

ORIGINAL RESEARCH ARTICLE

Nitrogen, irrigation, and alley management effects on nitrate leaching from raspberry

Shawn Kuchta¹ | Denise Neilsen¹ | Thomas Forge¹  | Bernie J. Zebarth²  |
Craig Nichol³ 

¹ Summerland Research and Development Centre, Agriculture and Agri-Food Canada, 4200 Highway 97, Summerland, BC V0H 1Z0, Canada

² Fredericton Research and Development Centre, Agriculture and Agri-Food Canada, 850 Lincoln Road, PO Box 20280, Fredericton, NB E3B 4Z7, Canada

³ Univ. of British Columbia Okanagan, 3333 University Way, Kelowna, BC V1V 1V7, Canada

Correspondence

Bernie J. Zebarth, Agriculture and Agri-Food Canada, Fredericton Research and Development Centre, 850 Lincoln Road, PO Box 20280, Fredericton, NB E3B 4Z7, Canada.

Email: Bernie.Zebarth@Canada.ca

Abstract

High NO₃ concentrations in the Abbotsford-Sumas aquifer are linked to raspberry (*Rubus idaeus* L.) production. Passive capillary wick samplers were used to quantify the impacts of N, irrigation, and alley managements on drainage and NO₃ leaching from raspberry rows and alleys over 4 yr. Conventional management (100 kg N ha⁻¹ surface broadcast on the row as a split application, clean cultivation of alleys, and fixed-duration drip irrigation) was compared with different mineral fertilizer N rates, N applied as manure, alleys seeded to a perennial forage grass or an autumn-seeded spring barley (*Hordeum vulgare* L.) crop, or evapotranspiration (ET)-scheduled irrigation. The temporal pattern of drainage and NO₃ leaching was driven by seasonal precipitation and growing season irrigation. Growing season drainage and NO₃ leaching were much lower under ET-scheduled irrigation compared with fixed irrigation. Nitrate leaching was high (up to 90 kg N ha⁻¹), even with no managed N inputs due to high inherent soil fertility and large quantities of N applied in irrigation water. Nitrate leaching was insensitive to N fertilizer rate. Application of N as poultry manure more than doubled NO₃ leaching compared with fertilizer, emphasizing the need to use organic N inputs judiciously. The perennial grass alley cover crop resulted in the greatest overall reduction in NO₃ leaching. Our data indicate that no single management strategy is sufficient to protect groundwater quality. Rather, an integrated package of improved practices (i.e., application of a reduced rate of mineral N through fertigation, combined with ET-scheduled irrigation and perennial alley crop) is necessary to protect groundwater quality.

1 | INTRODUCTION

Groundwater NO₃ contamination is a growing global concern with implications for human, animal, and environmental health (Carpenter et al., 1998; Health Canada, 2017). Unconfined aquifers in regions of intensive agricultural production are particularly susceptible to NO₃

Abbreviations: ASA, Abbotsford-Sumas aquifer; BMP, best management practice; ET, evapotranspiration; PCAPS, passive capillary wick sampler(s).

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. *Vadose Zone Journal* published by Wiley Periodicals, Inc. on behalf of Soil Science Society of America

contamination (Böhlke, 2002; Zebarth, Ryan, Graham, Forge, & Neilsen, 2015). Development and implementation of improved agricultural management practices are necessary to reverse current trends of increasing groundwater NO₃ concentrations (Hansen, Thorling, Dalgaard, & Erlandsen, 2011).

The Abbotsford-Sumas aquifer (ASA) is a 200-km² unconfined sand and gravel aquifer located on the border of British Columbia, Canada, and Washington, USA (Chesnaux, Allen, & Graham, 2007; Liebscher, Hii, & McNaughton, 1992), that supplies drinking water to >100,000 people (Mitchell, Babcock, Gelin, Nanus, & Stasney, 2003). Widespread NO₃ contamination of the ASA has been attributed primarily to intensive agricultural production (Zebarth, Ryan, et al., 2015). Groundwater NO₃ isotope composition (Wassenaar, 1995; Wassenaar, Hendry, & Harrington, 2006) and soil N budgets (Zebarth et al., 1998) suggest that the groundwater NO₃ originated mostly from poultry manure, and to a lesser extent from mineral fertilizer sources, and is primarily associated with red raspberry (*Rubus idaeus* L.) production. Despite the revision of fertility recommendations for raspberry production (British Columbia Ministry of Agriculture and Lands, 2009), recent estimates of NO₃ leaching from commercial raspberry fields and NO₃ concentrations in the ASA remain high (Kuipers, Ryan, & Zebarth, 2014; Malekani et al., 2018). Consequently, there is a need to identify management practices that can reduce NO₃ leaching under raspberry production without compromising productivity.

The potential for NO₃ leaching from the raspberry root zone generally reflects the surplus of N inputs over N removal from the root zone (Zebarth, Ryan, et al., 2015). Important N inputs in fields over the ASA include managed N inputs of mineral fertilizer and in some cases animal manures, as well as nonmanaged inputs including net soil N mineralization, atmospheric N deposition, and N in irrigation water (Kuipers et al., 2014; Zebarth et al., 1998). Previous N budget studies suggest that nonmanaged N sources can be important N inputs in this region (Kuipers et al., 2014; Zebarth et al., 1998). Although significant removal of N from the soil occurs as a result of plant N uptake, the N removal from the field as berries is quite small, and the majority of plant residues are retained in the field and contribute to future net soil N mineralization (Kuipers et al., 2014). There is limited evidence of denitrification in these well-aerated soils (Suchy, Wassenaar, Graham, & Zebarth, 2018), and consequently NO₃ leaching is the primary pathway for N loss from the root zone.

Recommended N inputs for raspberry production in this region range from 0 to 100 kg N ha⁻¹ of plant available N and are commonly applied as mineral fertilizer or poultry manure (British Columbia Ministry of Agriculture, 2018). However, choosing the optimum N rate for rasp-

Core Ideas

- Nitrate leaching from the root zone was high and insensitive to fertilizer N rate.
- Poultry manure greatly increased NO₃ leaching compared with fertilizer.
- ET-scheduled irrigation reduced growing season drainage and NO₃ leaching.
- Perennial grass alley crop reduced NO₃ leaching from the alley.
- An integrated package of improved practices is necessary to reduce leaching.

berry production is difficult due to variability among cultivars, management practices, and inherent site soil fertility (Rempel, Strik, & Righetti, 2004; Strik, 2008). A postharvest test for residual soil NO₃ is often used to determine how well current year N inputs were matched to plant requirements and is an indication of the NO₃ available to be leached during the following winter rainy period (British Columbia Ministry of Agriculture, 2009; Dean, Zebarth, Kowalenko, Paul, & Chipperfield, 2000; Zebarth, Kowalenko, & Harding, 2007). Residual soil NO₃ was greatest in raspberry fields that had received manure applications (Jeffries, Hughes-Games, & Sweeney, 2008; Zebarth et al., 2007) and also generally increased with increasing mineral fertilizer N application rate (Dean et al., 2000; Zebarth et al., 2007). Due to the high inherent soil fertility in this region, high residual NO₃ has been measured in some raspberry fields even when no fertilizer N was applied (Dean et al., 2000; Zebarth et al., 2007). Direct estimates of NO₃ leaching losses under different N rates and N sources (i.e., mineral fertilizer vs. manure) are, however, not available.

Irrigation is required for raspberry production over the ASA (Dale, 1989), which is now delivered mostly through drip irrigation. Growers typically irrigate on a fixed duration and frequency, with variability in irrigation practices among growers being high (Chesnaux & Allen, 2008). Although it had generally been assumed that NO₃ leaching during the growing season was limited due to a water deficit (Zebarth et al., 2007), there is some evidence that drip irrigation contributes to NO₃ leaching under the raspberry row (Loo, Zebarth, Ryan, Forge, & Cey, 2019). Studies across other crops and systems have shown that scheduling irrigation to match plant water demand can reduce water use (Grant, Davies, Longbottom, & Atkinson, 2009; Neilsen & Neilsen, 2002) and may also reduce NO₃ leaching. In addition, delivery of nutrients through the irrigation system (i.e., fertigation) can be timed to meet plant

demand, thereby reducing potential leaching losses (Bar-Yosef, 1999) and minimizing impacts to groundwater. Fertilization has been used to optimize berry yield and quality in raspberry production (Gurovich, 2008).

