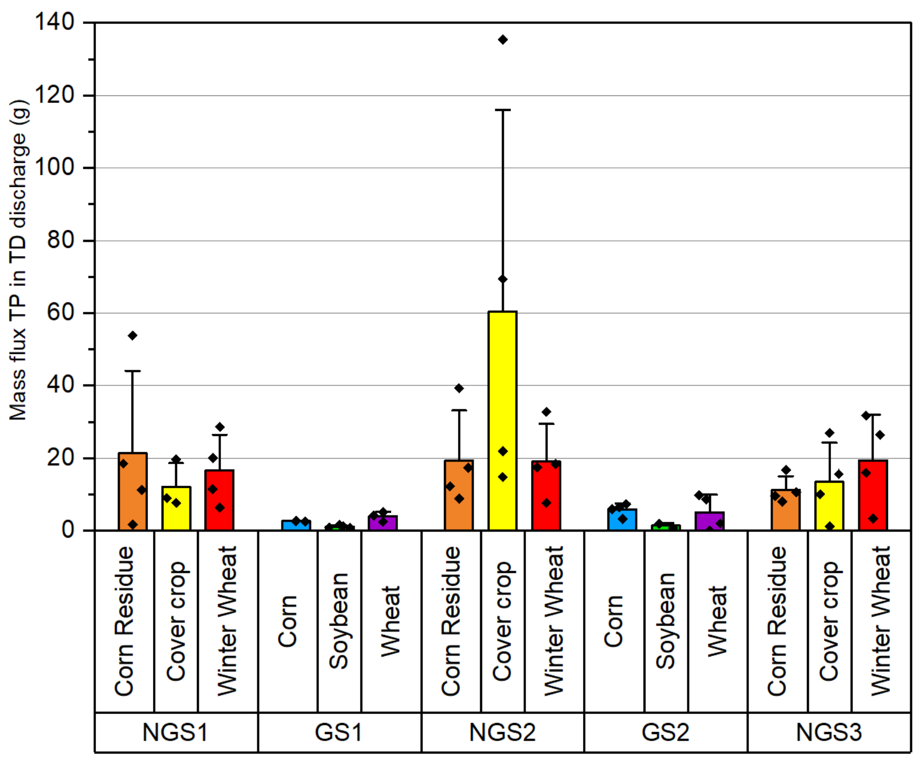

Figure 3-11: Mean mass flux of TP normalized by dividing the sum of TP (mg) of individual sample events (η) during each season. Black diamonds represent mean field-specific TP mass flux.

3.3.2.1 Crop rotational influence on volume weighted P concentrations.

A LMM was used to evaluate the effects of year and crop cover on concentrations of P in tile eluent. Volume weighted TP concentrations in the GS indicated greater within site variability, like due to the influence event flow on P losses, yet no significant crop or yearly effect (**Table 3-5, 3-6)**. Overall, as there is very little tile discharge in the GS, it is difficult to evaluate the influence of crop cover on P leaching losses to tiles. Nevertheless, despite greater TD discharge within the NGS, the LMM indicated no significant effect of crop cover on TP losses, however, the LMM did indicate a year effect (ρ=0.0415). The yearly effect indicates that seasonal TP concentrations differed by year likely due to the higher TP concentrations at the CC fields in NGS2 in comparison with other crops/ cover in other NGSs (**Table 3-5).** To further examine the significant yearly effect a post hoc test was completed which indicated that volume weighted TP concentrations within the GS and NGS were not significantly different between crops/covers. This suggests that P concentrations in tile discharge were not sensitive to overwinter crop cover. Although not statistically significant (ρ=0.8), the multi-species cover crop fields were associated with the highest concentrations of TP (both measured and volume-weighted), especially in NGS2 **(Table 3-6, Figure 3-9, 3-10)**. Within the NGS2, repeated freeze-thaw conditions can amplify the potential for P losses from CC as during freezing ice crystals can disrupt the plant cells leading to the release of P (Freppaz et al., 2007; Lozier et al., 2017; Riddle & Bergstrom, 2013). The breakdown of plant cells and the release of P is an important process for all winter cover/ residues; however, CC species including brassicas with high biomass (i.e., turnip, radish) have been found to contribute to higher TP leaching in comparison with crop residues or grasses (Liu et al., 2019). Overall, previous literature is unclear on the influence of winter cover on P leaching as Aronsson et al. (2016), found that the effect of cover crops on P leaching in tile drains ranged from a relative increase of 86% to a relative decrease of 43% in comparison with fields without winter cover crops in Scandinavia and Finland.

Table 3-5: The statistical significance (ρ-values) of study year and crop effect on P concentrations in TD discharge determined using a LMM where NS indicates not significant.

Season	Year Effect	Crop effect	Year X Crop effect	Post-Hoc Tukey multiple comparison
NGS	0.0415	NS	NS	NS
GS	NS	NS	NS	NS

Table 3-6: Mean seasonal flow-weighted TP concentrations (µg L^{-1}) based on crop cover at the study tile drain outlets. Values are reported as means +/- standard deviation. Within the GS, C indicates corn, S indicates soybean and W indicates wheat. In the NGS CC indicates cover crop, CR indicates corn residue and WW indicates winter wheat.

Season	CR	CC	WW	C	S	W
NGS1	37 ± 20	24 ± 16	38 ± 19	N/A		
GS1	N/A			23 ± 10	13 ± 6	36 ± 13
NGS2	32 ± 18	92 ± 46	53 ± 22	N/A		
GS2	N/A			36 ± 18	30 ± 8	31 ± 15
NGS3	24 ± 9	40 ± 19	35 ± 23	N/A		

3.4 Soil nutrient conditions

3.4.1 Total and labile soil nutrient conditions

Total and labile nutrient concentrations were measured spring and fall to test the hypothesis that total nutrient concentrations (N, C, and P) would be relatively stable through the crop rotation whereas labile/ bioavailable nutrient concentrations (water-extractable; Olsen-P) would be more sensitive to crop cover/residue. As predicted, total C and N concentrations in soil (determined by combustion) ranged from 12 to 58 mg g^{-1} and 1.1 to 5.0 mg g^{-1}, respectively and were not significantly different across fields (**Table 3-7)**. Likewise, the C: N ratio at the 12 fields ranged from 10 to 14 across the four sample periods (**Table 3-7)**. The C:N ratios measured in this study were consistently below the threshold for mineralization (25:1) indicating adequate N availability for SOM mineralization (**Table 4-7;** OMAFRA, Moran, et al., 2017). These findings are similar to those reported by Amorim et al. (2022), which found C:N ratios in bulk soils can be very stable even after land use changes. Furthermore, SOM (determined by LOI) was consistent across all fields over the study period ranging from 4.0 to 14% and there was no significant ($p \leq 0.05$) difference in LOI based on season or crop cover (**Table 3-7).** These findings are consistent with various studies that found that C: N ratios and SOM can take years to respond to changes in management practices (Saljnikov et al., 2013; Verberne et al., 1990; Zhou et al., 2012). Overall, SOM, C, N, and C: N ratio data indicate that total nutrients within the study fields were stable throughout the study period confirming the hypothesis that total nutrients were not impacted by crop rotation or season. As such, the total nutrient composition of soils is not a good predictor of nutrient losses to TD discharge.

Table 3-7: Total carbon, nitrogen, and carbon-to-nitrogen ratios (via combustion) of composite soil samples and SOM % (via LOI) from all fields based on sample collection period.

Field	**Spring 2021**				**Fall 2021**				**Spring 2022**				**Fall 2022**			
	C	**N**	**C: N**	**SOM**	**C**	**N**	**C: N**	**SOM**	**C**	**N**	**C: N**	**SOM**	**C**	**N**	**C: N**	**SOM**
Units	*mg/g*	*mg/g*		*%*	*mg/g*	*mg/g*		*%*	*mg/g*	*mg/g*		*%*	*mg/g*	*mg/g*		*%*
Jason's	20	1.8	11	6.3	18	1.7	11	5.0	18	1.6	11	5.3	21	1.8	11	N/A
H7A2	27	2.4	12	5.6	30	2.4	12	8.8	20	1.6	12	4.3	26	2.2	12	N/A
H7B	28	2.4	12	6.3	23	2.1	11	8.1	21	1.8	12	5.3	22	2.0	11	N/A
Welcome	22	1.8	12	6.9	19	1.9	10	6.7	19	1.8	11	5.3	20	2.1	10	N/A
N. House	23	2.0	12	5.8	16	1.5	11	4.5	19	1.6	12	5.3	18	1.5	12	N/A
Hubicki's	18	1.5	12	5.0	16	1.5	11	6.6	38	1.1	15	4.0	19	1.8	11	N/A
Lovshin	34	2.5	14	6.2	15	1.5	10	5.1	17	1.7	11	3.9	23	2.2	11	N/A
Gravel	15	1.5	11	5.0	12	1.2	10	5.0	13	1.1	13	4.8	13	1.3	10	N/A
Carr's	39	3.1	12	9.9	51	4.1	12	14	58	5.0	12	13	38	3.2	12	N/A
S. Lakes	24	1.9	12	6.9	29	2.2	13	6.7	27	2.0	14	7.6	36	2.9	12	N/A
Beers	43	3.2	14	11	37	3.0	12	10	37	2.9	13	7.7	37	2.7	13	N/A
Burnham	22	1.7	13	5.6	21	2.0	11	6.8	21	1.9	11	5.7	16	1.5	10	N/A

It was hypothesized that the water-extractable fraction of soil nutrients would be sensitive to crop cover/ residue and may help to explain why some crops experienced greater nutrient leaching in TD discharge than others (i.e., higher TN and NO_3-N concentrations in TD discharge from the WW fields in comparison with CC fields). However, there was no clear association between labile N or C concentrations relative to the crop or crop cover present at the time of sampling despite some crops being N-fixing legumes (i.e., soybean and cover crops; **Table 3-8).** For instance, soybeans can fix on average 80 kg N ha^{-1} throughout the GS, and corn can deplete over 130 kg N ha^{-1} throughout the GS (Banks, 2019; Ding et al., 1997; Ravuri & Hume, 1992). As a result, labile TN and NO_3-N were expected to be significantly greater in soybean fields relative to corn, especially in the fall (Banks, 2019; Ding et al., 1997; Ravuri & Hume, 1992). However, the results from the current study indicated that labile concentrations of TN and NO_3-N in the A horizon of the agricultural fields were not significantly different amongst crops in either spring or fall (**Table 3-8**). Similarly, labile C concentrations were not significantly different amongst crop covers with averages ranging from 3.0 to 7.3% (of total C) across the four sample periods (**Table 3-8)**. The findings from the current study align with those reported by Zhou et al. (2012), which found that there were no significant differences in soil labile organic N and C pools between legume crops and non-legume crops in a study out of southeastern Australia.

Table 3-8: Mean labile soil nutrient concentrations across the four sample periods based on crop cover/ residue from the season before sample collection (i.e., NGS or GS). Where C indicates corn, S indicates soybean, and W indicates wheat in the GS and CC indicates cover crop, CR indicates corn residue, WW indicates winter wheat in the NGS.

Crop	**Spring 2021**			**Fall 2021**			**Spring 2022**			**Fall 2022**		
	Labile TN (%)	Labile NO_3-N (%)	Labile TC (%)	Labile TN (%)	Labile NO_3-N (%)	Labile TC (%)	Labile TN (%)	Labile NO_3-N (%)	Labile TC (%)	Labile TN (%)	Labile NO_3-N (%)	Labile TC (%)
C	N/A			3.0	0.1	3.0	N/A			3.5	0.3	7.3
S				3.2	0.3	3.4				0.4	0.1	3.5
W				3.0	0.2	3.3				1.6	0.4	4.6
CC	2.5	0.2	3.8	N/A			3.4	0.2	3.6	N/A		
CR	2.9	0.3	4.7				1.2	0.1	3.0			
WW	3.4	1.2	4.1				2.7	0.2	3.3			

In addition to assessing the proportion of soil N that was labile, this study also compared water-extractable concentrations against crop needs and fertilizer recommendations. Across the four sample periods, water extractable TN and NO_3-N concentrations ranged from 5 to 140 and 0.7 to 39 μg g^{-1}, respectively (**Figure 3-12).** Although not statistically significant, the soil samples collected in the Spring of 2022 had lower mean soil TN and NO_3-N concentrations in comparison with the other sample periods (**Figure 3-12).** The lower soil N concentrations in the Spring of 2022 may reflect the elevated N leaching via TDs over the prior season (i.e., NGS2; **Figure 3-4, 3-5, 3-6).** Within the Spring 2021 and 2022 sample periods, soil N concentrations were marginally higher in the WW fields in comparison with the CC or CR fields, which aligns with observations in TD eluent **(Figure 3-4, 3-5).** Furthermore, OMAFRA's recommendation for fertilizer application is based on spring soil NO_3-N concentrations, specifically, it recommends applying N-based fertilizer to fields with a spring soil NO_3-N concentration of 17 μg g^{-1} or less (OMAFRA, 2022a; OMAFRA et al., 2017; **Appendix E; Table 6-7**). Within the current study, mean soil NO_3-N concentrations were mostly below 10 μg g^{-1}, except for the WW fields in the spring 2021 sample period when mean soil NO_3-N concentrations were 22 μg g^{-1}. Higher spring soil NO_3-N concentrations at the WW fields may be due to the previous legume crop (i.e., soybean), the application of N-based fertilizer the prior fall, or various other soil properties (i.e., high SOM, microbial activity/ C:N ratios; OMAFRA, 2022a; OMAFRA et al., 2017).

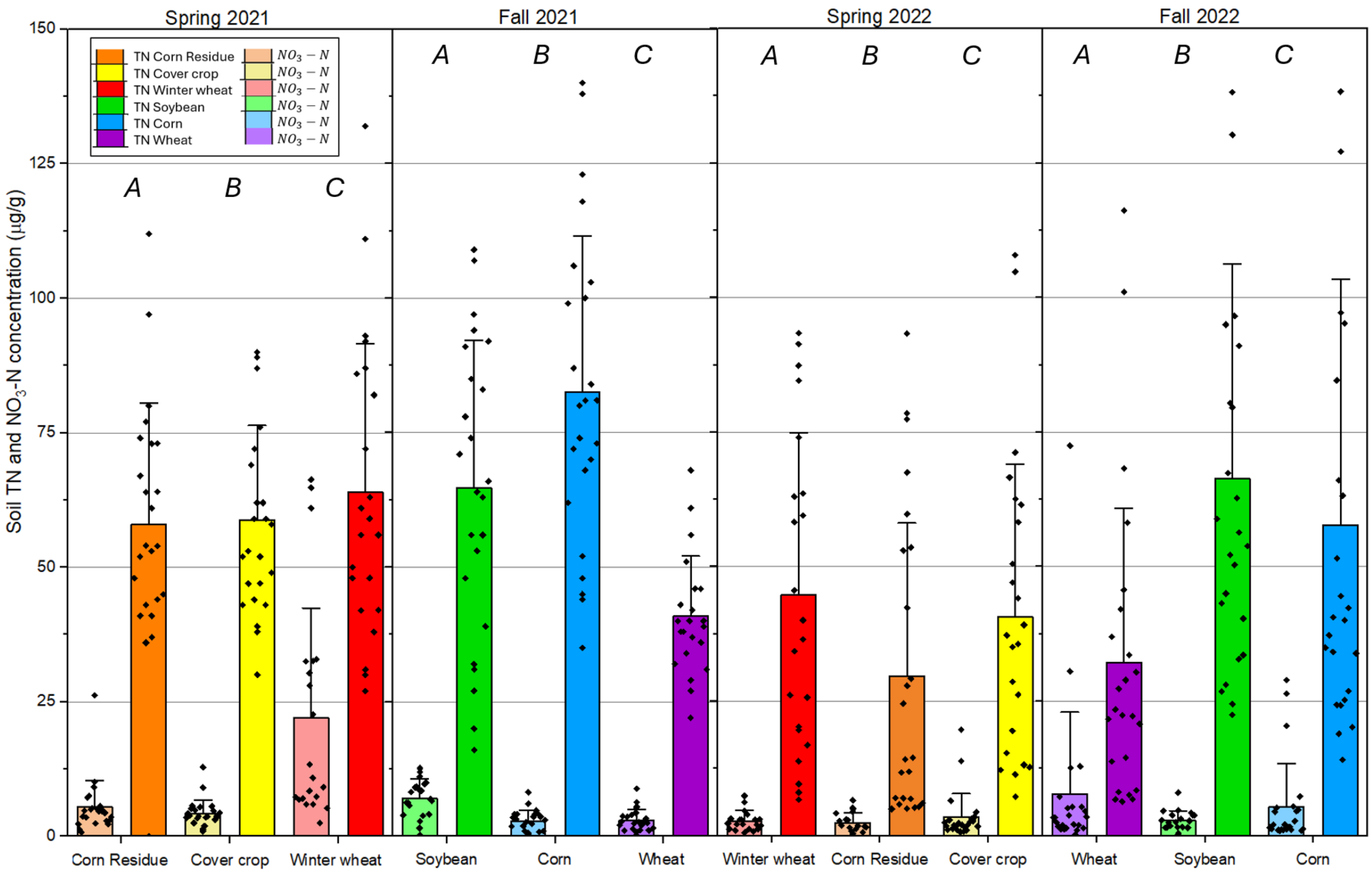

Figure 3-12: Mean water-extractable soil TN and NO_3-N concentrations (µg g^{-1}) across the four sample periods based on crop cover/ residue of the fields at the time of sampling. Bars indicate standard deviation, and the dots represent the spread of data. Italicized letters (i.e., A, B and C) indicate the crop rotation groups throughout the four sample periods.