In raspberry plantings, ~60% of the land area is managed as between-row alleyways and may contribute as much as 60% of the NO_3 leaching (Loo et al., 2019). The appropriate management of these “alleys” is therefore important. Conventionally, clean cultivation (tillage), with no N applied, is used during the growing season to control weeds and facilitate machine access. An alternative management strategy is to seed an annual cover crop (e.g., barley [*Hordeum vulgare* L.]) in autumn to trap residual soil NO_3 in the alleys. Perennial alley crops would be expected to be more effective in trapping soil NO_3 on a year-round basis but may compete with the raspberry crop for water and nutrients (Sanderson & Cutcliffe, 1988; Zebarth, Freyman, & Kowalenko, 1993).

Passive capillary wick samplers (PCAPS) can be used to simultaneously measure water flux and NO_3 leaching from the root zone under a wide range of soil and climatic conditions (Brandi-Dohrn, Dick, Hess, & Selker, 1996; Gee, Ward, Caldwell, & Ritter, 2002). These samplers apply a passive suction to the soil through a wick that acts as a hanging water column to capture water moving through the profile (Boll, Steenhuis, & Selker, 1992; Knutson & Selker, 1994). Using a water balance to compare expected drainage with PCAPS-measured drainage, researchers have found good sampler collection efficiencies and have collected solutes that were largely unaffected (i.e., not altered or adsorbed) by the wicks (Boll et al., 1992; Brandi-Dohrn et al., 1997). This makes PCAPS superior to other sampler types as a means of continuous monitoring of soil solution in unsaturated field conditions (Boll et al., 1992; Gee, Zhang, Ward, & Keller, 2004; Knutson & Selker, 1994; Louie et al., 2000). There is no evidence of significant transformation of NO_3 during transport through the sand and gravel vadose zone in the ASA (Chesnaux et al., 2007); therefore, the drainage and NO_3 leaching collected by PCAPS from the bottom of the root zone, which is close to the interface between the surface soil zone and underlying sand and gravel, can be taken to be an estimate of recharge and of NO_3 loading to groundwater.

The objective of this study was to quantify the effects of different N, irrigation, and alley management strategies on the magnitude and timing of drainage and NO_3 leaching from the root zone in a raspberry planting over the ASA. This was achieved by measuring leachate under the raspberry row and alley using PCAPS over a 4-yr period including the establishment year (April 2009 to March 2010) and three cropping years (April 2010 to March 2013). Leachate NO_3 concentration and NO_3 isotope composition for two treatments on selected sampling dates over a 1-yr period

from this study have been previously reported (Loo et al., 2017).

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted at the Clearbrook Substation of Agriculture and Agri-Food Canada (49°0.702' N, 122°20.097' W), which is located over the ASA, south of Abbotsford, BC, Canada. The loamy soil is well drained and representative of those used for raspberry production in the region. The soils belong to the Marble Hill series and were developed on 20–50 cm of loamy-textured eolian deposits overlying coarse, gravelly glaciofluvial deposits and are classified as Orthic Humo-Ferric Podzols in the Canadian soil classification system (Luttmerding, 1981). The surface soil (0- to 26-cm depth) had soil pH of 6.0 and soil organic matter content of 74 g kg^{-1} . The field site received a poultry manure application in 2001 (estimated rate of 211 kg plant available N ha^{-1}) and was cropped to raspberry from 2001 to 2004. For the 4 yr prior to the current experiment, the field was not cropped and received no managed nutrient inputs.

The site has a temperate maritime climate. Long-term (1981–2010) average annual precipitation at the Abbotsford Airport was 1,538 mm, including 55 mm as snow (Environment and Climate Change Canada, 2018). On average, 70% of total precipitation occurs outside of the April to September crop growing season (Supplemental Table S1). This results in essentially complete leaching of NO_3 from the soil zone over the autumn and winter period, and a water deficit and the need for irrigation during the growing season (Zebarth, Ryan, et al., 2015). In this study, growing season evapotranspiration (ET) averaged 578 mm and average monthly temperatures ranged from 2.9 °C in December to 18.2 °C in August (Supplemental Table S1).

2.2 | Passive capillary wick sampler design and installation

Passive capillary wick samplers were constructed to measure water and NO_3 flux from the bottom of the raspberry root zone. The PCAPS wicks (Intertex Textiles #10, 863KR089, 2.5-cm-diam. medium-density braided fibre-glass rope; Intertex Textiles) had properties matched to the site soil according to Knutson and Selker (1994) and were prepared according to Knutson, Lee, Zhang, and Selker (1993). Each PCAPS lid (60 × 60 cm) was sectioned into four equal quadrants with a hole in the center of each quadrant for a wick. The hanging wick length (40 cm) was

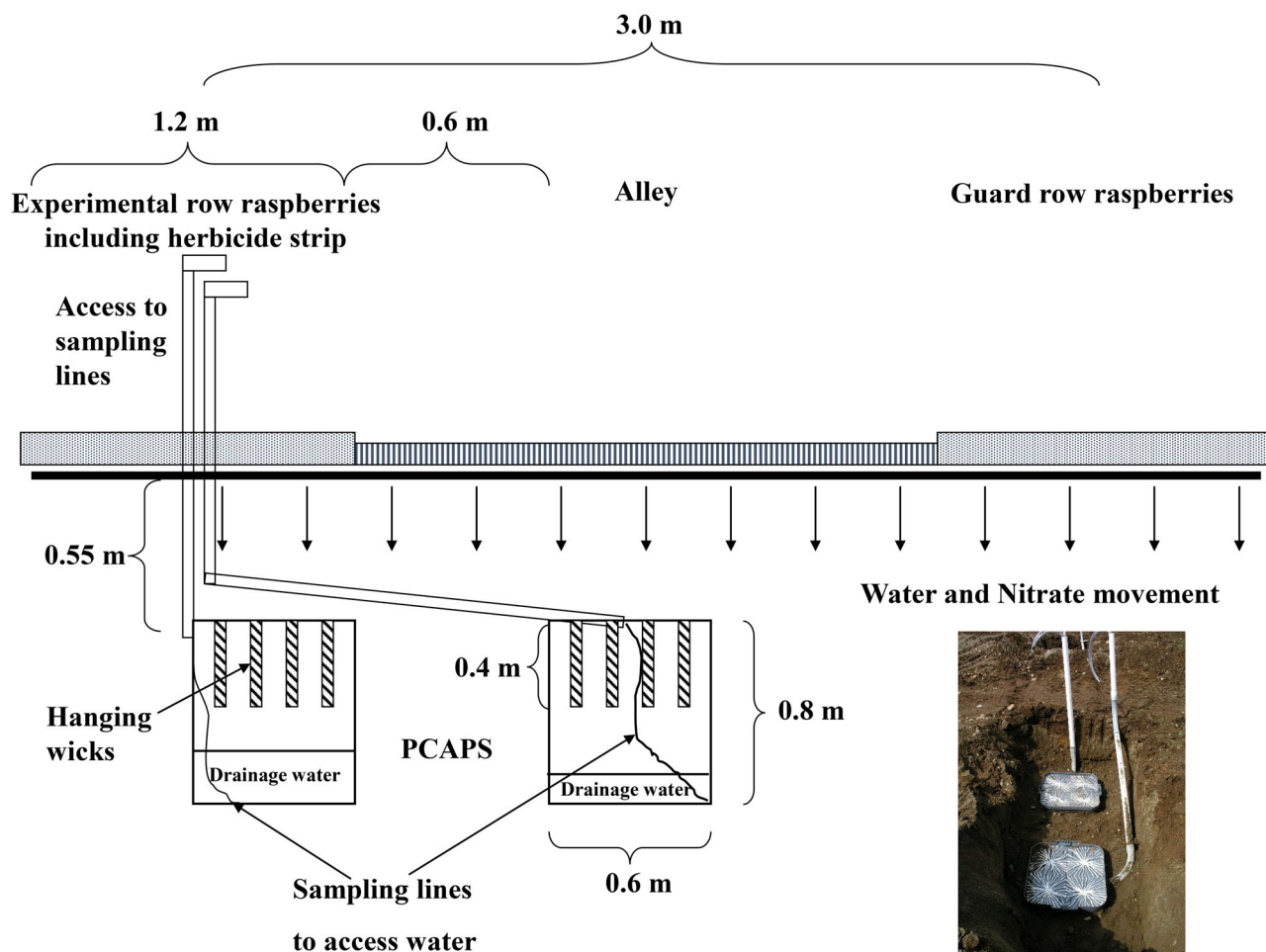


FIGURE 1 Schematic diagram showing the placement of the passive capillary wick samplers (PCAPS) relative to the row and alley and a conceptual drawing of the PCAPS design. Inset photo shows installed PCAPS just prior to burial

passed through the lid leaving the unraveled tails (18 cm long) to be laid flat, evenly spaced within the quadrant, and secured to the PCAPS lid using hot glue. Thus, the lid created a flat, square surface to intercept water flow through the soil profile, which was transported by the wicks into the sampler body for storage. The PCAPS sampler body was a 150-L Rubbermaid Brute #3536 (Rubbermaid Commercial Products) low-density polyethylene container, which was tall enough that large volumes of drainage water could collect without contacting the hanging wicks. Drilled access holes provided passage for vinyl sampling tubes for sample removal that were glued to the bottom corners in each sampler.

Passive capillary wick samplers were buried in excavated holes with the lids at 50- to 55-cm depth, which was considered the bottom of the functional root zone of raspberries, as this was close to the interface between the surface soil and underlying sand and gravel. As a growth inhibitor to invading raspberry plant roots, Biobarrier Root Control System (Reemay) geotextile fabric was cut into strips and

was placed on top of each PCAPS before burying the samplers. Soils were replaced by horizon.

One PCAPS was installed under each of what would be the row and alley in each plot (Figure 1) on 7–11 Apr. 2008. In the row, each PCAPS was placed with one edge under the dripline down the center of the row and the other at 60 cm out from the center of the row (i.e., at the outer edge of the row) such that the PCAPS obtained representative estimates of water and N flux. The PCAPS were also located in the middle of each alley. No data were collected from the PCAPS until the initiation of experimental treatments in spring 2009 to allow the soil to settle.

Annual PCAPS sampler collection efficiency was calculated using a simple water balance to compare expected drainage with PCAPS-measured drainage. Expected PCAPS drainage was calculated as precipitation plus irrigation minus ET_0 , where ET_0 (ET from a grass reference crop; Supplemental Table S1) was obtained from Farmwest (2019). Comparisons were done separately for alley vs. row and for the two different irrigation regimes in each year.

TABLE 1 Nitrogen, irrigation, and alley management treatments, where the N_{100} treatment represents current industry practice

Treatment	Nitrogen ^a kg N ha ⁻¹	Irrigation ^b	Alley
N_0	0	Fixed	Clean cultivated
N_{50}	50	Fixed	Clean cultivated
N_{100}	100	Fixed	Clean cultivated
M_{100}	100 ^c	Fixed	Clean cultivated
A_P	100	Fixed	Perennial grass cover crop
A_B	100	Fixed	Autumn-seeded spring barley cover crop
I_{ET}	100	ET-scheduled	Clean cultivated
$I_{ET}+N_{50F}$	50 ^d	ET-scheduled	Clean cultivated

^aNitrogen applied as a split application of urea (46–0–0 N–P–K) unless otherwise stated.

^bIrrigation regime was fixed duration every 2 d (fixed) or scheduled based on daily evaporative demand (evapotranspiration [ET]-scheduled).

^cNitrogen applied in a single annual application as poultry broiler manure to supply 100 kg plant available N ha⁻¹.

^dNitrogen applied as fertigation using calcium nitrate.

2.3 | Research plot establishment

Roots of ‘Saanich’ raspberry, a florican fruiting red raspberry cultivar, were planted 24 Apr. 2008 to grow into hedgerows with 3-m row spacing. A 0.6-m strip was established on either side of the hedgerow and maintained weed free through repeated applications of herbicide, resulting in a 1.2-m-wide row and a 1.8-m-wide alley (Figure 1). In 2008, prior to the current study, the stand was managed uniformly according to recommended practice (British Columbia Ministry of Agriculture, 2009) and with N fertilizer surface broadcast to all raspberry rows at 100 kg N ha⁻¹ according to grower practice. Irrigation water was supplied from an onsite well and delivered through suspended drip line (30 cm above the soil) down the center of each row and 2 L h⁻¹ pressure compensating drip emitters at standard 46-cm spacing.

2.4 | Experimental design

The experiment used a randomized complete block design with eight treatments (Table 1) and four blocks. The experimental unit was a plot consisting of an 8-m section of raspberry row and the adjacent alley on each side of the row. There were eight contiguous plots in each of four rows, where test rows were separated by guard rows.

Treatments were selected to examine a series of options for N, irrigation, and alley management (Table 1). In this region, a postharvest soil NO₃ test to 30 cm is used to help guide mineral fertilizer N rates for raspberry production (British Columbia Ministry of Agriculture, 2009). Mean soil NO₃ content to 30-cm depth in a composite sample taken on 12 Aug. 2008 was 24 mg N kg⁻¹ dry soil, and based strictly on this analysis, the recommended annual fertil-

izer N rate would have been up to 50 kg N ha⁻¹ (British Columbia Ministry of Agriculture, 2009). However, grower practice for similar plantings in this region would include annual N applications up to 100 kg N ha⁻¹. The fertilizer N rates for the study were therefore chosen to reflect the range of annual N application rates relevant to the region (0–100 kg N ha⁻¹), and for the purpose of this study, we identified 100 kg N ha⁻¹ as the conventional practice. The N_{100} treatment received the rate of 100 kg N ha⁻¹ as a split application of urea, used fixed irrigation application and clean cultivation of alleys, and represented conventional management practices. Note that the fertilizer N rate was 100 kg N ha⁻¹ on a field basis but was applied only on the row, and consequently the effective N rate applied to the row was 250 kg N ha⁻¹. Conventional management was compared with different mineral fertilizer N rates (N_0 and N_{50}), application of N as manure (M_{100}), seeding the alley to either a perennial forage grass (A_P) or an autumn-seeded spring barley crop (A_B), or ET-scheduled irrigation (I_{ET}). The combination of ET-scheduled irrigation plus fertigation of a reduced rate of N ($I_{ET}+N_{50F}$) was compared with conventional practices at the corresponding N rate (N_{50}).

Production, maintenance, and pest management practices in the raspberry stand were standardized across treatments according to recommended practice (British Columbia Ministry of Agriculture, 2009), except as noted below.

2.5 | Nutrient management

All granular fertilizers were surface applied by hand broadcast, spread uniformly over the raspberry row as a split application of urea (46–0–0 N–P–K) in early and late spring each year. Split applications were made 7 wk apart

(April and June) in 2009, and 4 wk apart (current industry practice of April and May) in subsequent years (Supplemental Table S2). Wood shavings-bedded poultry broiler manure was analyzed each year for total N and bulk density, and the required volume of manure to provide 100 kg plant available N ha⁻¹ (following the recommended approach that 33% of the total N was available in the year of application; British Columbia Ministry of Agriculture, 2009) was surface applied each year at the same time as the first mineral fertilizer application. Total N concentrations in the manures were 44, 51, 41, and 33 g N kg⁻¹ dry weight in 2009–2012, respectively. Corresponding estimates of bulk manure applications were 6,887, 5,907, 7,320, and 9,183 Mg dry manure ha⁻¹, respectively. Fertigation of N was achieved by injection of the weekly amount of calcium nitrate (15.5–0–0), dissolved in ~50 L of water, into the irrigation water at a rate of 0.6 L min⁻¹ for 10 min each day using a Jaeco AgriFram (Jaeco Fluid Systems) injection pump. In 2009, fertilizer injection began midway between the two split applications of N as urea; however, for all subsequent years, the beginning of the 6 wk of fertilizer injection was matched with the timing of the first split N application. Annual split applications of P, K, and micronutrients (as 0–20–20 + micros, Evergrow “Post Harvest Blueberry” blend, Terralink Horticulture) were timed with urea applications and hand broadcast over the raspberry row area (British Columbia Ministry of Agriculture, 2009).

2.6 | Irrigation management

Fixed irrigation typically started in mid-June (Supplemental Table S2) in each year to coincide with the initiation of vigorous primocane growth and the reduction of monthly precipitation according to grower practice. Irrigation shutdown typically occurred in late September or early October and coincided with the arrival of fall rains according to grower practice. Overall water demand was lower in 2009 because it was an establishment year for the crop (i.e., no berry-producing floricanes were present). The fixed irrigation regime in 2009 followed grower practice and was applied every second day for 4 h to supply 5.6 mm on a field scale, which corresponds to the equivalent of 14 mm on the raspberry row. Similar irrigation was applied in 2010–2012 except during peak periods when irrigation was increased to 6 h every second day to supply 8.4 mm on a field scale, which was equivalent to 21 mm on the raspberry row. Precipitation was measured onsite using a tipping-bucket rain gauge (Spectrum Technologies). Fixed irrigation was disabled after rainfall events with >15 mm of precipitation to allow the soil adequate time to drain.