Similar to water-extractable N and C, average soil HPO_4 concentrations (Olsen P) were relatively similar across the four sample periods (range: 12-26 μg g^{-1}; **Figure 3-13**). However, there were some differences between the 2021 and 2022 seasons. Most notably, the CC fields in the Spring of 2021 had a mean HPO_4 concentration of 12 μg g^{-1} which was approximately half of the value measured in the spring of 2022 (mean 26 μg g^{-1}; **Figure 3-13).** Furthermore, Olsen P levels at the CC fields in Spring 2022 were higher than levels in the same fields in the previous season (i.e. wheat in the Fall 2021: 17 μg g^{-1}), although differences were not statistically significant. Higher HPO_4 concentrations in the CC fields in Spring 2022 may reflect the more frequent freeze-thaw conditions experienced throughout NGS2 paired with the observation of greater establishment of tuber cover species (i.e., radish and turnip). For instance, the breakdown of CC species due to repeated freeze-thaw events can allow for the rapid decomposition of plant organic matter leading to increased nutrient leaching, especially through the root channels left behind from decaying tubers (Lozier et al., 2017; Lozier & Macrae, 2017; Riddle & Bergstrom, 2013). Overall, Olsen P concentrations across the study fields are low compared with OMAFRA recommendations for corn-soy-wheat fields, which recommends the application of P-based fertilizer to fields when soil levels fall below 30 μg g^{-1} (**Appendix E; Table 6-8;** OMAFRA, 2020, 2022a). However, it's important to note that the OMAFRA recommendations have not been updated since the 1970s, and more recent research by Janovicek et al. (2015), which assessed 368 Ontario crop response trials to P and/or K fertilizer application, suggests that optimum soil P levels are 12-18 μg g^{-1} as the economic yield responses for corn, soybeans, wheat and alfalfa were typically small above an Olsen

P level of 12 μg g^{-1}. The soil P levels suggested by Janovicek et al. (2015), align with the results from the 12 agricultural fields within this study (**Figure 3-13).**

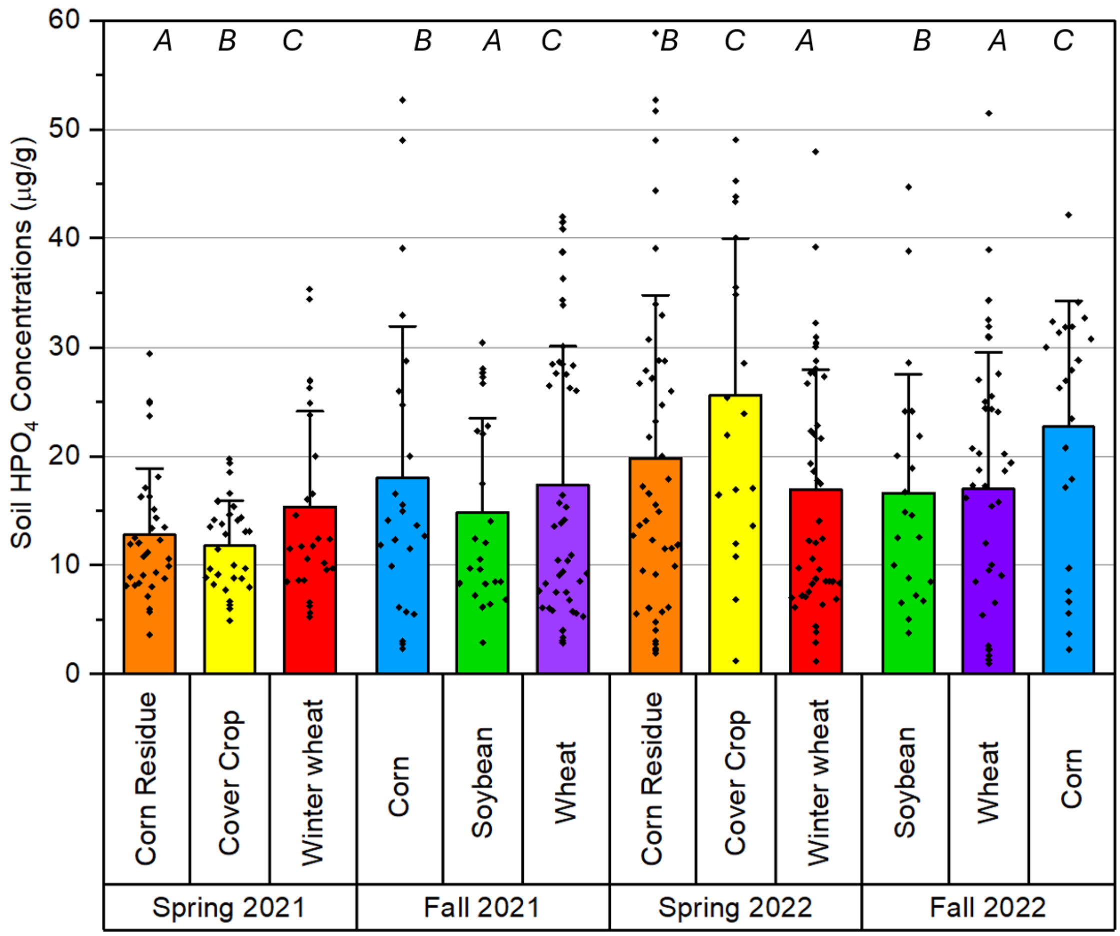

Figure 3-13: Mean soil HPO_4 (Olsen) concentrations (μg g^{-1}) across the four soil sample periods based on crop cover/ residue of the fields at the time of sampling where the mean is indicated by the top of the bar, the error bars represent the mean + 1 standard deviation and the dots represent the spread of data. Italicized letters (i.e., A, B and C) indicate the crop rotation group.

To further evaluate labile nutrient conditions in the NGS vs GS and across crop covers, PRS probes were installed through two incubation periods: Winter 2021 (27 November 2021 to 5 April 2022, 130 days), and Summer 2022 (21 June 2022 to 9 August 2022, 50 days), which partially aligned with NGS2 and GS2. The Winter 2021 incubation period experienced several soil freezing events (**Figure 3-3**) which may have limited the movement of soil nutrients to the PRS probes as soil moisture is needed to transport nutrients across the exchange resin (Western AG, 2023). Furthermore, the Summer 2022 incubation, which partially aligned with GS2, was relatively wet in comparison to long-term climate normals.

Nitrate, being a soluble anion, can easily move in soil solution and adsorb to the cationic PRS probe membrane. The PRS probes captured significantly less NO_3-N during the Winter 2021 incubation compared with the Summer 2022 incubation (**Figure 3-14).** The significantly lower NO_3-N concentrations in the winter incubation suggest that nitrogen cycling is slower within the winter incubation when soil temperatures are cooler and microbial activity is decreased. Although differences in NO_3-N fluxes within the Winter incubation were not significantly different amongst the three crop covers, NO_3-N fluxes in the WW and CR fields were as much as 2-times higher than in the CC fields. This finding is consistent with the TD water chemistry which indicated that N losses were greatest from WW and CR fields in comparison to CC fields **(Figure 3-4, 3-5, 3-6, Table 3-4).** Interestingly, within the Summer 2022 incubation, there was a significant difference in labile NO_3-N among the three crops. Corn had the greatest average flux of NO_3-N with 110 g $ha^{-1}day^{-1}$, whereas the average soybean flux was 67 g $ha^{-1}day^{-1}$, and wheat was 31 g $ha^{-1}day^{-1}$ **(Figure 3-14)**. This finding is contrary to TD water chemistry, which indicated that N concentrations from corn fields were significantly lower in comparison to wheat and soybean fields **Table 3-4).** The variation in nitrate fluxes under the different crops suggests that crops or the management practices applied to various crop covers can play an integral role in NO_3-N availability. Due to limited TD discharge within the GS, PRS probes may be an especially useful tool to evaluate N availability in soils during the growing season.

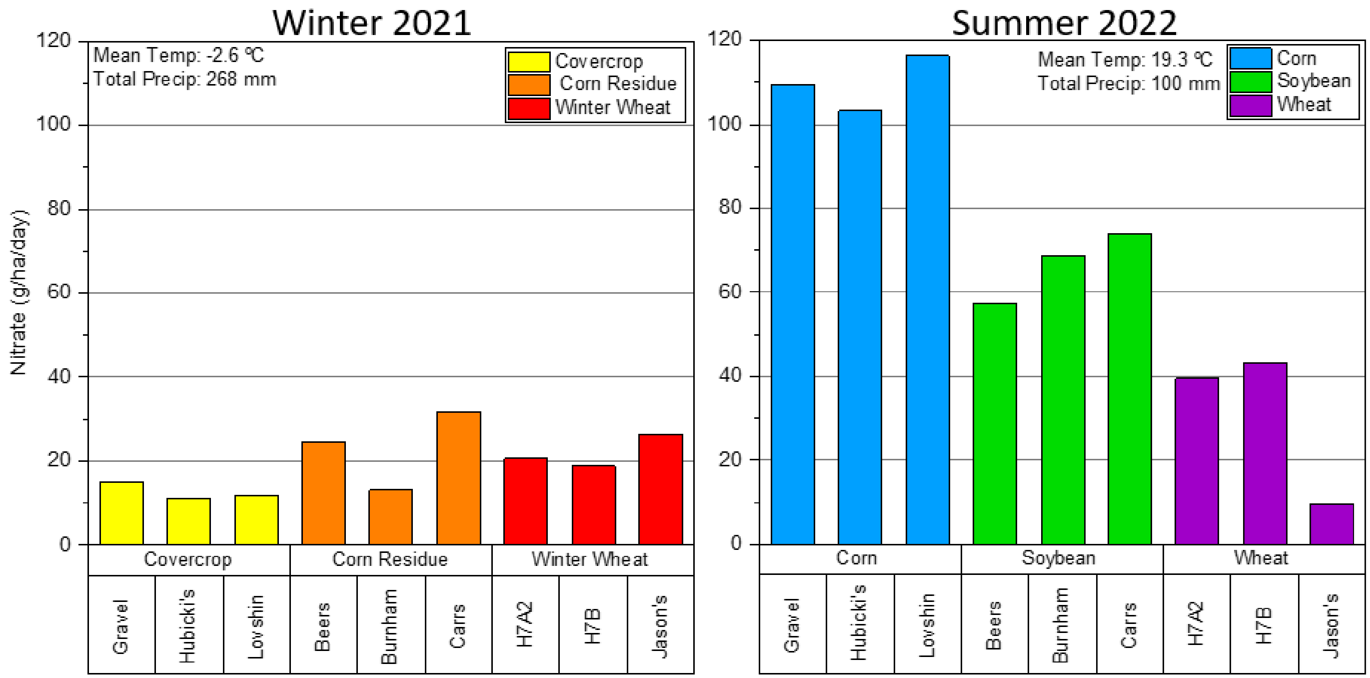

Figure 3-14: Daily PRS probe NO_3-N fluxes at a 15 cm depth over the two incubation periods; Winter 2021 (27 November 2021 to 5 April 2022, 130 days), and Summer 2022 (21 June 2022 to 9 August 2022, 50 days).

In general, due to the tendency of P to bind with soil particles and form mineral complexes, it can be difficult to accurately quantify available P levels within soils. Unlike NO_3-N, which is highly soluble, diffusion regulates the movement of P through the soil matrix from areas of high concentrations to low. Other studies have shown how conventional chemical extraction methods to measure bioavailable P are often inadequate, especially for in-situ P dynamics (e.g., Cooperband & Logan, 1994). The passive ion sink of PRS probes is analogous to biological uptake which could offer a better understanding of P availability than conventional soil P tests (Cheesman et al., 2010). The PRS probe results indicated that labile P fluxes were not significantly different across seasons (i.e., Winter 2021 vs. Summer 2022) or amongst crops/ crop residues (**Figure 3-15).** Despite no significant difference in PRS probe P fluxes within the Winter incubation, the CC fields had relativity high P fluxes in comparison to the CR fields, which aligns with observations of TD water chemistry. Overall, the PRS probe P results indicated very low fluxes of P which is likely due to its tendency to bind strongly with soil particles and exhibit low mobility in soil solution. This finding only further confirmed the complicated nature of assessing soil P levels.

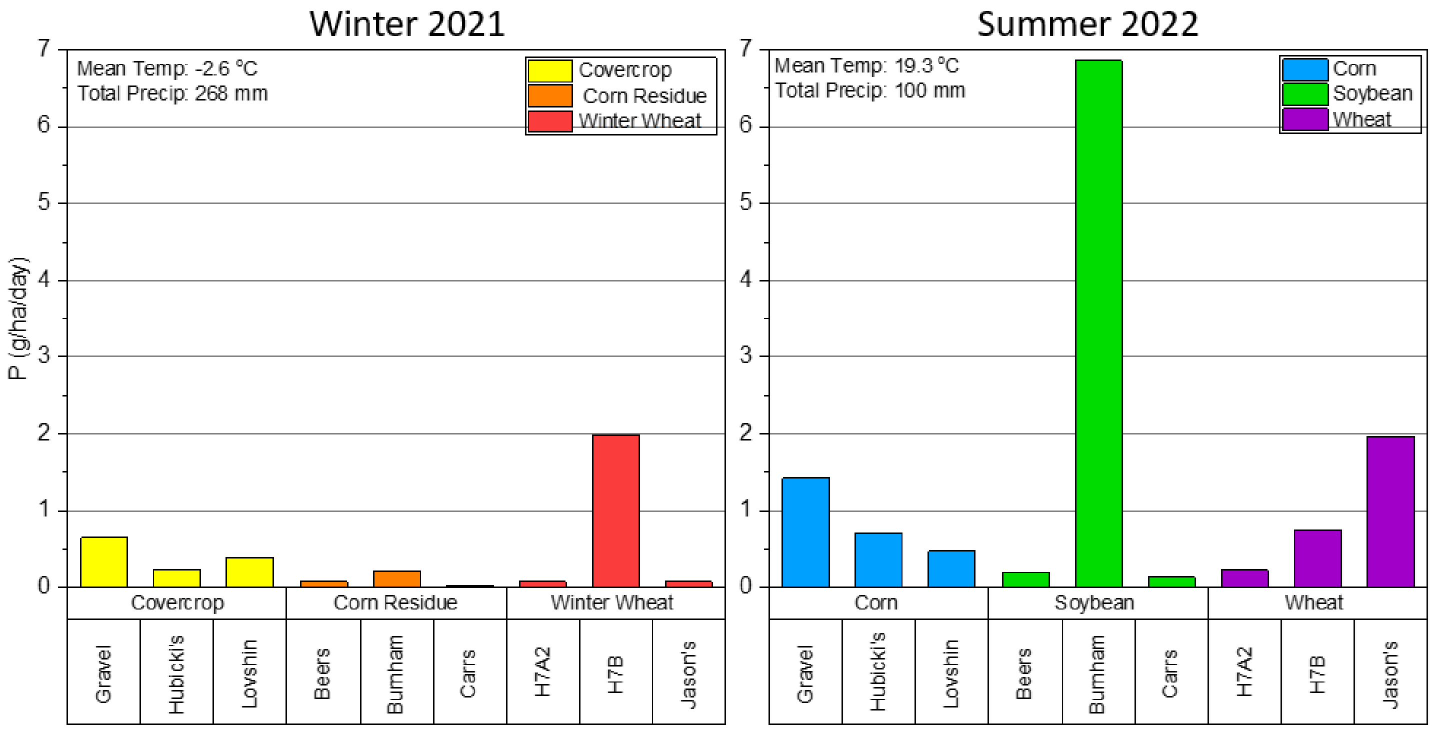

Figure 3-15: Daily PRS probe P fluxes at a 15 cm depth for two incubation periods.