The ET-scheduled irrigation regime used a Model E ETgage ET simulator (ETgage Company) to measure daily

evaporative demand. The daily ET accumulated up to midnight each day, minus any effective (>5 mm) precipitation recorded, was used along with a raspberry crop coefficient polynomial for modifying ET_o based on seasonal canopy development (Allen, Pereira, Raes, & Smith, 1998), planted row area, and irrigation specifications to determine next-day irrigation duration. Therefore, the daily ET-scheduled irrigation regime replaced water used or lost by the raspberry system during the previous growing day. Irrigation valve, flow meter, ETgage, and rain gauge control and monitoring was accomplished through connection to a Campbell Scientific datalogger. The dates for ET-scheduled irrigation startup and shutdown were synchronized with those for fixed irrigation (Supplemental Table S2).

2.7 | Alley management

Clean cultivation was achieved by tillage to 25-cm depth with a tractor-mounted roto-tiller for weed control on four dates in each growing season (Supplemental Table S2). The perennial cover seed (Richardson Seed’s “Alleyway” blend, Terralink Horticulture) was a mixture of ‘Keystone 2’ perennial ryegrass (*Lolium perenne* L.) and ‘Bridgeport II’ chewings fescue (*Festuca rubra* ssp. *commutate* Gaudin) and was hand seeded at a rate of 44.4 kg ha⁻¹ on 10 Sept. 2008. The barley cover crop (Terralink’s ‘Common Barley’) was hand seeded at 174 kg ha⁻¹ in 2008 and reseeded each autumn in September (Supplemental Table S2) at the rate of 348 kg ha⁻¹ to ensure growth of a strong stand. If winter kill of the barley was not complete, a routine herbicide application with glyphosate was made in the spring and the stubble was incorporated by roto-tilling. An early winter freeze during the week of 20–27 Nov. 2011 resulted in premature winter kill of the barley cover crop.

2.8 | Sampling and analysis

This study used hydrologic years running from April to the subsequent March (e.g., April 2009 to March 2010) that are named according to the year in which the hydrologic year was initiated. The PCAPS were sampled every 2 wk through two hydrologic seasons each year: the growing season and the rainy season. The growing season in each year was represented by all sampling events from the initial spring nutrient application to the onset of heavy autumn rains, and the remainder of the year is referred to as the rainy season (Supplemental Table S3). On each sampling date, samples were collected using a Welch dry vacuum pump (Model 2585B-50, Gardner Denver Welch Vacuum Technology), total drainage volume was recorded, and a subsample of the leachate was collected in a 250-ml

high-density polyethylene Nalgene sample bottle and frozen until analysis. Irrigation water samples were also taken for analysis on the same 2-wk schedule during the irrigated portions of the growing seasons. The leachate and irrigation water samples were thawed immediately prior to analysis and analyzed colorimetrically using a segmented flow analyzer (SFA, Model 305D, Astoria Pacific International) according to manufacturer's procedures for the determination of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$.

2.9 | Statistical analysis

All data were tested for the assumptions of normality, independence of samples, equality of variance, and linearity of data. A $\log_{10}$ transformation was performed on the PCAPS $\text{NO}_3\text{-N}$ data to normalize it. Analysis of variance was performed using PROC MIXED in SAS (SAS Institute, 2019), with year as a repeated measure, block as a random factor, and treatment as a fixed factor in the model. In almost all cases, there was no significant year $\times$ treatment interaction, with the exception of NO_3 leaching in the alley for the rainy and growing seasons. This interaction primarily reflected the year-to-year variability in the growth of the alley barley cover crop, particularly in response to the premature winter kill of the barley crop in 2011. Consequently, results are presented averaged across all 4 yr. Single-degree-of-freedom contrasts were used to test for the significance ($p < .05$) of effects of linear N rate (N_0 vs. N_{100}), quadratic N rate (N_0 vs. N_{50} vs. N_{100}), N source (M_{100} vs. N_{100}), alley perennial grass cover crop (A_P vs. N_{100}), alley annual barley cover crop (A_B vs. N_{100}), irrigation management (I_{ET} vs. N_{100}), and N application method ($I_{ET}+N_{50F}$ vs. N_{50}) over all the years. The PCAPS data were analyzed separately by row and alley locations. Values presented in tables and figures are means and SEs computed from nontransformed data. The PCAPS data were expressed per hectare of land under a row or alley management basis as appropriate.

3 | RESULTS AND DISCUSSION

Mean monthly air temperature during the 4-yr study was generally similar to the long-term (1981–2010) climate normal during both the April to September crop growing seasons and the October to March rainy seasons (Supplemental Table S1). Precipitation during the growing seasons in 2009 and 2012 was 10–16% below, and in 2010 and 2011 was 16–19% above, the long-term average of 458 mm. Precipitation during the rainy season was 1–16% below the long-term average of 1,081 mm in each hydrologic year.

3.1 | Passive capillary wick sampler collection efficiency

Measured and expected drainage matched well, with annual PCAPS collection efficiencies ranging between 70 and 135%, with a mean of 96%. The PCAPS collection efficiencies in the current study were comparable with those reported previously: 66–80% (Brandi-Dohrn et al., 1996), 70–100% (Gee et al., 2004), 125% (Louie et al., 2000), 101% (Zhu, Fox, & Toth, 2002), and 81% (measured under commercial raspberry production; Loo et al., 2019). Average annual drainage in the nonirrigated alley ranged from 661 to 915 mm, which is consistent with the model estimates of recharge rates for the ASA, which range spatially from 650 to 1,150 mm yr^{-1} (Holländer, Wang, Assefa, & Woodbury, 2016; Scibek & Allen, 2006). The water and NO_3 flux data collected by PCAPS were therefore assumed to be representative of drainage and NO_3 leaching from the experimental site based on the PCAPS placement and on the good collection efficiencies.

3.2 | Drainage

The temporal pattern of drainage within a hydrologic year in the row and alley was driven primarily by the seasonal pattern of precipitation (Supplemental Figures S1 and S2). The temporal pattern of drainage in the row during the growing season was also influenced by irrigation management (Supplemental Figure S1).

Drainage in the row (Table 2) and alley (Table 3) was significantly greater for fixed (N_{100} treatment) than for ET-scheduled irrigation (I_{ET} treatment) during the growing season. This resulted in significantly lower annual drainage in the row, but not the alley. Mean area-weighted (i.e., calculated according to the relative proportion of row and alley area) drainage for the I_{ET} treatment was 60 and 97% of drainage under the N_{100} treatment during the growing season and annually, respectively.

In the growing season, drainage from the nonirrigated alley averaged 103 mm. In comparison, growing season drainage from the row under ET-scheduled irrigation averaged 89 mm. This suggests that the water applied under ET-scheduled irrigation on the row (average of 155 mm irrigation water) resulted in a negligible change in drainage compared with that driven by precipitation alone. In comparison, under fixed irrigation, for which an average of 333 mm irrigation water was applied each year, growing season drainage averaged 320 mm. When comparing fixed irrigation with ET-scheduled irrigation, the increase in drainage was comparable with the increase in irrigation applied under fixed irrigation, which suggests that

TABLE 2 Effect of N, alley, and irrigation management treatments on drainage and NO₃ leaching in the row over the growing, rainy, and annual seasons, 2009–2012

Treatment ^a (2009–2012)	Drainage losses			NO ₃ -N leaching		
	Growing	Rainy	Annual	Growing	Rainy	Annual
	mm			kg N ha ⁻¹		
N ₀	364	667	1,031	51	39	90
N ₅₀	344	731	1,076	57	40	97
N ₁₀₀	296	688	984	46	47	93
M ₁₀₀	518	798	1,317	98	133	231
A _P	308	686	994	51	42	92
A _B	388	755	1,143	60	45	105
I _{ET}	85	661	747	14	70	84
I _{ET} +N _{50F}	92	626	718	20	32	52
Standard error	55	64	109	9	7	13
Contrasts ^b	Significance					
N rate linear	ns [†]	ns	ns	ns	ns	ns
N rate quadratic	ns	ns	ns	ns	ns	ns
N source	***	ns	**	***	***	***
Perennial alley	ns	ns	ns	ns	ns	ns
Barley alley	ns	ns	ns	ns	ns	ns
Irrigation	***	ns	*	***	**	ns
Fertigation	***	ns	**	***	ns	***

^aTreatments described in Table 1.