3.4.2 Soil stratification

Nitrogen concentrations (in the soil solid phase) were almost always greater in surface soils (1.5 to 3.9 mg g^{-1}) compared with deeper soils (0.9 to 3.7 mg g^{-1}), although differences were not statistically significant when evaluated via a paired t-test (**Table 3-9).** Likewise, water-extractable TN concentrations in surface soil (50 to 81 mg kg^{-1}) were consistently greater than in deeper soil (26 to 56 mg kg^{-1}), although differences were not statistically significant (**Table 3-9).** In contrast, water extractable NO_3-N concentrations were not significantly different between surface (1.3 to 20 mg kg^{-1}) and deeper soil (2.6 to 14 mg kg^{-1}) and some fields had greater NO_3-N concentrations at the deeper depth (i.e., Burnham, H7B, Lovshin, Carr's, S. Lakes, Beers; **Table 3-9).** Generally small and insignificant differences in NO_3-N concentrations between shallow and deep soil samples are likely due to the relative mobility of the NO_3^- anion. Anions are generally poorly retained in soils due to the predominantly negatively charged surfaces of soil colloids, and consequently, NO_3-N is readily mobilized in soil solution rather than binding to soil particles (Krzic et al., 2021). As NO_3-N readily dissolves in soil solution it can move vertically through the soil matrix relatively quickly allowing N in surface-applied fertilizer or NO_3-N released via organic matter mineralization to migrate to lower soil layers (and ultimately tiles) thus resulting in less stratification (Gramlich et al., 2018).

In contrast to N, total C concentrations (in soil solid phase) were consistently greater in surface samples (1.7 to 5.0 %) than in deep (1.0 to 3.0 %), and likewise, mean concentrations of water-extractable TC were significantly ($p<0.05$) greater in shallow samples (0.76 to 1.7 mg g^{-1}) compared with deep (0.49 to 1.0 mg g^{-1}; **Table 3-9)**. The stratification of C within the Ah horizon may be due to surface-applied fertilizer or the release of C via organic matter mineralization of crop residues at the soil surface (Robertson & Paul, 2000). Similar findings were reported by Yang and Kay (2001) who found that organic carbon concentrations were significantly greater in surface soils (0-10 cm) than in deeper soils (10-20) in fields under reduced tillage across a range of crop rotations including continuous corn and corn-soy-wheat in Guelph, Ontario.

Lastly, except Beers, all fields had higher extractable P concentrations (Olsen P) in surface soils (12 to 30 μg g^{-1}) in comparison to deeper soils (8.1 to 22 μg g^{-1}) and differences were statistically significant ($p < 0.05$) at nine of the 12 fields (**Table 3-9**). Similar findings were reported by Crozier et al. (1999), who found that concentrations of P were significantly greater in surface soils (0 - 10 cm) than in underlying soils (10 - 20 cm) in North Carolina under no-till conditions. The stratification of soil P is likely due to P's ability to bind to soil particles and in turn, the movement of P through the soil matrix is slow, especially in comparison to N (Gramlich et al., 2018; Lvet al., 2023). Although orthophosphate (HPO_4^{2-}) is an anion, it can bind tightly to soil minerals that generate a high anion exchange capacity such as iron (Fe^{2+}), aluminum (Al^{2+}), and calcium (Ca^{2+}) which limits its release to soil solution (Pierzynski et al., 2015). Consequently, P stratification is common in no-till agriculture and can result in the surface soil layer becoming enriched with P. The stratification of nutrients such as C and P within the Ah layer may have implications for TD water chemistry. For instance, within the western Lake Erie basin, the stratification of P is prevalent due to the widespread adoption of no-till practices, and this has been identified as a potential contributor to the resurgence of HABs in Lake Erie (Smith, 2015; Smith et al., 2015, 2017).

Table 3-9: Mean soil nutrient concentrations all study fields ordered from north to south, where S (shallow) indicates soils collected from 0-5cm depth and D (deep) indicates soils collected from 15-20cm depth. Statistical significance: *(p<0.05), **(p<0.005) ***(p<0.0005).

Field	**N $_{Combustion}$ (mg/g)**		**TN (mg/kg)**		**NO_3-N (mg/kg)**		**C $_{Combustion}$ (%)**		**TC (mg/g)**		**PO_4 (µg/g)**	
Depth	S	D	S	D	S	D	S	D	S	D	S	D
H7B	2.6 ± 0.5	1.5 ± 0.3	62 ± 37	40 ± 31	4.2 ± 0.8	5.9 ± 0.6	2.9 ± 0.6	1.8 ± 0.2	1.1 ± 0.4***	0.69 ±0.3***	19 ± 8.9 ***	8.1 ± 8.3***
Jason's	2.3 ± 0.1	1.2 ± 0.2	61 ± 32	38 ± 21	9.1 ± 0.6	8.4 ± 0.6	2.6 ± 0.2	1.3 ± 0.1	0.82 ± 0.3**	0.52 ± 0.3 **	27 ± 8.4 **	15 ± 12**
H7A	2.4 ± 0.2	1.9 ± 0.5	58 ± 33	39 ± 19	2.0 ± 4.5	7.2 ± 1.8	2.9 ± 0.2	2.2 ± 0.6	0.76 ± 0.2**	0.49 ±0.2**	14 ± 7.7**	9.6 ± 7.8**
Welcome	2.2 ± 0.2	1.5 ± 0.1	51 ± 29	51 ± 25	7.9 ± 3.9	5.9 ± 1.9	2.4 ± 0.2	1.6 ± 0.1	1.5 ± 0.9**	0.99 ±0.7**	19 ± 7.1**	13 ± 9.0**
Lovshin	2.5 ± 0.4	1.5 ± 0.4	50 ± 38	39 ± 14	2.3 ± 3.9	14 ± 1.8	2.8 ± 0.7	1.7 ± 0.8	1.4 ± 0.6***	0.73 ±0.3***	30 ± 13**	13 ± 8.9**
Gravel	1.5 ± 0.1	0.9 ± 0.3	59 ± 30	26 ± 10	8.0 ± 0.8	4.2 ± 0.5	1.7 ± 0.3	1.0 ± 0.2	0.85 ± 0.4**	0.50 ±0.2**	25 ± 11 ***	10 ± 6.7***
N. House	1.9 ± 0.2	1.3 ± 0.2	52 ± 28	40 ± 16	20 ± 3.0	10 ± 1.8	2.2 ± 0.2	1.6 ± 0.4	1.1 ± 0.5*	0.72 ±0.3*	23 ± 12	12 ± 11
Hubicki's	1.9 ± 0.2	1.0 ± 0.2	81 ± 45	55 ± 33	5.2 ± 1.3	3.2 ± 0.6	2.8 ± 0.9	2.0 ± 1.2	0.88 ± 0.4**	0.51 ±0.2**	24 ± 9.5 **	12 ± 10 **
Carrs	3.9 ± 0.3	3.7 ± 0.5	69 ± 30	47 ± 24	2.8 ± 0.6	4.5 ± 0.6	5.0 ± 0.6	4.5 ± 1.7	1.7 ± 0.5***	1.0 ±0.7***	29 ± 18	22 ± 16
S. Lakes	2.8 ± 0.6	1.7 ± 0.3	82 ± 48	56 ± 22	5.6 ± 0.3	7.2 ± 0.3	3.7 ± 0.6	2.1 ± 0.3	1.5 ± 0.7***	0.82 ±0.7***	17 ± 8.6*	9.9 ±9.2*
Beers	3.8 ± 0.4	2.1 ± 0.3	63 ± 36	55 ± 26	1.3 ± 0.5	2.6 ± 0.3	4.7 ± 0.5	3.0 ± 0.2	1.3 ± 0.4***	0.92 ± 0.5***	12 ± 5.5	14 ± 5.4
Burnham	1.9 ± 0.2	1.6 ± 0.2	61 ± 33	43 ± 20	2.4 ± 0.3	4.7 ± 0.6	2.3 ± 0.2	1.7 ± 0.3	0.86 ± 0.2*	0.60 ±0.2*	22 ± 9.6***	8.5 ± 4.5***

3.5. The NGS: A critical period of TD discharge and nutrient loss

This study hypothesized that measured and volume-weighted N and P concentrations within TD discharge would be higher in the NGS compared with the GS due to reduced plant uptake of nutrients in the dormant season. However, this hypothesis was only partly supported, as measured N concentrations in tile eluent were high year-round. Furthermore, measured and volume-weighted concentrations of P were highest following extreme precipitation events in both seasons. Although measured and volume-weighted concentrations of nutrients in tile discharge were similar across the three NGSs and the two GSs, the volume of discharge was much greater in the NGSs **(Figure 3-1).** As such, the total mass export of N and P via tile drains correlated mainly with the volume of discharge resulting in the NGSs being the primary leaching period within this study. Similarly, Bjorneberg et al. 1996, reported that up to 85% of annual NO_3-N mass export occurred within the NGS in Iowa, specifically in the spring or fall when vegetative growth was not active, which correlated mainly with the volume of TD discharge rather than the NO_3-N concentration. Furthermore, Van Esbroeck et al. (2016), found that the most critical period for hydrologic losses and P export was the NGS when up to 98% of the annual TP losses occurred from three tiles in southern Ontario. In conclusion, due to the variation in volume of discharge across seasons, the most critical period for nutrient losses in regions with a comparable climate is the NGS. The greater volume of discharge throughout the NGS contributes to greater mass export of N and P which can have a negative influence on downstream waterways such as eutrophication. Therefore, it is critical to prioritize the NGS when creating and implementing BMPs to reduce nutrient leaching in agriculturally dominated watersheds.

3.6 The effect of winter cover crops and other BMPs on N and P leaching via TDs

Winter cover crops are considered a BMP in seasonally snow-covered watersheds, where they are planted to improve SOM levels, provide surface protection, and reduce off-site nutrient leaching by scavenging excess soil nutrients and moisture. This study compared nutrient concentrations in TD discharge, labile soil nutrients in agricultural soils, and PRS probe nutrient fluxes from fields planted in different over-winter-covers/ residues to test the hypothesis that overwinter cover, either non-living (i.e., CC) or living but dormant (i.e., WW) would reduce tile drain nutrient leaching in the NGS in comparison to crop residue (i.e., CR). Furthermore, this analysis was done in the context of other commonly used BMPs such as no-till and crop rotation of corn-soybean-wheat (as opposed to monoculture cropping). The results only partly supported this hypothesis, as N losses were lower from fields planted to CC but were unexpectedly high from WW fields **(Figure 3-4, 3-5, 3-6, Table 3-4).** Likewise, measured and volume-weighted P concentrations were numerically, but not significantly, greater from CC fields than from WW or CR fields during the NGS. Overall, the findings from this study indicate that over-winter cover (i.e., CC and WW) differentially influenced N and P concentrations in TD leachate. Although fields planted to CC contributed to the lowest measured and volume-weighted N concentrations in TD discharge, these fields also leached some of the highest TP concentrations in TD discharge. Therefore, to reduce N and P leaching in agricultural-dominated watersheds, BMPs may have to target specific nutrients rather than a 'one-size-fits-all' approach. This is a similar conclusion to Hanrahan et al. (2021), who found that average monthly tile NO_3-N and TN loads were more than 50% less from over-winter cover fields in comparison to non-winter cover fields, however, there was no significant difference in TP loads between winter cover and non-winter cover fields. As such quantifying the factors that drive nutrient losses (e.g., recent fertilizer application, legacy soil nutrients, crop prosperity, physical soil properties) can be critical for assessing the environmental impacts of TD infrastructure. Furthermore, examining TD discharge and nutrient losses in the presence of BMPs such as over winter cover or no-till allows for a critical analysis of the practices that often target improving soil properties rather than water quality.

3.6.1 Fertilizer application impact on seasonal nutrient losses in TD landscapes

The differences in nutrient leaching observed between over-winter covers and residues presented in this study may depend on the timing and amount of fertilizer applied to the crop before the NGS. Corn fields typically receive their application of fertilizer in the spring, whereas winter wheat and cover crop mixtures receive fertilizer in the fall. Specifically, WW fields are fertilized in mid-October and CC fields are fertilized in late August (**Table 2-2).** The application of fall fertilizer prior to the NGS is common in cold-temperate regions, such as Ontario, as it allows farmers to avoid applying fertilizer in the spring when soils may have extensive moisture and heavy machinery can get stuck (Grant et al., 2019; OMAFRA, 2020). There are concerns regarding the leaching of nutrients from fall-applied fertilizer with some researchers stating that fall-applied fertilizer can greatly increase nutrient leaching (Grant et al., 2019; Hart et al., 2004). Despite the influence fall fertilizer application may have on nutrient leaching to tiles, no fertilizer was applied to any fields in the fall prior to NGS3 due to high costs related to the Ukraine war (Shahini et al., 2022). Despite this, N leaching from WW fields and P leaching from CC fields remained high and was higher than from CR fields in NGS3 **(Figure 3-4, 3-5, 3-6, 3-9, 3-10, Table 3-3, 3-5).** A study by Bjorneberg et al. (1996), which examined NO_3-N leaching in TDs from April to December across three years found that high NO_3-N leaching occurred throughout the study period both prior to fertilization and after crop harvest demonstrating that fertilizer was not the only source of NO_3-N in TD discharge. Likewise, a review paper by King et al. (2015), found that multiple factors influence P leaching such as soil characteristics, drainage design, management practices (e.g., fertilizer application timing and amount), and climatic variables (e.g., storm events). Therefore, the application of fall fertilizer is not the only factor that governs P leaching in TD landscapes and several recent studies have pointed to the influence of 'legacy nutrients' in soils.

3.6.2. The impact of legacy soil nutrients on TD discharge nutrient concentrations

'Legacy nutrients' within this study refers to the retention of N within the rooting zone for a relatively short period (i.e., year or season) and the magnitude of legacy nutrients is a function of not only the mass of N accumulation but also the rates of organic N mineralization and the loss of dissolved N (i.e., through biogeochemical and hydrologic pathways; Van Meter et al., 2016). As such, legacy soil nutrients could be an additional factor influencing nutrient leaching via TD. Notably, WW is planted following soybeans which are legumes that can fix atmospheric N_2 through their symbiotic association with rhizobia, and thus N levels in soil solution are often higher within soybean fields (Ciampitti et al., 2021; Vanotti & Bundy, 1995). The influence of soybean on soil N concentrations is suggested by the relatively high PRS probe NO_3-N concentrations at the soybean fields (average: 67 g/ha/day) in comparison to the wheat fields (average: 31 g/ha/day); however, it should be noted that NO_3-N concentrations in PRS probes were greatest at the corn fields (average: 110 g/ha/day) during the Summer 2022 (i.e., GS2) incubation period (**Figure 3-14**). Relatively high NO_3-N concentrations at the corn fields may be due to the recent application of fertilizer at the corn fields, less than 2 months prior to the incubation period. In contrast, fertilizer was applied at least 8 months prior to PRS probe incubation at the wheat and soybean fields. Studies have suggested that soybeans can supply as much as 45 to 67 kg N ha^{-1} to the subsequent crop (Vanotti & Bundy, 1995). Winter wheat is typically planted into soybean residue at no-till fields in Ontario, including the operational fields of the current study (OMAFRA, Agriculture and Agri-food Canada, et al., 2017). Soybeans are often harvested in the late fall which gives the following WW crop minimal time to establish itself and utilize the 'N credit' before the dormant winter period. Additionally, N fixation occurs along the soybean roots, which can grow to depths of 2 m (Borg & Grimes, 1986; Dwyer et al., 1988; Ordóñez et al., 2018). As such, the soybean 'N credit' could be at a depth beyond the reach of the juvenile WW rooting system planted in mid-October (Endres et al., 2021). For instance, Portela et al. (2024), found that early sown WW (i.e., planted in August) only reached rooting depths of 0.5 m by November, and given the greater number of growing days for early sown WW in comparison to WW planted in October it could be assumed that WW rooting depths in the current study would be shallower than 0.5 m. Indeed, observations across the three NGSs in this study indicated large differences in WW establishment, with minimal plant establishment in NGS1 & 3 (see **Figure 3-17).** Although the inclusion of soybean in a crop rotation is believed to be beneficial by providing a 'N credit' to the subsequent crop, thereby decreasing fertilizer demand, soybeans may increase N leaching in tiled agricultural fields if the following crop is not able to utilize the N credit prior to winter senescence. As such this study suggests that higher N leaching at WW fields in comparison to CC or CR fields could be a result of the legacy 'N credit' from the prior soybean crop.

Legacy soil nutrients from prior crops or crop residues may also influence P leaching throughout the NGS. Firstly, over-winter cover and crop residues can be a source of P within the NGS. Freeze-thaw cycles can stimulate the release of soluble P during the NGS as the cells of the vegetative matter break down (Cober et al., 2018; Hanrahan et al., 2021; Liu et al., 2019; Riddle & Bergstrom, 2013; Tukey & Morgan, 1963). The decomposition of frost-intolerant, high biomass CC species such as radish and turnip during the dormant season may contribute to higher TP leaching from CC fields in comparison to fields planted to WW or CR fields. For instance, a review by Liu et al. (2019) , found that crop residue (e.g., corn residue) contained significantly lower TP concentrations (mean = 0.9 mg kg^{-1}) in comparison to brassica CC (e.g., turnips, radish; mean = 4.6 mg kg^{-1}) or grass CC (e.g., WW; mean = 3.6 mg kg^{-1}). Furthermore, water extractable P in non-brassica cover crops ranged from 16-29 % of the plant total whereas brassica cover crops ranged from 31-58% of the plant total (Liu et al., 2019). Overall, P concentrations in over-winter cover crops are greater in brassica species compared with grasses or crop residues which may contribute to greater P losses at the CC fields in comparison to the WW or CR fields (**Figure 3-9, 3-10**). Secondly, greater P concentrations in soils can lead to greater P losses to TD discharge (Leverich Nigon et al., 2022). Within the current study, soil HPO_4 concentrations were relatively similar across seasons and crops; however, the CC fields had the highest soil P concentrations in the spring of 2022 (i.e., the spring after NGS2; 26 µg g^{-1}; **Figure 3-13).** High soil P concentrations in CC fields in spring 2022 align with the high tile discharge P concentrations (i.e., measured and volume-weighted) at the CC fields throughout NGS2. Higher soil and tile drainage P concentrations may be related to increased freeze/thaw events in NGS2 in comparison to NGS1 & 3 and greater brassica CC establishment which will be explored in greater detail in *section 4.6.3*. As depicted in **Figure 3-3,** soil temperature within NGS2 frequently fluctuated below 0^{o}C which can stimulate the release of soluble P due to vegetative matter breakdown. Although winter CC is a BMP by providing soil cover and reducing erosional losses, the current study suggests that CC may be an important source of P to tile drainage due to their high labile P content and potential to augment macropore drainage.

3.6.3 Over-winter cover crop development as a factor influencing nutrient leaching via TDs

The difference in nutrient leaching between the overwinter covers throughout the NGS could be further explained by the growing conditions prior to winter dormancy. Poor growing conditions in the early fall, which limit plant establishment prior to winter senescence, could contribute to lower-than-expected nutrient scavenging by over-winter cover. As CCs are planted following wheat harvest, which typically occurs in late August, they normally have approximately 50 to 60 growing days prior to winter dormancy to establish. As such, CC fields should be well established prior to winter dormancy resulting in dense plant cover that limits soil exposure over the NGS (see **Figure 3-16).** However, field observations indicated that not all plants within the CC mixtures were well established each year, despite similar seed mixes. For example, in NGS1 the plant cover at the CC fields was primarily comprised of grasses (i.e., oats, rye, buckwheat). In contrast, in NGS2 and NGS3 the plant cover was more diverse with species such as berseem clover, sunflowers, hairy vetch, peas, turnip, and daikon radish being more established within the CC fields in comparison to NGS1. As explained in *section 4.6.2* the decomposition of brassicas can leach high amounts of P to tiles. This may explain why P levels in PRS probes and tile drainage were higher in NGS2 & 3 compared with NGS1. In contrast to the CC fields, WW was generally seeded following soybean harvest in mid-October leaving on average only 15-25 growing days before the first frost. Field observations indicated that WW was less established in NGS1 & 3, with an average height of approximately three cm prior to winter senescence. In contrast, winter wheat was somewhat better established in

NGS2 as it reached a maximum height of approximately 10 cm prior to winter dormancy (see **Figure 3-17).** Poor WW establishment prior to the winter could influence P and N concentrations in TD discharge through the NGS. For instance, a study by Drury et al. (2014), found that in years when WW was not fully established prior to winter senescence NO_3-N loads in TD were higher in Ontario, Canada. However, within the current study, volume-weighted N concentrations in tile drainage were consistently higher in WW fields in all three NGSs despite slight differences in WW establishment. As such, it appears that crop growth prior to winter senescence is not the only factor influencing the relatively high N leaching rates from WW fields compared with CC or CR fields.

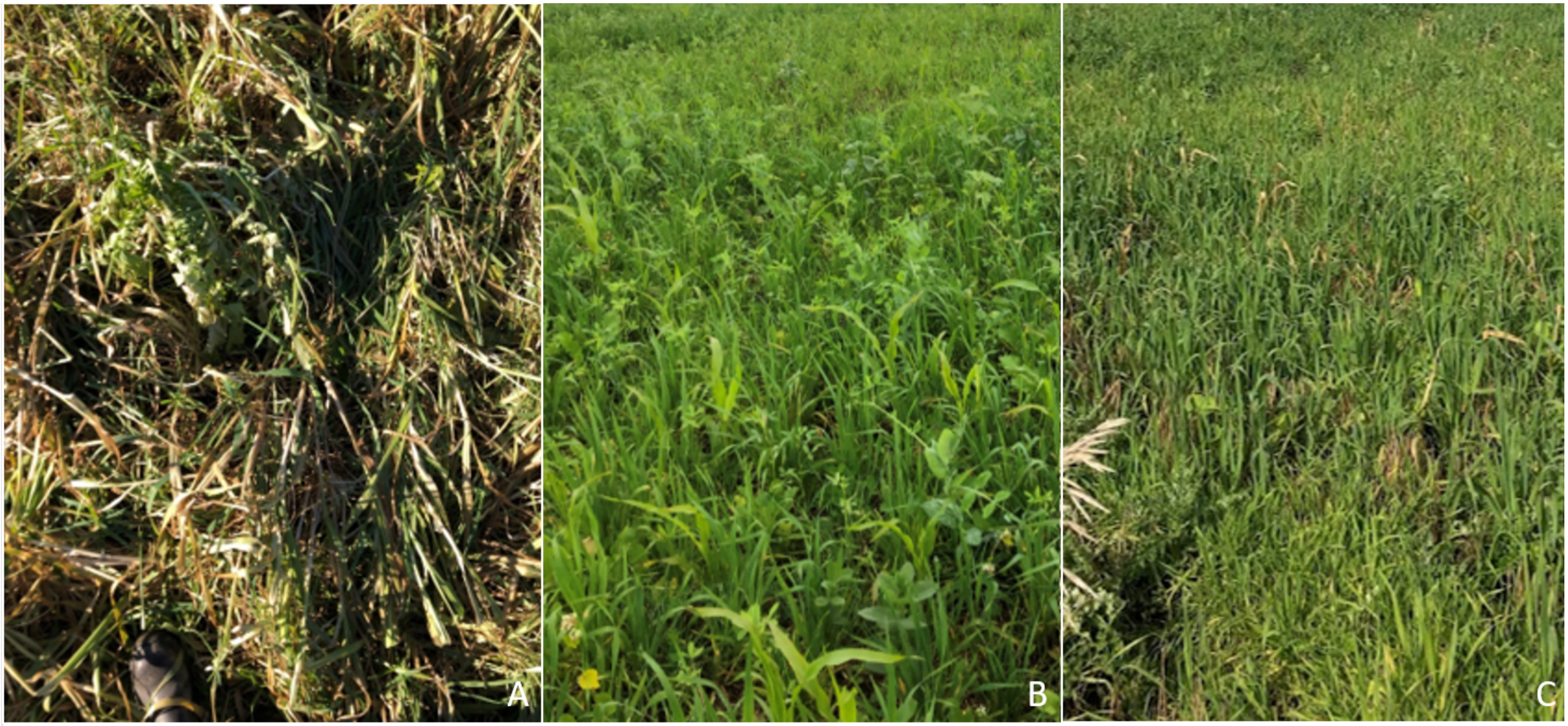

Figure 3-16: Extent of soil cover in cover crop fields prior to snowfall in a) NGS1 (November 25, 2020), b) NGS2 (October 13, 2021), and c) NGS3 (October 14, 2022).

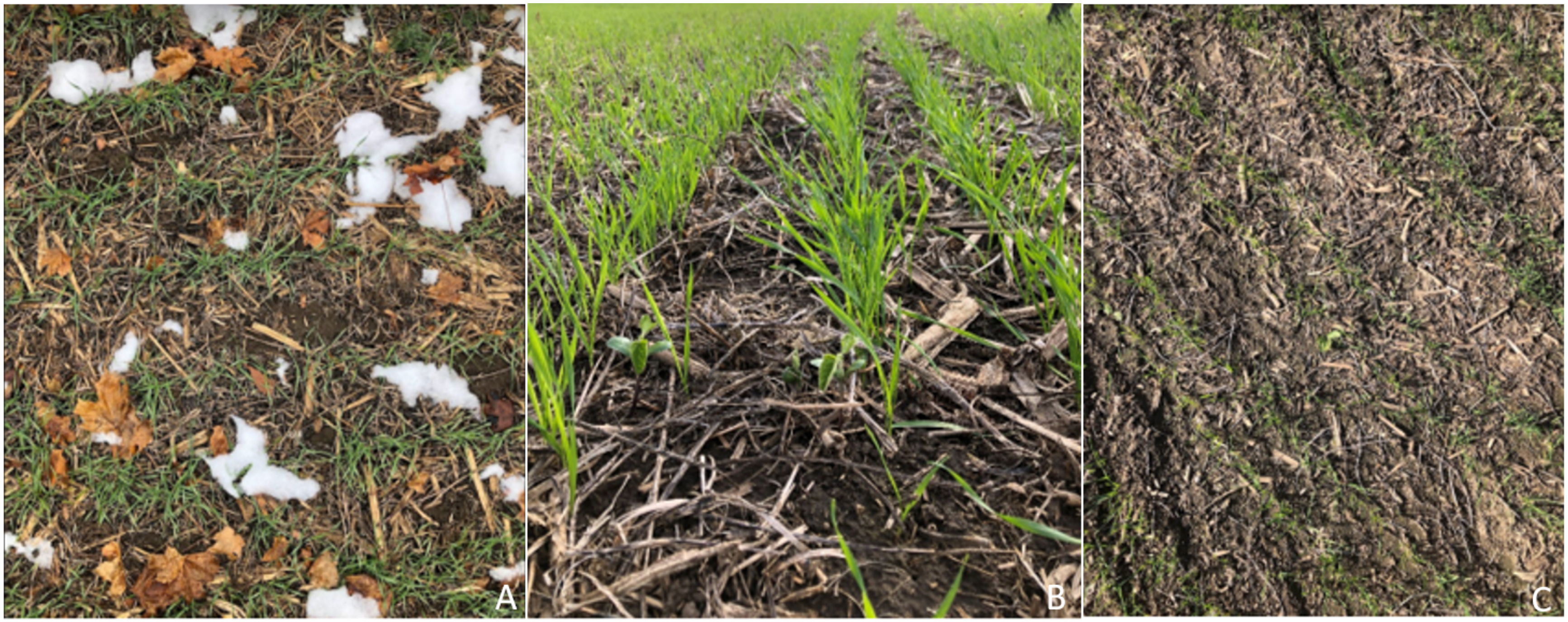

Figure 3-17: Extent of plant cover in the winter wheat fields in a) NGS1 (November 25, 2020), b) NGS2 (October 18, 2021), and c) NGS3 October 28, 2022. Note, fall fertilizer was not applied in NGS3.

3.6.4 Soil physical properties and their influence on nutrient leaching via TD

The physical properties of soils in an agricultural setting play a vital role in influencing crop growth/ prosperity but also may influence nutrient leaching, especially in the presence of TD. No-till or conservation tillage has become a common BMP across Canada (i.e., 81% of farmland in Canada; Statistics Canada 2017a) due to its tendency to improve SOM and reduce erosion (Blanco-Canqui & Ruis, 2018; Busari et al., 2015; Lv et al., 2023). However, the absence of mechanical mixing in no-till soils can cause nutrients to become enriched in surface soil. Specifically, increases in SOM are often limited to the soil surface which can lead to the stratification of immobile nutrients such as P rather than water-soluble nutrients such as N (Blanco-Canqui & Ruis, 2018). The significant stratification of P at the study fields (**Table 3-9**) could have implications for nutrient losses in tile eluent as both dissolved (i.e., TDP) and PP can be lost via tile drain discharge in the presence of preferential pathway networks (Lam et al., 2016; Williams et al., 2016). In no-till systems, preferential pathways can form and persist across multiple years, possibly getting worse with age (i.e., deepening and widening). Preferential pathways can contribute up to 30% of discharge from agricultural fields, especially in the NGS when the soil-saturated zone is close to the soil surface (Gaillot et al., 2023). In the current study, the TD agricultural fields were close to or exceeded soil saturation during event conditions (i.e., heavy rainfall events, rain on snow, spring melt) and throughout the NGSs (**Figure 3-3).**

Tile flow via preferential pathways within no-till agricultural fields could have severe consequences for nutrient losses in TD discharge. Throughout the NGS, nutrients that are enriched in topsoil can leach more readily in the presence of preferential pathways as they can bypass the soil matrix (Grant et al., 2019; Tiessen et al., 2010). Using tracers, previous research has found that preferential flow is a critical pathway for P movement to tile drains after the onset of precipitation events (Laubel et al., 1999). Elevated P concentrations in tile drainage that occur immediately after the onset of precipitation support the idea that preferential flow pathways are a significant hydrological pathway for P leaching (King et al., 2015; Laubel et al., 1999). Likewise, high organic C concentrations that were observed in the current study during both NGS and GS events suggest the importance of bypass flow through the soil profile. Furthermore, field observations indicated that certain cover crop species including turnips and daikon radishes very quickly decayed and left behind deep and wide macropores in their place (see **Figure 3-18**). For instance, daikon radishes extended to depths greater than 30 cm and were as wide as 6 cm. These large macropores could act as conduits for TP and TDP to enter TD. Macropore development is an unexpected byproduct of no-tillage, and in combination with tile drainage, nutrient stratification, and decay of nutrient-rich winter cover crops, could contribute to the eutrophication of downstream waterbodies and has been suggested as a potential contributor to rising SRP in Lake Erie (Joosse & Baker, 2011).