^bContrasts showed significant effect ($p < .05$) of N rate linear (N₀ vs. N₁₀₀), N rate quadratic (N₀ vs. N₅₀ vs. N₁₀₀), N source (M₁₀₀ vs. N₁₀₀), perennial alley crop (A_P vs. N₁₀₀), barley alley crop (A_B vs. N₁₀₀), irrigation (I_{ET} vs. N₁₀₀), and fertigation (I_{ET}+N_{50F} vs. N₅₀).

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

[†]ns, not significant.

much of the additional water applied under fixed irrigation contributed to drainage. These findings are consistent with previous studies, which demonstrated the potential to use ET-scheduled irrigation to reduce water application by 39–73% in raspberry production (Gurovich, 2008), 22% in highbush blueberry (*Vaccinium corymbosum* L.) production (Keen & Slavich, 2012), and by ~50%, while lowering NO₃ leaching losses, in high-density apple (*Malus pumila* Mill.) production (Neilsen & Neilsen, 2002).

Fertilizer N rate had no significant effect on cumulative drainage from the row or alley as would be expected (Tables 2 and 3). In contrast, drainage for the M₁₀₀ treatment was greater than for the N₁₀₀ treatment, except for drainage from the row in the rainy season. Annual mean area-weighted drainage was 36% greater for the M₁₀₀ treatment than for the N₁₀₀ treatment. Manure-induced changes in drainage may reflect the enhancement of soil biological activity, aggregation, and other pathways such as earthworm channels for preferential flow, as a result of the addition of manure organic matter to the raspberry row.

Alley management had no significant effect on drainage from the row, and cover crops generally increased drainage

from the alley (Tables 2 and 3). Annual mean area-weighted drainage was 25 and 12% greater for the annual (A_B) and perennial (A_P) alley cover crop treatments, respectively, than for the N₁₀₀ treatment. Increased drainage under alley crops is attributed to improved infiltration of water where the alley crop was present to stabilize and protect the soil structure compared with the degradation observed under clean cultivation.

3.3 | Nitrate leaching

3.3.1 | Temporal dynamics of nitrate leaching

Nitrate leaching from the root zone within each year generally followed a similar temporal pattern as drainage losses and was controlled primarily by seasonal precipitation patterns and growing season irrigation inputs (Supplemental Figures S1–S4). There were, however, generally greater differences among treatments in NO₃

TABLE 3 Effect of N, alley, and irrigation management treatments on drainage and NO₃ leaching in the alley over the growing, rainy, and annual seasons, 2009–2012

Treatment ^a (2009–2012)	Drainage losses			NO ₃ -N leaching		
	Growing	Rainy	Annual	Growing	Rainy	Annual
	mm			kg N ha ⁻¹		
N ₀	96	670	766	10	39	50
N ₅₀	93	587	680	8	38	47
N ₁₀₀	76	585	661	9	41	51
M ₁₀₀	124	791	915	19	65	84
A _P	111	706	817	1	4	5
A _B	129	752	881	11	38	48
I _{ET}	109	674	783	13	53	66
I _{ET} +N _{50F}	84	597	681	6	29	34
Standard error	11	75	83	2	5	5
Contrasts ^b	Significance					
N ₀ vs. N ₁₀₀	ns [†]	ns	ns	ns	ns	ns
N ₀ vs. N ₅₀ vs. N ₁₀₀	ns	ns	ns	ns	ns	ns
M ₁₀₀ vs. N ₁₀₀	***	**	***	**	*	**
A _P vs. N ₁₀₀	**	ns	*	***	***	***
A _B vs. N ₁₀₀	***	**	**	ns	*	ns
I _{ET} vs. N ₁₀₀	*	ns	ns	ns	ns	ns
I _{ET} +N _{50F} vs. N ₅₀	ns	ns	ns	ns	ns	ns

^aTreatments described in Table 1.^bContrasts showed significant effect ($p < .05$) of N rate linear (N₀ vs. N₁₀₀), N rate quadratic (N₀ vs. N₅₀ vs. N₁₀₀), N source (M₁₀₀ vs. N₁₀₀), perennial alley crop (A_P vs. N₁₀₀), barley alley crop (A_B vs. N₁₀₀), irrigation (I_{ET} vs. N₁₀₀), and fertigation (I_{ET}+N_{50F} vs. N₅₀).

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

[†]ns, not significant.

leaching than in drainage, which reflects the treatment variation in the soil NO₃ availability. Earlier studies with raspberry production under overhead irrigation had concluded that NO₃ leaching was limited during the growing season, and that essentially complete leaching of NO₃ from the root zone occurred over the rainy autumn and winter period (Kowalenko, 2000). However, in this study, growing season NO₃ leaching in the row under conventional raspberry management (i.e., N₁₀₀) was 49% of annual leaching. Loo et al. (2019) reported an average of 34% of annual NO₃ leaching during the growing season under drip-irrigated raspberry production over the ASA using PCAPS. Differences with the Loo et al. (2019) study may reflect different management practices (e.g., irrigation, N application rates) and site characteristics (e.g., soil properties) compared with this study. Kuipers et al. (2014) measured increased NO₃ loading at the water table below raspberry production over the ASA in August, also consistent with growing season leaching due to irrigation. Collectively, our data and these more recent studies suggest that growing season NO₃ leaching from the root zone may often be greater than expected.

3.3.2 | Nitrate leaching from nonmanaged nitrogen sources

Annual NO₃ leaching from the unfertilized control (N₀) can be used to estimate the NO₃ leaching which results from this production system in the absence of managed (i.e., manure or fertilizer) N inputs. Annual NO₃ leaching averaged over the four years of the study for the N₀ treatment was 90 and 50 kg N ha⁻¹ from the row and alley, respectively (Tables 2 and 3).

The flow- and area-weighted (i.e., row plus alley) mean NO₃ concentration in drainage for the N₀ treatment averaged 7 mg N L⁻¹ (Figure 2). This suggests that in this study, NO₃ concentration in drainage was already close to the Canadian drinking water guideline of 10 mg N L⁻¹ (Health Canada, 2017) in the unfertilized control. This high N loss is somewhat surprising given that this experimental site had no manure application since 2001, and was unplanted and received no nutrient inputs for the four years prior to the raspberry stand establishment. The high NO₃ leaching in the N₀ treatment is consistent with previous evidence of high residual soil NO₃ in some raspberry fields, even when

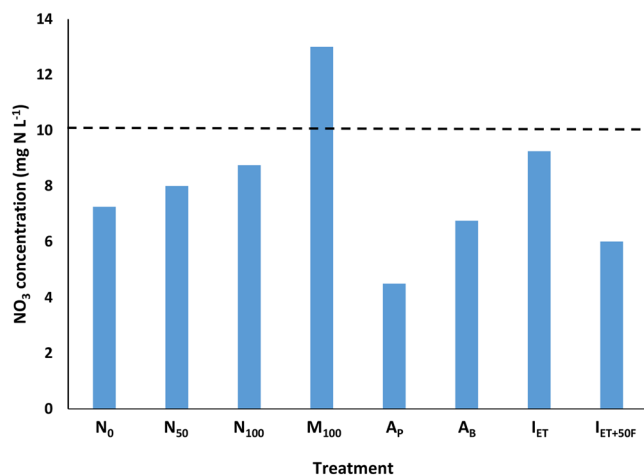


FIGURE 2 Effect of N, alley and irrigation management treatments on flow- and area-weighted NO₃ concentrations in leachate, averaged over 2009–2012. Guideline for Canadian Drinking Water Quality (GCDWQ) for NO₃ identified at 10 mg N L⁻¹ (Health Canada, 2017). See Table 1 for treatment abbreviations

no fertilizer N was applied (Dean et al., 2000; Zebarth et al., 2007). The relatively high NO₃ leaching where no fertilizer was applied primarily reflects two factors: N applied in irrigation water and soil N supply.

The NO₃ concentration in irrigation water collected during 2009–2012 was high, averaging 18.3 mg NO₃-N L⁻¹. Over the study, the calculated N application rates to the row through irrigation water alone were 61 kg N ha⁻¹ under fixed irrigation (including the N₀ treatment) and 28 kg N ha⁻¹ under ET-scheduled irrigation. As a result, the N inputs from irrigation water were relatively large in comparison with fertilizer and manure N inputs. There is a wide range of groundwater nitrate concentrations in the ASA (Zebarth, Ryan, et al., 2015) and this is the source of irrigation water for raspberry producers in the region. Only recently has N in irrigation water been accounted for in nutrient management plans (British Columbia Ministry of Agriculture, 2012, 2018).

Plant uptake in the clean cultivated, non-irrigated alleys was negligible, and therefore the NO₃ leaching losses primarily reflect the soil N supply. The NO₃ lost from all treatments with clean cultivated alleys averaged 63 kg N ha⁻¹ and was derived primarily from net N mineralization of soil organic matter and plant residues. Although there are few measurements of atmospheric deposition in the region of the ASA, atmospheric deposition may also represent an important source of N due to the high density of poultry production in the region (Kuipers et al., 2014; Zebarth et al., 1998). The soil N supply was likely greater in the row than the alley, as the low soil water content in the non-irrigated alley may have reduced net N mineralization (Dessureault-Rompré et al., 2010).

3.3.3 | Effect of fertilizer nitrogen rate on nitrate leaching

There was no effect of fertilizer N rate on mean annual NO₃ leaching in the row or alley (Tables 2 and 3). This suggests that NO₃ leaching is relatively insensitive to variation in fertilizer N rates within the range recommended for raspberry production in the region. The insensitivity of this production system to variation in N fertilization rates is partly due to the fact that N inputs from irrigation water and soil mineralization are large relative to fertilizer inputs; for example the average annual NO₃ leaching from the row in the N₀ treatment over the four year study (90 kg N ha⁻¹) approached the maximum fertilizer N rate applied. Reducing fertilizer N inputs is commonly recommended as a best management practice (BMP) to reduce the risk of NO₃ leaching to sensitive groundwater aquifers (Zebarth, Ryan, et al., 2015; Zebarth, Danielescu, et al., 2015). Our data suggest, however, that improved fertilizer N management alone may not be sufficient to protect groundwater quality in the region because of the large non-managed N sources.

3.3.4 | Effect of manure nitrogen source on nitrate leaching

Application of N as manure (M₁₀₀ treatment) increased annual NO₃ leaching from the row by 148% relative to the N₁₀₀ treatment over the 4-yr study (Table 2). Interestingly, although manure was applied only in the row, NO₃ leaching from the alley was also substantially (65%) greater for the M₁₀₀ than the N₁₀₀ treatment (Table 3). Consequently, the flow- and area-weighted mean NO₃ concentration in drainage for the M₁₀₀ treatment exceeded the Canadian drinking water guideline of 10 mg N L⁻¹ (Figure 2). Annual root zone losses of 231 kg N ha⁻¹ in the M₁₀₀ treatment compare closely with the 240 kg N ha⁻¹ measured by Loo et al. (2019), and the estimated NO₃ loading of 174 kg N ha⁻¹ (Kuipers et al., 2014), both from raspberry fields that had received recent manure inputs. Similarly, Kuipers et al. (2014) combined the estimated N surplus from manure-treated soil and annual recharge to calculate an average concentration of 16 mg N L⁻¹ as NO₃-N in the recharge water, which is very close to the measured 13 mg N L⁻¹ leaving the root zone under manure in the current study.

The increased NO₃ leaching from manure-treated plots likely reflects difficulties in estimating the availability of N in manure in the year of application, and the contribution of manure to N mineralization in subsequent years. Manure N availability varies widely, depending on manure properties, but also environmental conditions at the time of application (Cabrera & Gordillo, 1995). It is possible that

the manure N availability was underestimated, leading to greater than expected N availability in the year of application. Furthermore, this recommended application rate is based only on the expected N availability in the year of application and does not account for the potential for more stable organic N fractions in the manure to contribute to net N mineralization in the future (Klausner, Kanneganti, & Bouldin, 1992). Our data illustrate the difficulties of using raw manure judiciously as a source of N over vulnerable aquifers. One proposed solution for the ASA is to apply only organic amendments in which the N has been stabilized (e.g., compost) (Zebarth, Ryan, et al., 2015).

3.3.5 | Effect of irrigation and fertigation on nitrate leaching

Fixed irrigation (N_{100}) increased NO_3 leaching from the row during the growing season by 32 kg N ha^{-1} averaged over the 4-yr study compared with ET-scheduled (I_{ET}) irrigation (Table 2). This was attributed to both a greater quantity of NO_3 added in irrigation water, as well as greater drainage during the growing season for fixed compared with ET-scheduled irrigation. In contrast, ET-scheduled irrigation increased NO_3 leaching from the row during the rainy season by 23 kg N ha^{-1} compared with fixed irrigation. This likely reflects the greater accumulation of NO_3 in the root zone during the growing season for the ET-scheduled irrigation due to limited drainage, and the subsequent leaching of this NO_3 from the root zone with the onset of heavy autumn rainfall events. When compared on an annual basis, irrigation management alone had no effect on NO_3 leaching from the row or alley.

Evapotranspiration-scheduled irrigation was therefore effective in reducing NO_3 leaching from the row to low (<25 kg N ha^{-1}) quantities during the growing season by limiting drainage losses. However, due to the high inherent fertility in this production system (90 kg N ha^{-1} leached annually from the N_0 treatment) the NO_3 was not used by the raspberry crop, but rather was accumulated in the root zone and subsequently leached in autumn. Previous studies also documented the accumulation of NO_3 in the root zone, and subsequent leaching in autumn, under raspberry production over the ASA (Kuipers et al., 2014). This suggests that although improved irrigation management can reduce growing season NO_3 leaching, improved irrigation practices alone are likely not sufficient to protect groundwater quality in the ASA.

Fertigation in combination with ET-scheduled irrigation decreased NO_3 leaching from the row during the growing season by 37 kg N ha^{-1} compared with the N_{50} treatment (Table 2). As indicated above, this likely reflects

both decreased N addition in irrigation water and reduced drainage during the growing season in the $I_{ET}+N_{50F}$ treatment. However, in this case, NO_3 leaching during the rainy season was not greater for the $I_{ET}+N_{50F}$ treatment than the N_{50} treatment and consequently the $I_{ET}+N_{50F}$ treatment reduced annual NO_3 leaching compared with the N_{50} treatment. This suggests that delivering N to a raspberry crop through fertigation may decrease the risk of leaching and could be an efficient method to deliver N to meet raspberry plant requirements.

3.4 | Alley management

In raspberry production in this region, an autumn-seeded barley cover crop is recommended to protect the soil from erosion and also to scavenge residual soil NO_3 . In this study, any NO_3 taken up by the barley was insufficient to measurably reduce annual NO_3 leaching from the root zone compared with the clean cultivated alleys of the N_{100} treatment (Table 3), and the resulting effect on the flow- and area-weighted NO_3 -N concentration in leachate was minimal.

The perennial forage grass alley crop reduced NO_3 leaching from the alley in the growing seasons by 8 kg N ha^{-1} , in the rainy seasons by 37 kg N ha^{-1} , and on an annual basis by 46 kg N ha^{-1} , compared with the clean cultivated alleys of the N_{100} treatment (Table 3). These reductions in NO_3 leaching occurred despite increased drainage in the growing season and annually in the presence of the perennial cover crop. Therefore, the reduced NO_3 leaching reflects decreased availability of NO_3 in the alley due to N uptake by the forage crop. The resulting flow- and area-weighted NO_3 -N concentration in leachate was 5 mg N L^{-1} (Figure 2), well below the Canadian drinking water guideline of 10 mg N L^{-1} (Health Canada, 2017). The selection of an appropriate cover crop can reduce NO_3 leaching (Brandi-Dohrn et al., 1997; Drury et al., 2014), and the reduction can be as great as 67% (Martinez & Guirard, 1990). In this study, the perennial alley crop, with no other change in nutrient or irrigation management, was found to result in a measurable decrease in leachate NO_3 concentration. The potential implications of plow-down of the forage alley crop when the raspberry stand is renovated are, however, unclear.

4 | CONCLUSIONS

This study quantified the impacts of N (rate, source, and method of application), irrigation, and alley management strategies on drainage and NO_3 leaching under raspberry production over the ASA using PCAPS. The temporal patterns of drainage and NO_3 leaching were driven

primarily by the seasonal pattern of precipitation, and to a lesser extent by irrigation in the row during the growing season. Nitrate leaching was high even with no managed N inputs due to high inherent soil fertility and a large quantity of N applied in irrigation water. Producers in the region should be careful to account for the N inputs made through irrigation and adapt their nutrient management plans accordingly to effectively utilize this source of N. The general insensitivity of NO₃ leaching over the range of fertilizer N likely to be applied suggests that improved fertilizer N practices alone are unlikely to protect groundwater quality. Application of N as poultry manure substantially increased NO₃ leaching and emphasizes the need to use organic N inputs judiciously. Evapotranspiration-scheduled irrigation decreased drainage and, as a result, NO₃ leaching during the growing season relative to fixed irrigation. The use of a perennial grass alley cover crop had the largest overall impact on NO₃ leaching.