Figure 3-18: Field observations of bio pore created by the growth of daikon radish in the fall at S. Carr (A) and in the spring (B; Frances & Schultz, 2016)

4. Conclusion

In conclusion, this study found that the NGS is the most critical period of nutrient loss via TD. Although concentrations of N and P were relatively similar across seasons, the NGS experienced the greatest mass loss of nutrients as a result of higher tile discharge during the NGS. In seasonally snow-covered regions, winter BMPs are an important way to limit nutrient losses as well as improve soil conditions. However, in combination, some winter BMPs may inadvertently increase nutrient losses, and effects on P vs. N may differ. For instance, this study concluded that within the NGS, TN and NO_3-N concentrations were significantly higher at the WW fields in comparison with the CC fields; however, TP losses were greatest from CC fields in comparison with WW and CR fields.

Nitrogen concentrations in tiles draining WW fields were consistently higher than from CC or CR fields in all three NGSs despite differences in fertilizer application and crop establishment over the years. Although WW fields received fall fertilizer application in NGS1 & 2 and were poorly established prior to winter senescence in NGS1 & 3, the N-credit provided by the previous soybean crop likely explained the consistently high N concentrations in WW eluent. Furthermore, although TP concentrations were not significantly greater from CC fields they were numerically higher, especially in NGS2. The observation of preferential flow pathways, such as those brought on by the decomposition of tuber species, suggests that high TP concentrations in tiles draining CC fields in NGS2 & 3 may be due to preferential flow pathways and the decomposition of brassica species. Additionally, P transfer to tile drains may have been exacerbated by nutrient stratification, as preferential flow pathways in no-till, surface-broadcast fertilized fields allow surface-enriched nutrients to bypass the soil matrix (Crozier et al., 1999; Vidon & Cuadra, 2011).

Overall, although over-winter cover is a BMP for soils, the benefits do not always apply to water resources and could exacerbate the negative impacts of row crop agriculture on surrounding waterways. Further research is needed to explain the high rates of N leaching from WW and unexpectedly high P losses from CC fields and to identify solutions to prevent or mitigate these losses. Furthermore, future efforts to improve agricultural BMP performance need to take a more integrated, watershed view, and consider both soil preservation as well as water resource protection. As this study discovered, the effects of over-winter BMPs were different for N vs. P, which highlights the need to have BMPs that target each nutrient individually with a focus on their individual nutrient loss pathways.

5. References

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6. Appendix

Appendix A

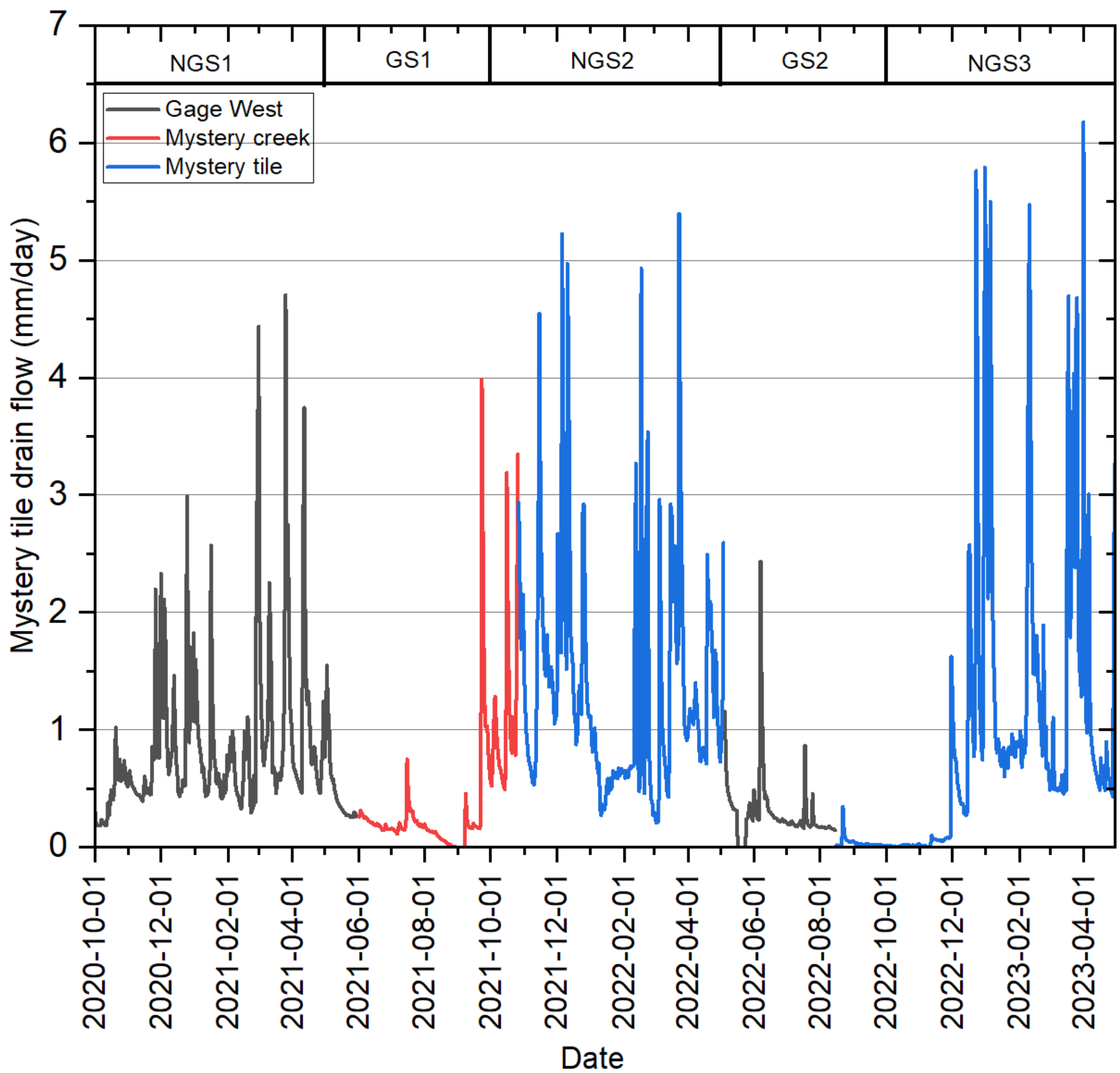

Figure 6-1. A complete record of tile drainage discharge at Mystery from October 2020 to April 2023 where black indicates discharge estimated from the Gage West relationship, red indicates discharge estimated from the Mystery Creek relationship and blue represents discharge from the mystery tile drain FloWav logger.

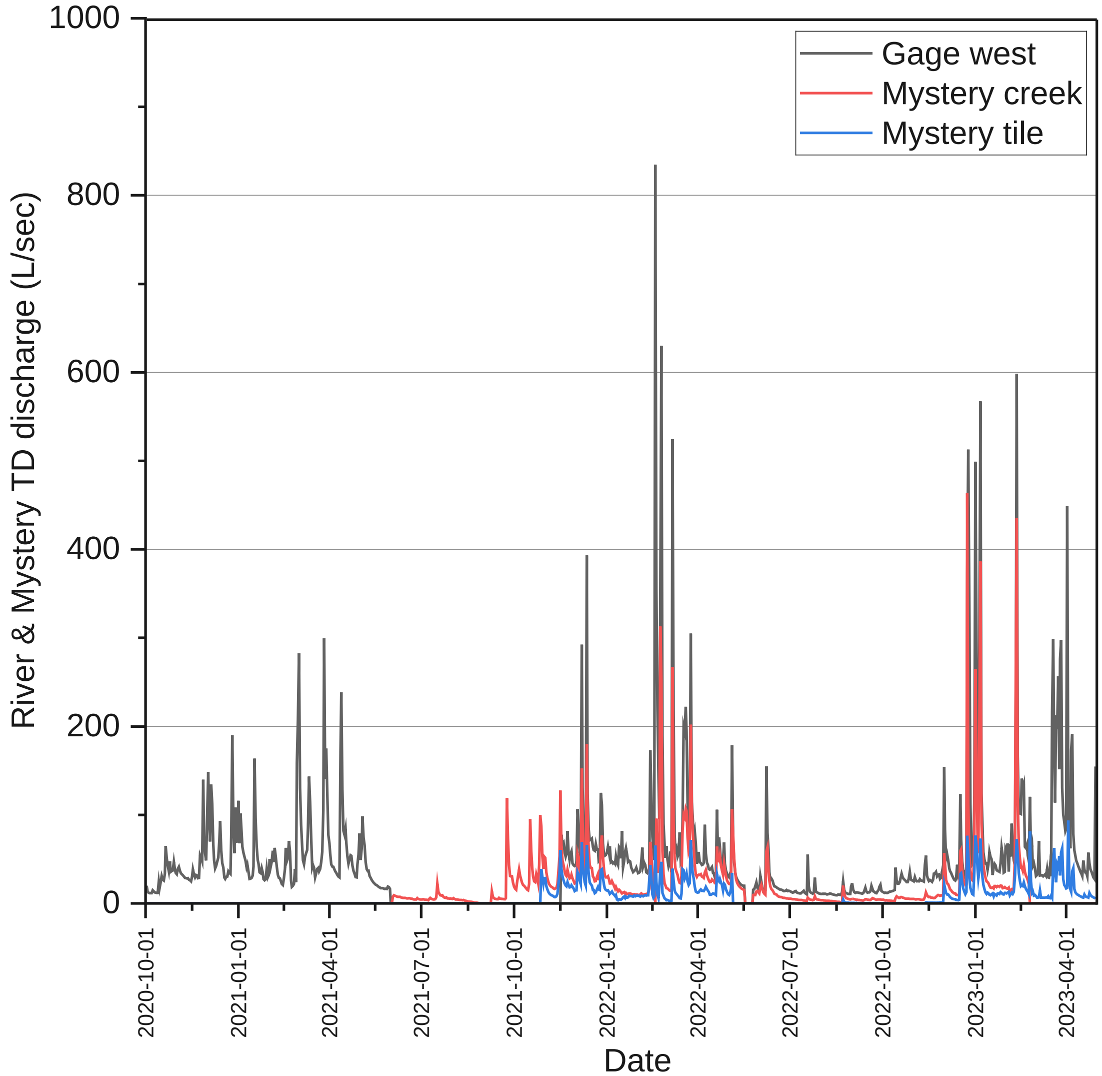

Figure 6-2. River discharge at Gage West (grey) and Mystery Creek (red), in relation to the Mystery TD discharge volume (blue).

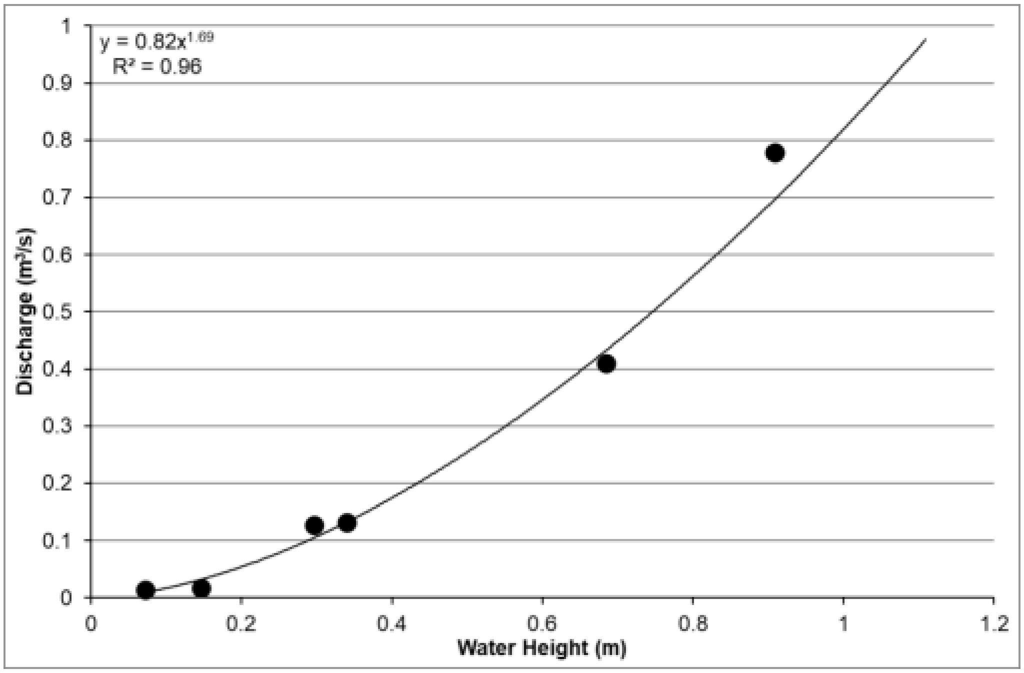

Figure 6-3. Discharge rating curve for Gage West (Liu et al., 2022).

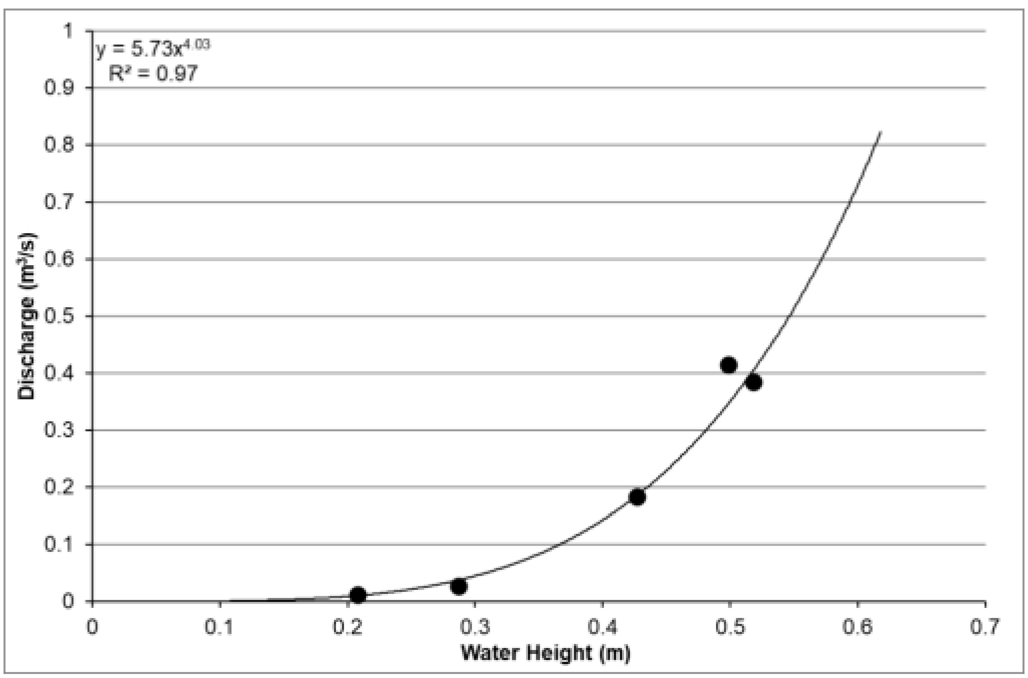

Figure 6-4. Discharge rating curve for Mystery Creek (Liu et al., 2022).

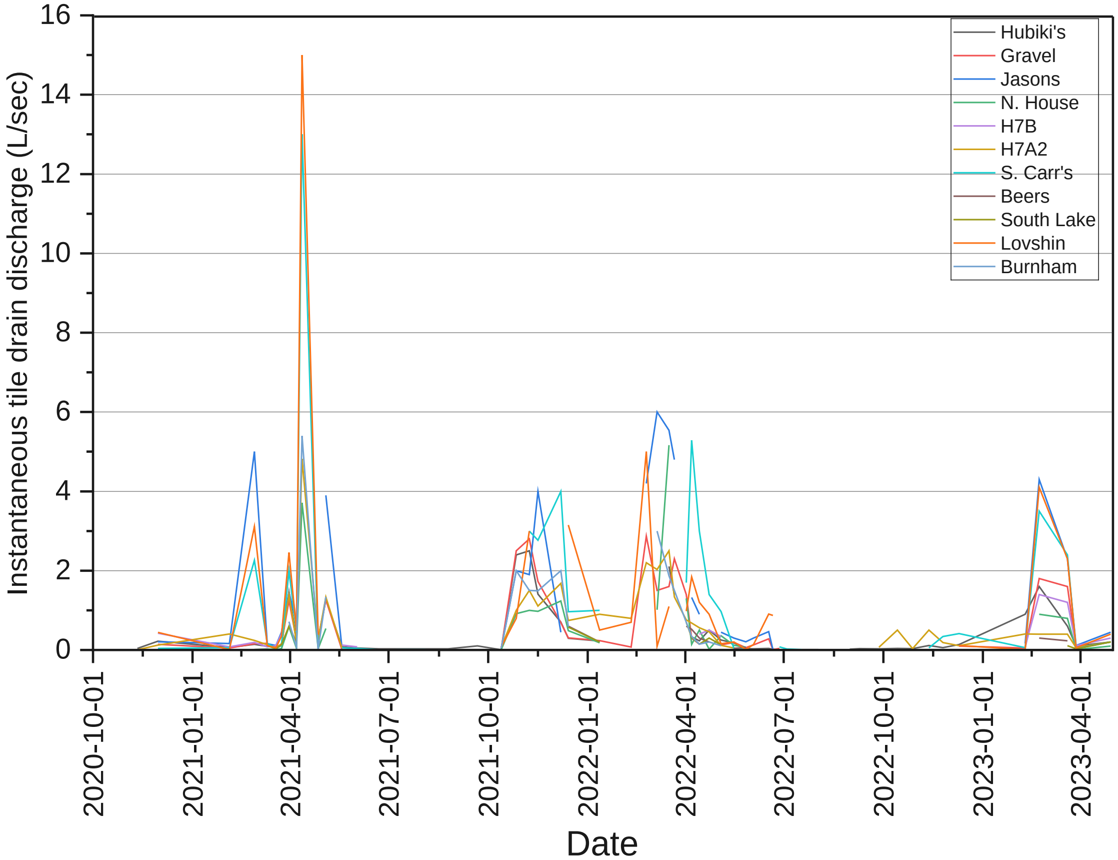

Figure 6-5. The coherence of instantaneous TD discharge across the 11 TD sampled within this study. The Welcome TD outlet is excluded due to its continuous submergence in the stream it discharges into.

Figure 6-6. Visual representation of the change in Mystery TD discharge due to melting snow on March 6, 2022, where A) was taken at 11:00 am and B) was taken at 1:30 pm.

Table 6-1. Monthly and seasonal air temperature, precipitation, and tile discharge from Mystery TD. Values in parentheses following discharge represent discharge as a fraction of precipitation.

Month		**Mean Air Temperature (°C)**	**Precipitation (mm)**	**Mystery Discharge (mm)**
Oct 2020	NGS1	9.0	68	13 (0.19)
Nov 2020		5.6	58	20 (0.34)
Dec 2020		-0.4	67	34 (0.51)
Jan 2021		-3.1	32	24 (0.77)
Feb 2021		-5.0	39	22 (0.56)
Mar2021		1.5	40	42 (1)
Apr 2021		6.5	81	29 (0.36)
NGS1		**2.1**	**390**	**180 (0.48)**
May 2021	GS1	11	25	15 (0.58)
Jun 2021		17	42	6.0 (0.14)
Jul 2021		20	150	6.9 (0.05)
Aug 2021		22	24	2.5 (0.10)
Sep 2021		17	140	15 (0.11)
GS1		**17**	**380**	**45 (0.12)**
Oct 2021	NGS2	13	83	39 (0.47)
Nov 2021		3.5	52	43 (0.83)
Dec 2021		0.57	63	63 (1)
Jan 2022		-8.1	51	19 (0.38)
Feb 2022		-4.7	82	34 (0.41)
Mar2022		0.37	64	48 (0.75)
Apr 2022		5.7	1.8	37 (1)
NGS2		**1.5**	**400**	**280 (0.71)**
May 2022	GS2	13	36	13 (0.36)
Jun 2022		16	71	13 (0.18)
Jul 2022		20	85	7.0 (0.08)
Aug 2022		21	190	3.5 (0.02)
Sep 2022		16	160	0.7 (0.00)
GS2		**17**	**540**	**37 (0.07)**
Oct 2022	NGS3	9.4	5.9	0.4 (0.08)
Nov 2022		4.8	81.	3.0 (0.04)
Dec 2022		-0.28	130	44 (0.34)
Jan 2023		-1.5	73	45 (0.62)
Feb 2023		-2.6	64	44 (0.68)
Mar 2023		0.38	87	51 (0.58)
Apr 2023		6.9	101	36 (0.36)
NGS3		**2.4**	**540**	**220 (0.41)**

Appendix B

Table 6-2. Mean measured TDP concentrations by field and season order by crop rotation. Numbers in parentheses indicate sample number (η).

Crop rotation by season	Field	NGS1	GS1	NGS2	GS2	NGS3
CC – C – CR – S - WW	Beers	10 (2)		15 (3)		
	Burnham	10 (2)		83 (2)		12 (1)
	S. Lake			13 (1)		10 (2)
	Carr	32 (3)	8 (4)	17 (5)	8 (1)	26 (1)
WW – W – CC – C – CR	Gravel	13 (4)	7 (1)	119 (5)	7 (2)	
	Hubicki's	19 (5)		58 (4)		10 (1)
	Lovshin	20 (3)	8(1)	70 (3)	8 (4)	16 (3)
	N. House	10 (3)				12 (2)
C- S- WW – W- CC	H7A2	11 (4)		51 (5)		
	H7B	14 (1)	9 (2)	26 (6)	9 (1)	8(1)
	Jason's	50 (4)	12 (5)	43 (8)	12 (2)	30 (3)
	Welcome	15 (4)	13 (2)	24 (5)	13 (1)	6 (2)
Seasonal Average		23 ± 28 (44)	10 ± 4 (19)	56 ± 84 (65)	19 ± 18 (22)	29 ± 77 (27)

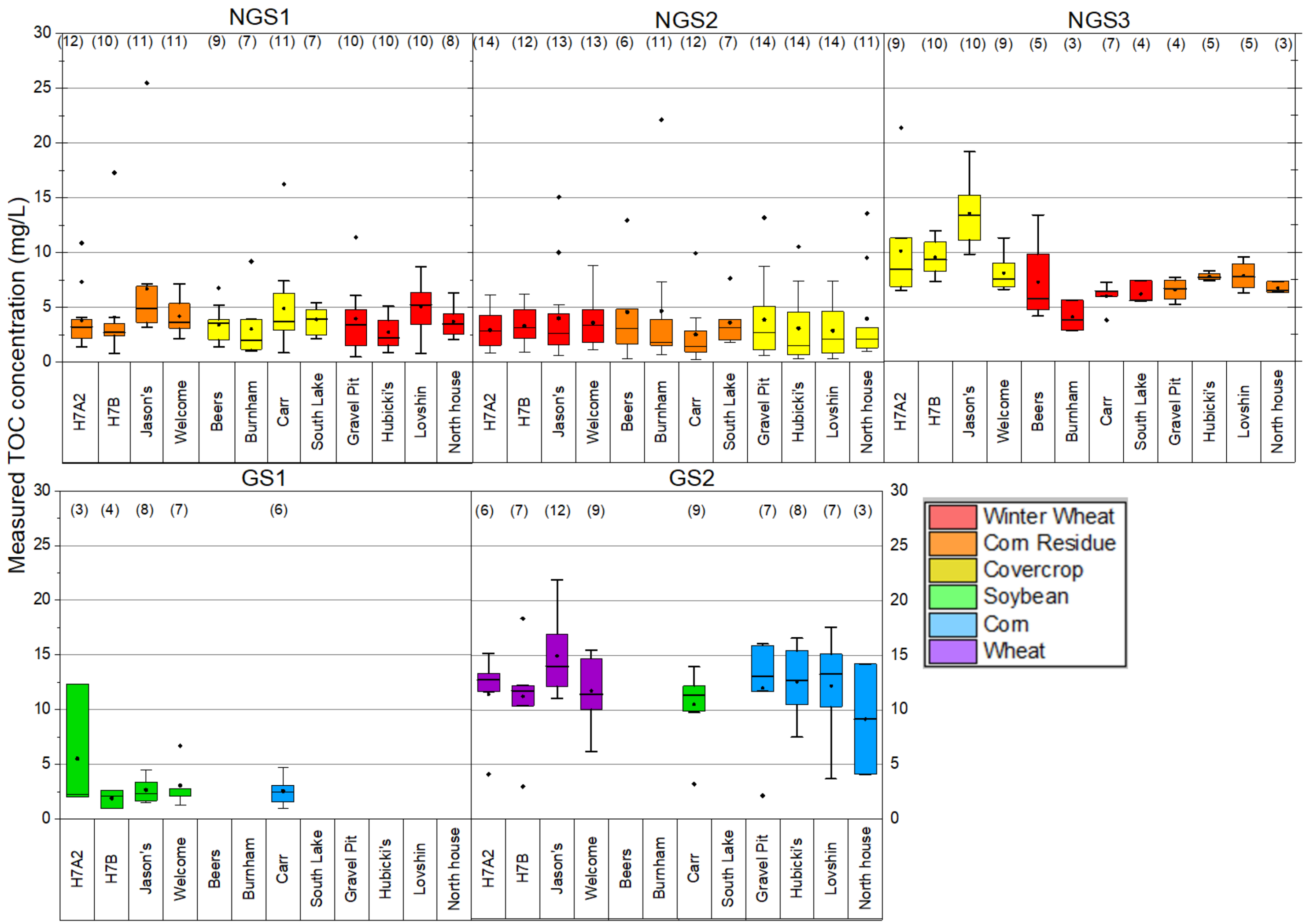

Figure 6-7: Seasonal boxplot of measured TOC concentrations (mg L^{-1}) at the 12 tiled fields. Boxes indicate the 25th-75th percentile concentrations, and the median is indicated by the central line. Whiskers indicate the upper and lower extents of the interquartile range multiplied by 1.5. Statistical outliers that exceed the whiskers are indicated by the dots. Numbers in brackets represent sample size (η) at each tile drain for the different seasons.

Table 6-3. Mean measured nutrient concentrations by river and season. Numbers in parentheses indicate sample number (η).

	Location	TN (mg/L)	NO_3-N (mg/L)	TP (µg/L)	TDP (µg/L)	TC (mg/L)	TIC (mg/L)	TOC (mg/L)
GS2	Bethyl grove	3.9 (14)	3.2 (13)	25 (7)	14 (4)	57 (14)	48 (14)	9.9 (14)
	Gage East	1.1 (14)	0.7 (14)	35 (11)	17 (6)	54 (14)	45 (14)	11 (14)
	Gage Urban	1.9 (14)	0.6 (14)	49 (13)	13 (7)	60 (14)	47 (14)	14 (14)
	Gage West	1.1 (14)	0.7 (13)	26 (10)	10 (5)	57 (14)	46 (14)	12 (14)
	Lovknee	0.6 (6)	0.2 (6)	41 (6)	15 (6)	77 (6)	60 (6)	17 (6)
	Mystery Creek	2.6 (6)	0.8 (6)	45 (5)	34 (5)	72 (6)	59 (6)	15 (6)
	Railway	3.2 (6)	1.3 (6)	21 (6)	10 (4)	61 (6)	52 (6)	11 (6)
	Williamsons	0.7 (14)	0.5 (13)	26 (8)	18 (4)	57 (14)	47 (14)	12 (14)
NGS2	Bethyl grove	3.9 (12)	2.7 (10)	110 (9)	100 (5)	53 (12)	50 (12)	3.8 (12)
	Gage East	1.4 (11)	1.2 (10)	110 (10)	50 (5)	60 (11)	56 (11)	4.9 (11)
	Gage Urban	2.3 (11)	1.6 (11)	100 (8)	71 (5)	57 (11)	54 (11)	6.6 (11)
	Gage West	2.3 (12)	1.5 (11)	160 (9)	100 (6)	57 (12)	53 (12)	4.6 (12)
	Lovknee	0.8 (9)	0.6 (8)	93 (6)	45 (4)	60 (9)	53 (9)	8.6 (9)
	Mystery Creek	4.4 (12)	3.5 (11)	62 (11)	48 (4)	54 (12)	52 (12)	4.8 (12)

	Railway	4.0 (10)	3.5 (9)	170 (7)	99 (2)	59 (10)	55 (10)	5.3 (10)
	Williamsons	1.2 (13)	0.8 (11)	95 (9)	52 (6)	56 (13)	53 (13)	4.1 (13)
NGS3	Bethel grove	3.5 (8)	3.0 (8)	45 (6)	14 (2)	66 (6)	59 (6)	7.2 (6)
	Gage East	1.4 (7)	1.3 (7)	72 (5)	13 (2)	68 (6)	59 (6)	8.8 (6)
	Gage Urban	0.8 (8)	0.7 (8)	55 (6)	15 (4)	64 (6)	52 (6)	11 (6)
	Gage West	1.5 (7)	1.4 (7)	120 (7)	110 (3)	69 (6)	60 (6)	8.8 (6)
	Lovknee	0.6 (3)	0.4 (3)	16 (3)	10 (1)	86 (2)	74 (2)	12 (2)
	Mystery Creek	2.7 (4)	2.7 (4)	17 (3)	9 (1)	80 (3)	72 (3)	8.2 (3)
	Railway	3.4 (1)	4.1 (1)	16 (1)		80 (1)	70 (1)	9.2 (1)
	Williamsons	1.3 (8)	1.0 (8)	45 (7)	17 (2)	65 (6)	58 (6)	6.8 (6)

Appendix C

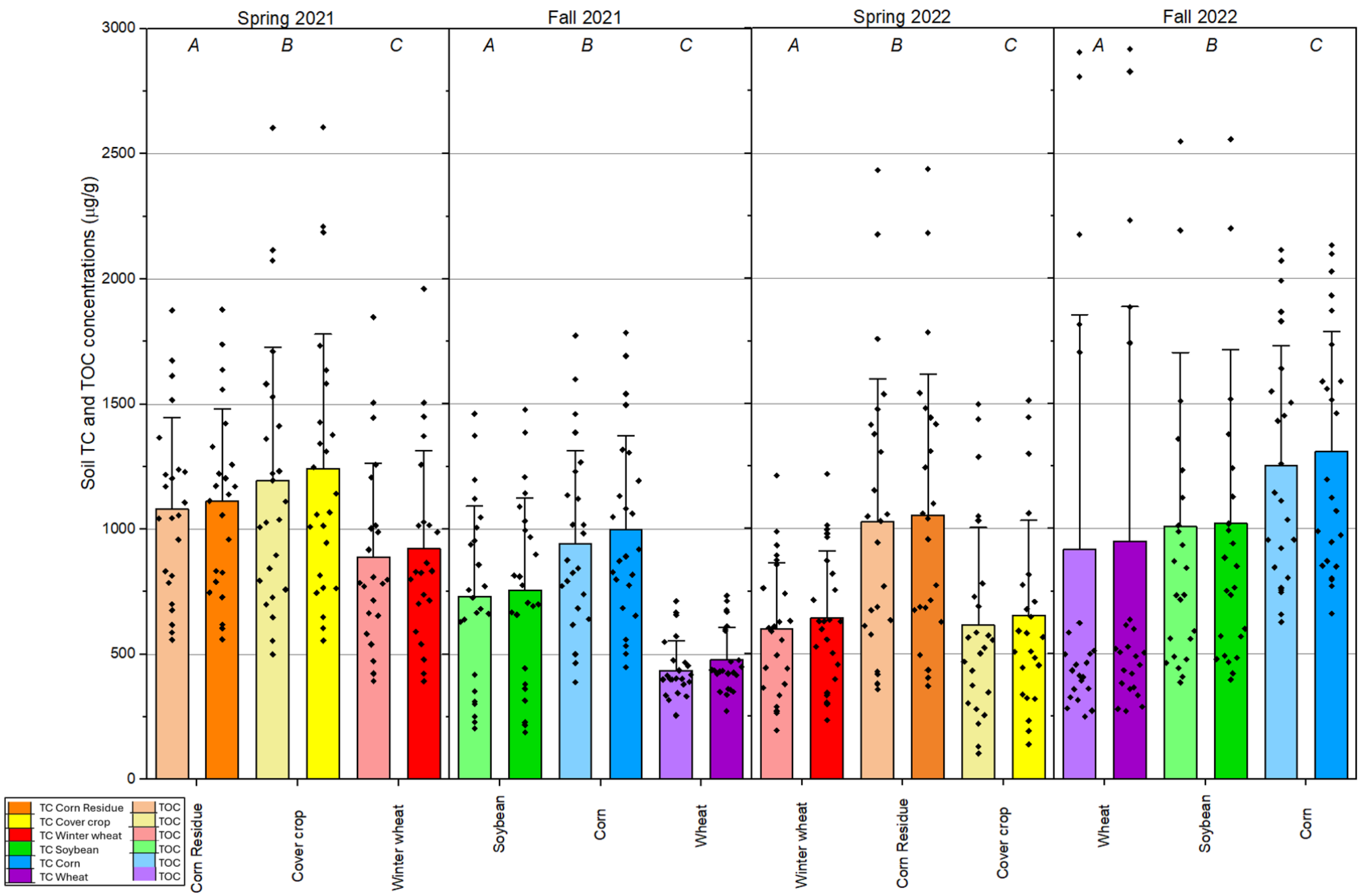

Figure 6-8. Seasonal bar plot of soil TC and TOC concentrations (µg g^{-1}) across the four soil sample periods based on crop cover/ residue of the fields at the time of sampling where the mean is indicated by the top of the bar, the error bars represent the mean + 1 standard deviation and the dots represent the spread of data. Italicized letters (i.e., A, B and C) indicate the crop rotation fields throughout the four sample periods.