There is a need for simple on-farm methods of implementing ET-scheduled irrigation to encourage adoption. The benefits of higher frequency irrigation to maximize the plant availability of water and nutrients, as well as the tolerance of raspberry to deficit irrigation, should also be investigated. Costs and limited understanding of long-term benefits are barriers to the use of stabilized organic amendments, such as composts, in lieu of raw poultry manures, which are available to raspberry producers at negligible cost. Perceived impacts on yield and limited understanding of long-term benefits of improved soil health are barriers to more widespread use of perennial alley cover crops. Future research to address these concerns and facilitate increased utilization of stabilized organic amendments and perennial cover crops could yield significant reductions in NO₃ leaching from raspberry fields and improve overall environmental performance of raspberry production. Our data demonstrate that no single alternative management strategy, but rather an integrated package of improved practices (e.g., application of a reduced rate of mineral N through fertigation in combination with ET-scheduled irrigation and a perennial alley crop), is likely necessary to protect groundwater quality. This integration may be a useful approach in other cropping systems and production regions located over vulnerable groundwater resources.

CONFLICT OF INTEREST

There are no conflicts of interest related to the data presented in this paper.

ACKNOWLEDGMENTS

Funding for this work was provided by Agriculture and Agri-Food Canada. Technical assistance was provided by Natalie Nick, Naomi Hashimoto, and Shaobing Yu.

ORCID

Thomas Forge  <https://orcid.org/0000-0001-5602-4317>

Bernie J. Zebarth  <https://orcid.org/0000-0003-1465-5051>

Craig Nichol  <https://orcid.org/0000-0002-4685-2116>

REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. Rome: FAO.
- Bar-Yosef, B. (1999). Advances in fertigation. *Advances in Agronomy*, 65, 1–77. [https://doi.org/10.1016/S0065-2113\(08\)60910-4](https://doi.org/10.1016/S0065-2113(08)60910-4)
- Böhlke, J.-K. (2002). Groundwater recharge and agricultural contamination. *Hydrogeology Journal*, 10, 153–179. <https://doi.org/10.1007/s10040-001-0183-3>
- Boll, J., Steenhuis, T. S., & Selker, J. S. (1992). Fiberglass wicks for sampling of water and solutes in the vadose zone. *Soil Science Society of America Journal*, 56, 701–707. <https://doi.org/10.2136/sssaj1992.03615995005600030005x>
- Brandi-Dohrn, F. M., Dick, R. P., Hess, M., Kauffman, S. M., Hemphill, D. D., Jr., & Selker, J. S. (1997). Nitrate leaching under a cereal rye cover crop. *Journal of Environmental Quality*, 26, 181–188. <https://doi.org/10.2134/jeq1997.00472425002600010026x>
- Brandi-Dohrn, F. M., Dick, R. P., Hess, M., & Selker, J. S. (1996). Field evaluation of passive capillary samplers. *Soil Science Society of America Journal*, 60, 1705–1713. <https://doi.org/10.2136/sssaj1996.03615995006000060014x>
- British Columbia Ministry of Agriculture and Lands. (2009). *Berry production guide 2009–2010: Beneficial management practices for berry growers in British Columbia*. Victoria, BC, Canada: Lower Mainland Horticulture Improvement Association.
- British Columbia Ministry of Agriculture. (2012). *Berry production guide 2012: Beneficial management practices for berry growers in British Columbia*. Victoria, BC, Canada: Lower Mainland Horticulture Improvement Association.
- British Columbia Ministry of Agriculture. (2018). *Berry production guide 2018: Beneficial management practices for berry growers in British Columbia*. Victoria, BC, Canada: Lower Mainland Horticulture Improvement Association. Retrieved from <https://www2.gov.bc.ca/gov/content/industry/agriservice-bc/production-guides/berries>
- Cabrera, M. L., & Gordillo, R. M. (1995). Nitrogen release from land-applied animal manures. In K. J. Hatcher (Ed.), *Proceedings of the 1995 Georgia Water Resources Conference*. (pp. 175–179). Atlanta: Georgia Institute of Technology.
- Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 8, 559–568. [https://doi.org/10.1890/1051-0761\(1998\)008\[0559:NPOSWW\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2)
- Chesnaux, R., & Allen, D. M. (2008). Simulating nitrate leaching profiles in a highly permeable vadose zone. *Environment Modeling and Assessment*, 13, 527–539. <https://doi.org/10.1007/s10666-007-9116-4>
- Chesnaux, R., Allen, D. M., & Graham, G. (2007). Assessment of the impact of nutrient management practices on nitrate contamination in the Abbotsford-Sumas aquifer. *Environmental Science & Technology*, 41, 7229–7234. <https://doi.org/10.1021/es0704131>

- Dale, A. (1989). Productivity in red raspberries. *Horticultural Reviews*, 11, 185–267. <https://doi.org/10.1002/9781118060841.ch6>
- Dean, D. M., Zebarth, B. J., Kowalenko, C. G., Paul, J. W., & Chipperfield, K. (2000). Poultry manure effects on soil nitrogen processes and nitrogen accumulation in red raspberry. *Canadian Journal of Plant Science*, 80, 849–860. <https://doi.org/10.4141/P99-136>
- Dessureault-Rompré, J., Zebarth, B. J., Georgallas, A., Burton, D. L., Grant, C. A., & Drury, C. F. (2010). Temperature dependence of soil nitrogen mineralization rate: Comparison of mathematical models, reference temperatures and origin of the soils. *Geoderma*, 157, 97–108. <https://doi.org/10.1016/j.geoderma.2011.10.005>
- Drury, C. F., Tan, C. S., Welacky, T. W., Reynolds, W. D., Zhang, T. Q., Oloya, T. O., ... Gaynor, J. D. (2014). Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. *Journal of Environmental Quality*, 43, 587–598. <https://doi.org/10.2134/jeq2012.0495>
- Environment and Climate Change Canada. (2018). *National Climate Data and Information Archive*. Environment and Climate Change Canada. Retrieved from <http://www.climate.weatheroffice.gc.ca/Farmwest>
- Farmwest. (2019). *Evapotranspiration*. Lindell Beach, BC, Canada: Pacific Field Corn Association. Retrieved from <http://farmwest.com/climate/et>
- Gee, G. W., Ward, A. L., Caldwell, T. G., & Ritter, J. C. (2002). A vadose zone water fluxmeter with divergence control. *Water Resources Research*, 38, 161–1617. <https://doi.org/10.1029/2001WR000816>
- Gee, G. W., Zhang, Z. F., Ward, A. L., & Keller, J. M. (2004). *Passive-wick water fluxmeters: Theory and practice*. Paper presented at the 3rd Australian New Zealand Soils Conference, Sydney, NSW, Australia. Retrieved from www.regional.org.au/au/asssi/
- Grant, O. M., Davies, M. J., Longbottom, H., & Atkinson, C. J. (2009). Irrigation scheduling and irrigation systems: Optimising irrigation efficiency for container ornamental shrubs. *Irrigation Science*, 27, 139–153. <https://doi.org/10.1007/s00271-008-0128-x>
- Gurovich, L. A. (2008). A model to define fertigation strategies for raspberries, integrating soil water and nutrient availability to cropping objectives. *Acta Horticulturae*, 777, 411–422. <https://doi.org/10.17660/ActaHortic.2008.777.62>
- Hansen, B., Thorling, L., Dalgaard, T., & Erlandsen, M. (2011). Trend reversal of nitrate in Danish groundwater - A reflection of agricultural practices and nitrogen surpluses since 1950. *Environmental Science & Technology*, 45, 228–234. <https://doi.org/10.1021/es102334u>
- Health Canada. (2017). *Guidelines for Canadian drinking water quality: Summary table*. Ottawa: Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada.
- Holländer, H. M., Wang, Z., Assefa, K. A., & Woodbury, A. D. (2016). Improved recharge estimation from portable, low-cost weather stations. *Groundwater*, 54, 243–254. <https://doi.org/10.1111/gwat.12346>
- Jeffries, M., Hughes-Games, G., & Sweeney, M. (2008). Sustainable nitrogen management in British Columbia raspberry crops. *Acta Horticulturae*, 777, 435–438. <https://doi.org/10.17660/ActaHortic.2008.777.65>
- Keen, B., & Slavich, P. (2012). Comparison of irrigation scheduling strategies for achieving water use efficiency in highbush blueberry. *New Zealand Journal of Crop and Horticultural Science*, 40, 3–20. <https://doi.org/10.1080/01140671.2011.599398>
- Klausner, S. D., Kanneganti, V. R., & Bouldin, D. R. (1992). An approach for estimating a decay series for organic nitrogen in animal manure. *Agronomy Journal*, 86, 897–903. <https://doi.org/10.2134/agronj1994.00021962008600050026x>
- Knutson, J. H., Lee, S. B., Zhang, W. Q., & Selker, J. S. (1993). Fiberglass wick preparation for use in passive capillary wick soil pore-water samplers. *Soil Science Society of America Journal*, 57, 1474–1476. <https://doi.org/10.2136/sssaj1993.03615995005700060013x>
- Knutson, J. H., & Selker, J. S. (1994). Unsaturated hydraulic conductivities of fiberglass wicks and designing capillary wick pore-water samplers. *Soil Science Society of America Journal*, 58, 721–729. <https://doi.org/10.2136/sssaj1994.03615995005800030012x>
- Kowalenko, C. G. (2000). Nitrogen pools and processes in agricultural systems of Coastal British Columbia: A review of published research. *Canadian Journal of Plant Science*, 80, 1–10. <https://doi.org/10.4141/p99-044>
- Kuipers, P. J., Ryan, M. C., & Zebarth, B. J. (2014). Estimating nitrate loading from an intensively managed agricultural field to a shallow unconfined aquifer. *Water Quality Research Journal of Canada*, 49, 10–22. <https://doi.org/10.2166/wqrjc.2013.136>
- Liebscher, H., Hii, B., & McNaughton, D. (1992). *Nitrates and pesticides in the Abbotsford aquifer, southwestern British Columbia*. Environment Canada, Inland Waters Directorate.
- Loo, S. E., Ryan, M. C., Zebarth, B. J., Kuchta, S. H., Neilsen, D., & Mayer, B. (2017). Use of $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ values for nitrate source identification under irrigated crops: A cautionary vadose zone tale. *Journal of Environmental Quality*, 46, 528–536. <https://doi.org/10.2134/jeq2016.08.0294>
- Loo, S. E., Zebarth, B. J., Ryan, M. C., Forge, T. A., & Cey, E. E. (2019). Quantifying nitrate leaching under commercial red raspberries using passive capillary wick samplers. *Vadose Zone Journal*, 18(1). <https://doi.org/10.2136/vzj2018.08.0152>
- Louie, M. J., Shelby, P. M., Smesrud, J. S., Gatchell, L. O., Selker, J. S., & Shelby, R. M. (2000). Field evaluation of passive capillary samplers for estimating groundwater recharge. *Water Resources Research*, 36, 2407–2416. <https://doi.org/10.1029/2000WR900135>
- Luttmerding, H. A. (1981). Description of the soils. In *Soils of the Langley-Vancouver map area* (Vol. 3, pp. 20–204). Kelowna, BC, Canada: Province of British Columbia. Ministry of the Environment.
- Malekani, F., Ryan, M. C., Zebarth, B. J., Loo, S. E., Suchy, M., & Cey, E. E. (2018). A field-scale approach to estimate nitrate loading to groundwater. *Journal of Environmental Quality*, 47, 795–804. <https://doi.org/10.2134/jeq2017.09.0369>
- Martinez, J., & Guirard, G. (1990). A lysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. *European Journal of Soil Science*, 41, 5–16. <https://doi.org/10.1111/j.1365-2389.1990.tb00040.x>
- Mitchell, R. J., Babcock, R. S., Gelinas, S., Nanus, L., & Stasney, D. E. (2003). Nitrate distributions and source identification in the Abbotsford-Sumas aquifer, northwestern Washington State. *Journal of Environmental Quality*, 32, 789–800. <https://doi.org/10.2134/jeq2003.7890>
- Neilsen, D., & Neilsen, G. H. (2002). Efficient use of nitrogen and water in high-density apple orchards. *HortTechnology*, 12, 19–25. <https://doi.org/10.21273/HORTTECH.12.1.19>
- Rempel, H. G., Strik, B. C., & Righetti, T. L. (2004). Uptake, partitioning, and storage of fertilizer nitrogen in red raspberry as affected by rate and timing of application. *Journal of the American Society*

- for *Horticultural Science*, 129, 439–448. <https://doi.org/10.21273/JASHS.129.3.0439>
- Sanderson, K. R., & Cutcliffe, J. A. (1988). Effect of inter-row soil management on growth and yield of red raspberry. *Canadian Journal of Plant Science*, 68, 283–285. <https://doi.org/10.4141/cjps88-035>
- SAS Institute. (2019). *SAS/STAT(R) 9.2 user's guide* (2nd ed.). Cary, NC: SAS Institute. Retrieved from https://support.sas.com/documentation/cdl/en/statug/63033/HTML/default/viewer.htm#glm_toc.htm
- Scibek, J., & Allen, D. M. (2006). Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change. *Global and Planetary Change*, 50, 50–62. <https://doi.org/10.1016/j.gloplacha.2005.10.002>
- Strik, B. C. (2008). A review of nitrogen nutrition of *Rubus*. *Acta Horticulturae*, 777, 403–410. <https://doi.org/10.17660/ActaHortic.2008.777.61>
- Suchy, M., Wassenaar, L. I., Graham, G., & Zebarth, B. J. (2018). High-frequency NO_3^- isotope ($\delta^{15}\text{N}$, $\delta^{18}\text{O}$) patterns in groundwater recharge reveal that short-term changes in land use and precipitation influence nitrate contamination trends. *Hydrology and Earth System Sciences*, 22, 4267–4279. <https://doi.org/10.5194/hess-22-4267-2018>
- Wassenaar, L. I. (1995). Evaluation of the origin and fate of nitrate in the Abbotsford aquifer using the isotopes of ^{15}N and ^{18}O in NO_3^- . *Applied Geochemistry*, 10, 391–405. [https://doi.org/10.1016/0883-2927\(95\)00013-A](https://doi.org/10.1016/0883-2927(95)00013-A)
- Wassenaar, L. I., Hendry, M. J., & Harrington, N. (2006). Decadal geochemical and isotopic trends for nitrate in a transboundary aquifer and implications for agricultural beneficial management practices. *Environmental Science & Technology*, 40, 4626–4632. <https://doi.org/10.1021/es060724w>
- Zebarth, B. J., Danielescu, S., Nyiraneza, J., Ryan, M. C., Jiang, Y., Grimmer, M., & Burton, D. L. (2015b). Controls on nitrate loading and implications for BMPs under intensive potato production systems in Prince Edward Island, Canada. *Groundwater Monitoring and Remediation*, 35, 30–42. <https://doi.org/10.1111/gwmmr.12088>
- Zebarth, B. J., Freyman, S., & Kowalenko, C. G. (1993). Effect of ground covers and tillage between raspberry rows on selected soil physical and chemical parameters and crop response. *Canadian Journal of Soil Science*, 73, 481–488. <https://doi.org/10.4141/cjss93-049>
- Zebarth, B. J., Hii, B., Liebscher, H., Chipperfield, K., Paul, J. W., Grove, G., & Szeto, S. (1998). Agricultural land use practices and nitrate contamination in the Abbotsford aquifer, British Columbia, Canada. *Agriculture, Ecosystems & Environment*, 69, 99–112. [https://doi.org/10.1016/S0167-8809\(98\)00100-5](https://doi.org/10.1016/S0167-8809(98)00100-5)
- Zebarth, B. J., Kowalenko, C. G., & Harding, B. (2007). Soil inorganic nitrogen content and indices of red raspberry yield, vigor, and nitrogen status as affected by rate and source of nitrogen fertilizer. *Communications in Soil Science and Plant Analysis*, 38, 637–660. <https://doi.org/10.1080/00103620701216054>
- Zebarth, B. J., Ryan, M. C., Graham, G., Forge, T. A., & Neilsen, D. (2015). Groundwater monitoring to support development of BMPs for groundwater protection: The Abbotsford-Sumas aquifer case study. *Groundwater Monitoring and Remediation*, 35, 82–96. <https://doi.org/10.1111/gwmmr.12092>
- Zhu, Y., Fox, R. H., & Toth, J. D. (2002). Leachate collection efficiency of zero-tension pan and passive capillary fiberglass wick lysimeters. *Soil Science Society of America Journal*, 66, 37–43. <https://doi.org/10.2136/sssaj2002.3700>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Kuchta S, Neilsen D, Forge T, Zebarth BJ, Nichol C. Nitrogen, irrigation, and alley management effects on nitrate leaching from raspberry. *Vadose Zone J.* 2020;19:e20054. <https://doi.org/10.1002/vzj2.20054>