Appendix D

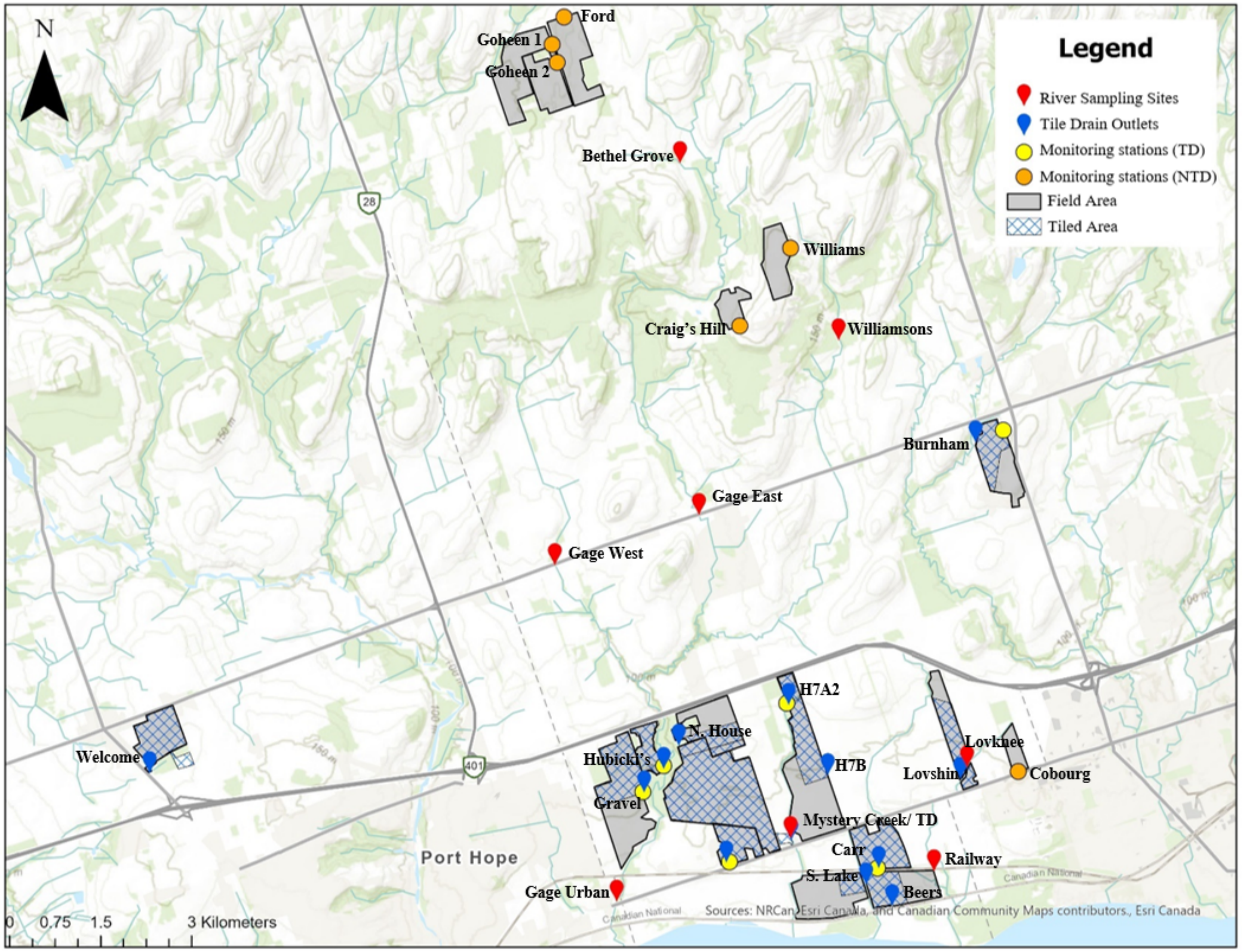

Figure 6-9. Map of sampling locations including tile outlets, rivers, and soil monitoring stations. Field outlines and tiled areas within each field are indicated.

Table 6-4. Non- TD soil characteristics ordered from north to south where * indicates fields which are seasonally conventionally tilled.

	SOM (%)	pH_{H_2O}	BD (g/cm3)	Soil texture *a*	Slope *a*
Ford	3.3 ± 1.2 (6)	7.1 (3)	1.4 (2)	Sandy loam	12
Goheen 1	4.4 ± 1.3 (6)	7.2 (3)	1.4 (2)	Sandy loam	12
Goheen 2	4.3 ± 1.4 (6)	7.5 (3)	1.4 (2)	Sandy loam	12
Craigs Hill	3.6 ± 0.8 (6)	7.6 (3)	1.1 (2)	Sandy loam	12
Williamsons	4.1 ± 1.1 (6)	7.9 (3)	1.4 (2)	Sandy loam	12
*Cobourg**	5.5 ± 0.8 (6)	8.3 (3)	1.3 (2)	Silt loam	3.5

a: Texture and slope values obtained from the Soil Survey Complex database (OMAFRA, 2019).

Table 6-5. Mean soil nutrient concentrations at six non-tile drained fields across the entire study period where S (shallow) indicates soils collected from 0-5cm depth and D (deep) indicates soils collected from 15-20cm depth. Statistical significance: *(p<0.05), **(p<0.005) ***(p<0.0005).

	TC_{H_2O}		TN_{H_2O}		NO_3-N		$HPO_{4(Olsen\text{-}P)}$		$C_{(combustion)}$		$N_{(combustion)}$	
Units	mg/g		kg/g		µg/g		µg/g		%		%	
Depth	S	D	S	D	S	D	S	D	S	D	S	D
Ford	1.2± 0.5***	0.8 ±0.5***	85 ± 55	71 ± 53	1.3 ± 0.2	2.1 ± 0.4	34 ± 12	30 ± 9.7	2.0 ± 0.1	1.2 ± 0.4	0.2 ± 0.01	0.1 ± 0.03
Goheen 1	0.9 ± 0.1***	0.5± 0.1 ***	25 ± 32	24 ± 13	0.6 ± 0.1	1.6 ± 0.2	24 ± 8.4	14 ± 5.4	3.4 ± 1.3	1.5 ± 0.4	0.2 ± 0.01	0.1 ± 0.04
Goheen 2	0.8 ± 0.1***	0.4 ± 0.1 ***	15 ± 9	47 ± 34	1.0 ± 0.2	1.6 ± 0.2	31 ± 11	22 ± 7.6	N/A	2.5 ± 0.1	N/A	0.2 ± 0.01
Craigs hill	0.4 ± 0.3	0.4 ± 0.3	49 ± 38	45 ± 39	0.5 ± 0.1	0.9 ± 0.1	20 ± 7.6	20 ± 6.5	2.5 ± 0.5	1.7 ± 0.1	0.2 ± 0.02	0.1 ± 0.01
Williamsons	0.5 ± 0.3	0.3 ± 0.1	57 ± 34	37 ± 27	0.5 ± 0.1	0.6 ± 0.1	37 ± 9.8 *	16 ± 7.8*	2.2 ± 0.1	1.4 ± 0.1	0.2 ± 0.01	0.1 ± 0.02
Coburg [+]	0.8 ± 0.2	0.5 ± 0.2	57 ± 35	58 ± 41	0.7 ±0.1	1.9 ±0.2	18 ± 6.5	8.9 ± 5.7	2.5 ± 0.5	1.9 ± 0.6	0.2 ± 0.04	0.2 ± 0.05

[+] indicated fields that are seasonally conventionally tilled.

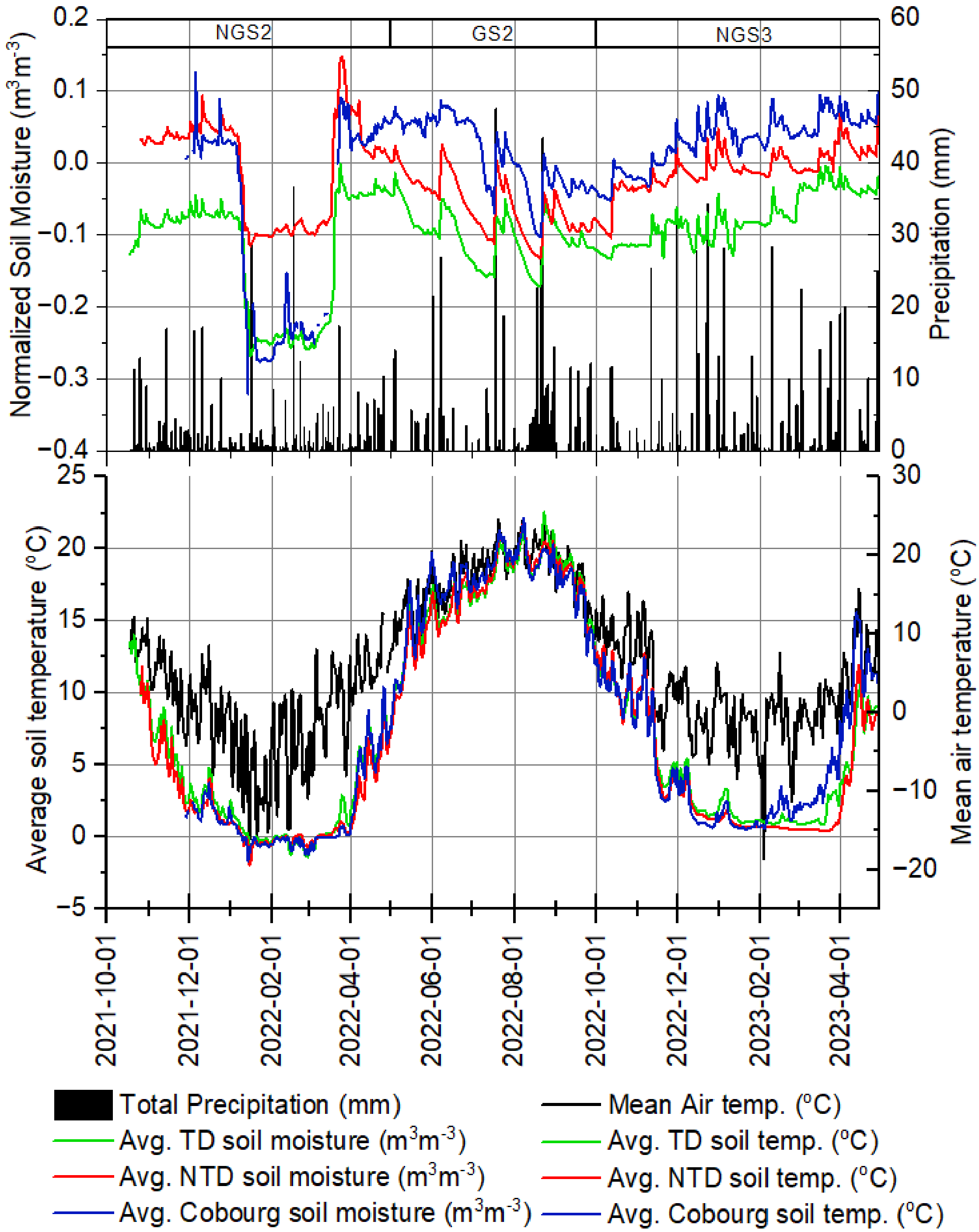

Figure 6-10: Average daily soil moisture and temperature data at TD fields (green), NTD fields (red), and the Cobourg field (NTD; blue) at a depth of 15cm. Climate conditions, including daily precipitation and daily mean temperature, were retrieved from the station Cobourg (AUT) weather station.

Table 6-6. Mean pre-incubation soil conditions and nutrient concentrations for the buried bag soil materials.

	Bag material	Soil moisture	HPO_4	$NO_3 - N_{H_2O}$	TN_{H_2O}	N Combustion	C Combustion
Units		*m^3m^{-3}*	*(μg/g)*	*(μg/g)*	*(μg/g)*	%	%
Summer 2022	Corn	0.21	17 ± 11	0.40 ± 0.3	25 ± 2.0	0.18 ±0.01	2.1 ± 0.1
	Cover crop	0.20	15 ± 7.2	1.5 ± 1.3	29 ± 1.2	0.19 ±0.04	2.6 ± 0.7
Winter 2021	Corn	0.22	26 ± 6.6	0.50 ± 0.4	18 ± 1.8	0.16 ± 0.01	1.8 ± 0.1
	Cover crop	0.15	35 ± 15	0.20 ± 0.1	22 ± 2.2	0.15 ± 0.01	1.9 ± 0.1

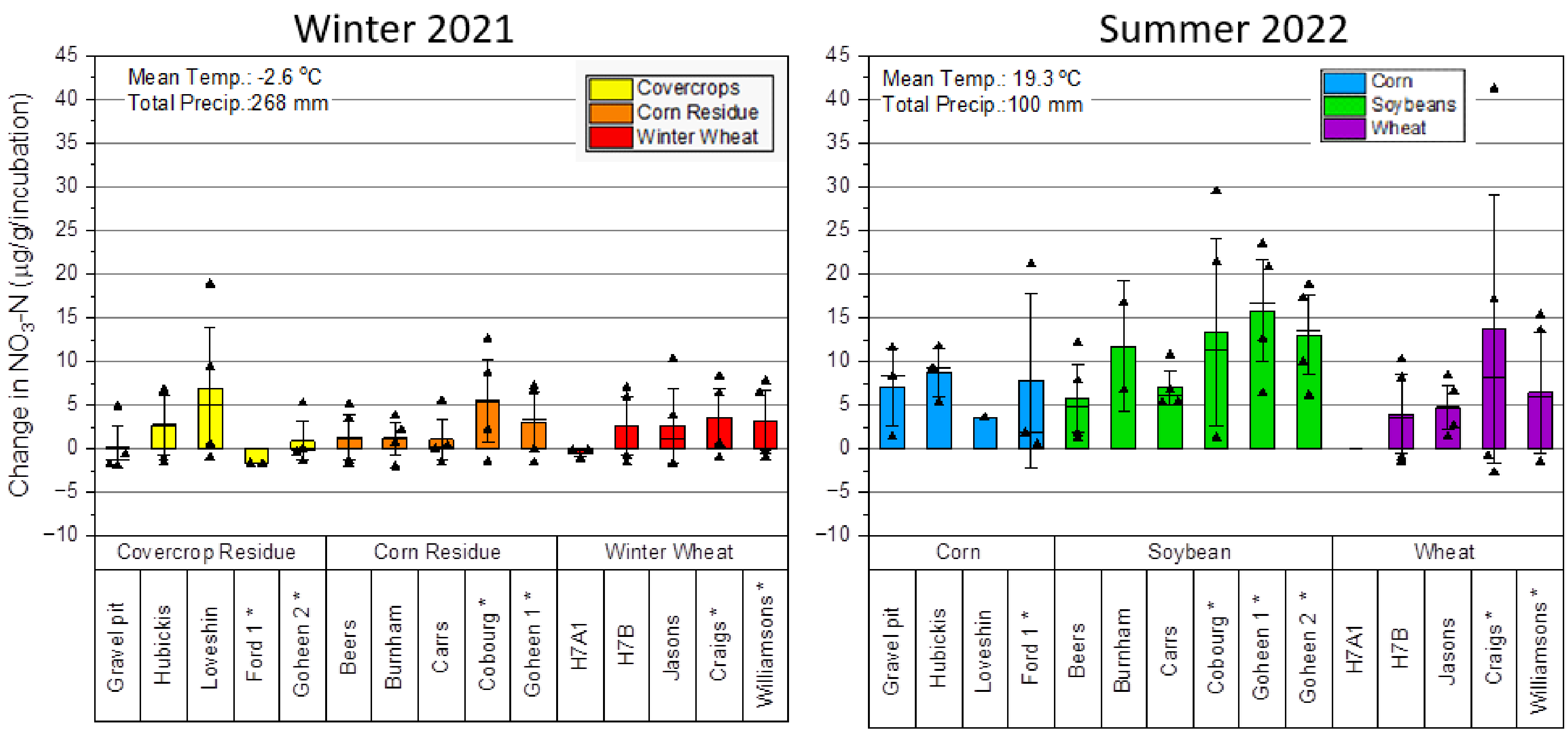

Figure 6-11. Seasonal change in BB NO_3-N concentrations under TD and NTD fields for two incubation periods, Winter 2021 (November 2021 to April 2022) and Summer 2022 (June 2022 to August 2022). The * indicates fields that are NTD.

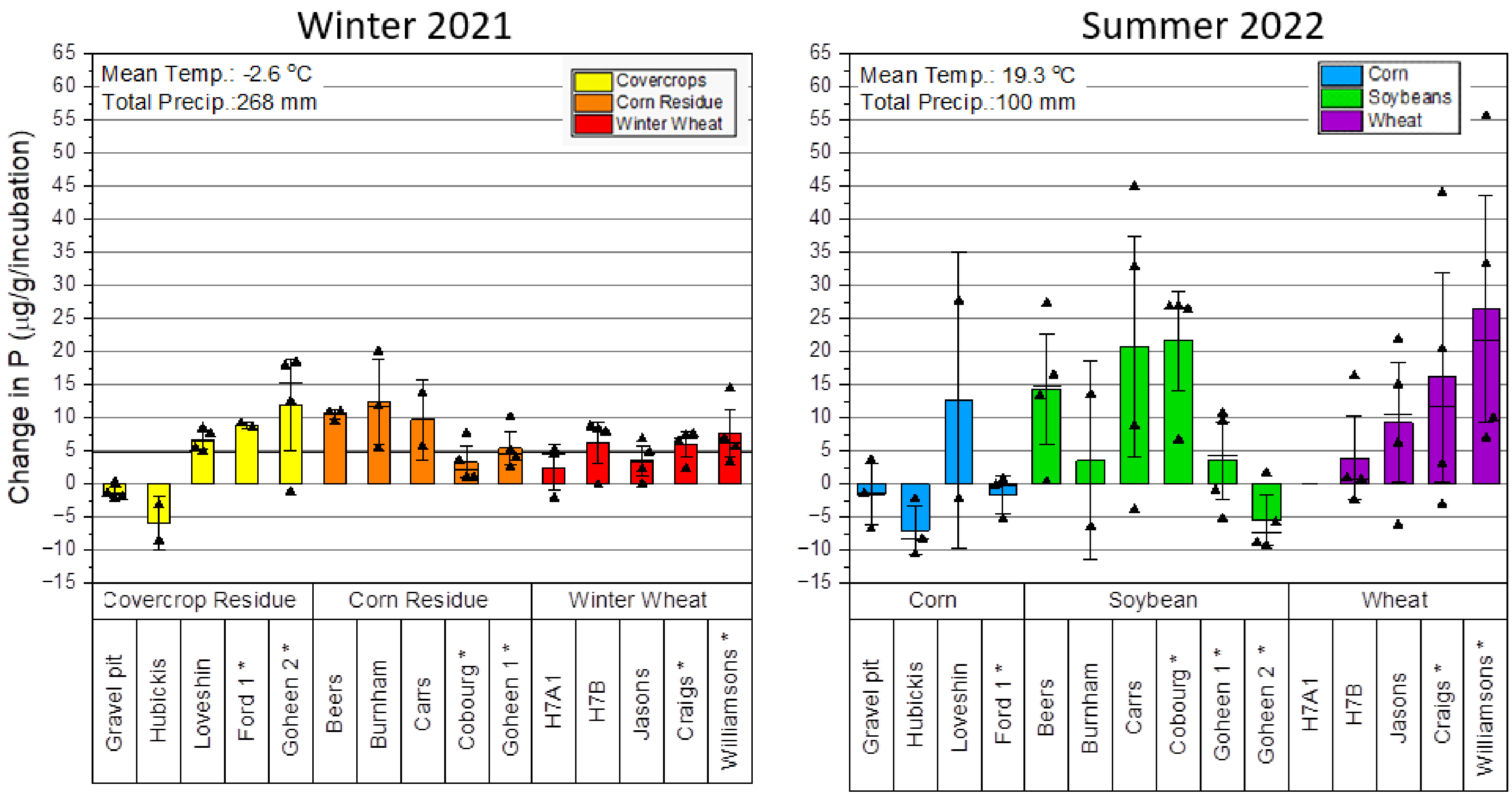

Figure 6-12. Seasonal change in BB P concentrations (Olsen P) under TD and NTD fields for two incubation periods. * Indicate fields that are NTD.

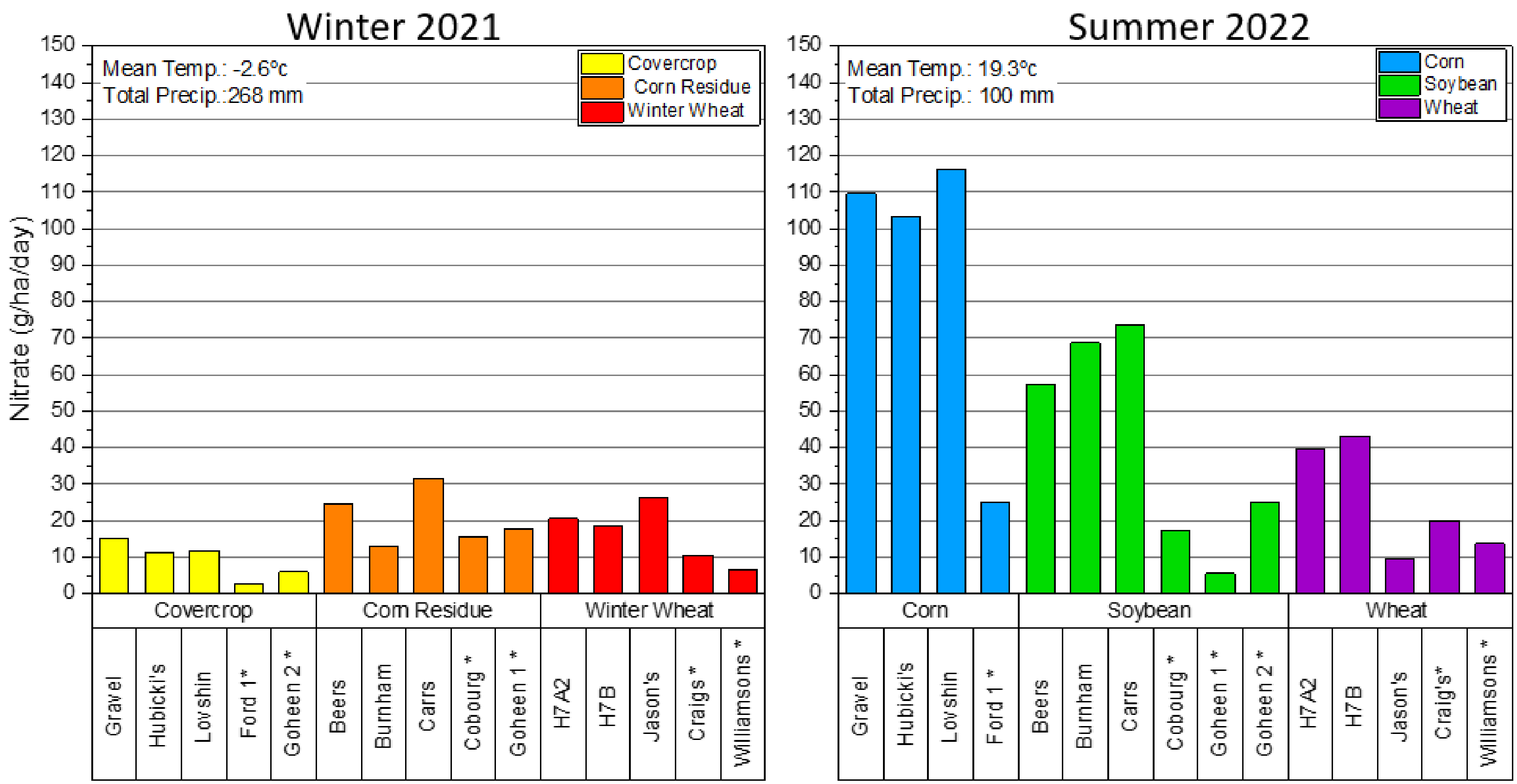

Figure 6-13. Daily PRS probe NO_3-N concentrations at a 15 cm depth below TD and NTD fields for two incubation periods. * Indicate fields that are NTD.

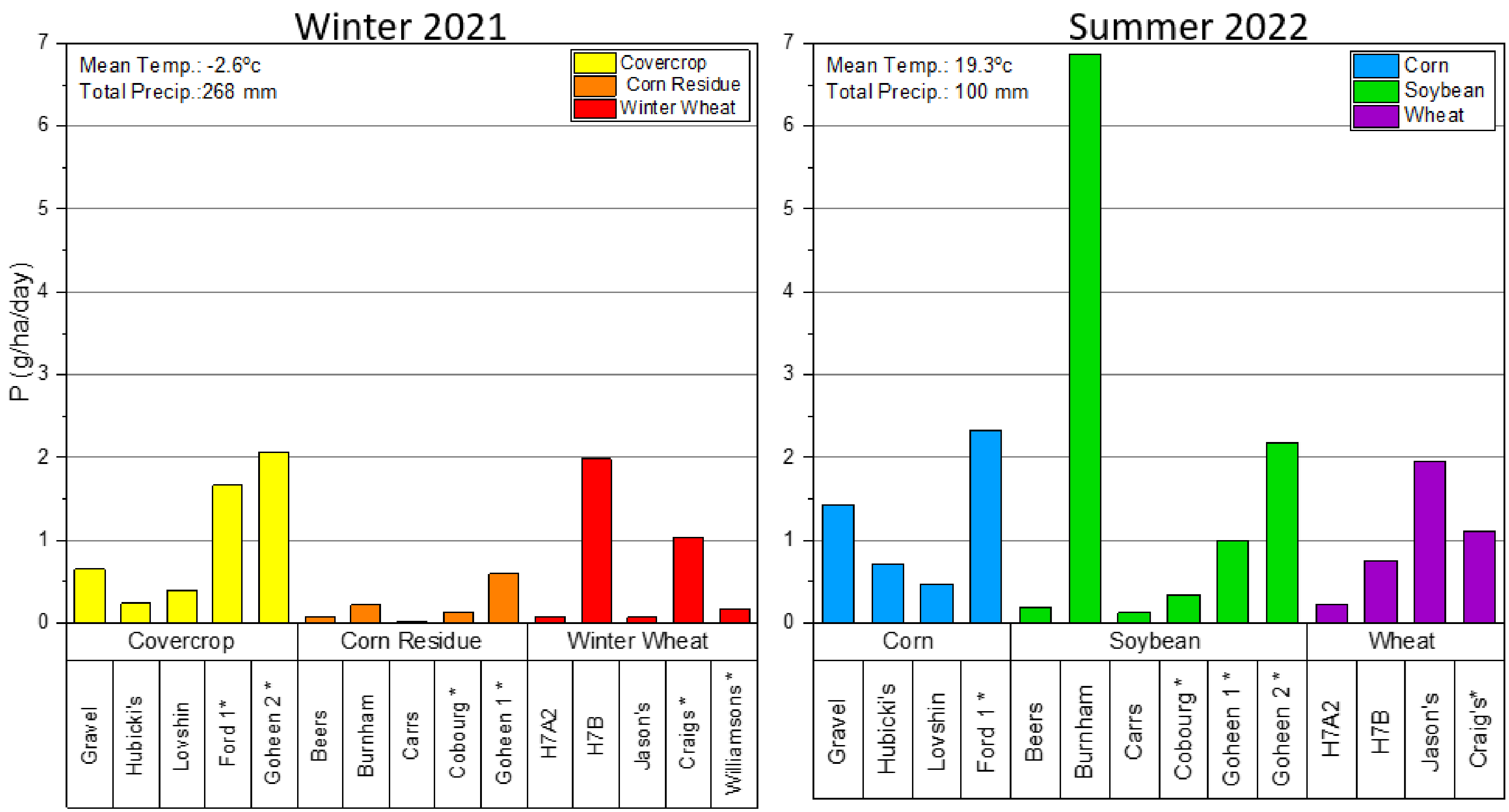

Figure 6-14. Daily PRS probe P concentrations at a 15 cm depth below TD and NTD fields for two incubation periods. * Indicate fields that are NTD.

Appendix E

Table 6-7. Nitrogen fertilizer guidelines are based on spring NO_3-N concentrations used by OMAFRA (OMAFRA et al., 2017).

Spring Nitrate Nitrogen[1] in top 30 cm (1 ft)	Actual Nitrogen Suggestion
1 ppm	211 kg N/ha
2 ppm	199 kg N/ha
3 ppm	186 kg N/ha
4 ppm	173 kg N/ha
5 ppm	161 kg N/ha
6 ppm	148 kg N/ha
7 ppm	135 kg N/ha
8 ppm	123 kg N/ha
9 ppm	110 kg N/ha
10 ppm	97 kg N/ha
11 ppm	85 kg N/ha
12 ppm	72 kg N/ha
13 ppm	59 kg N/ha
14 ppm	47 kg N/ha
15 ppm	34 kg N/ha
16 ppm	21 kg N/ha
17 ppm	9 kg N/ha
18 ppm	0 kg N/ha

Table 6-8. Phosphorus fertilizer guidelines based on HPO_4 (Olsen-P) concentrations used by OMAFRA (OMAFRA et al., 2017).

LEGEND: HR = high response; MR = medium response; LR = low response; RR = rare response; NR = no response

Sodium Bicarbonate Phosphorus Soil Test (ppm)	Phosphate Required
0–3 ppm	110 kg/ha (HR)
4–5 ppm	100 kg/ha (HR)
6–7 ppm	90 kg/ha (HR)
8–9 ppm	70 kg/ha (HR)
10–12 ppm	50 kg/ha (MR)
13–15 ppm	20 kg/ha (MR)
16–20 ppm	20 kg/ha (MR)
21–30 ppm	20 kg/ha (LR)
31–60 ppm	0 (RR)
61 ppm +	0 (NR)[1]