The effect of nitrogen, water and alley management strategies on nitrate and water loss from the root zone in perennial red raspberry

by

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Abstract

Groundwater nitrate (NO_3^-) contamination is a growing, global concern. The Abbotsford Aquifer is vulnerable to NO_3^- contamination with its high NO_3^- levels, in large part, linked to intensive agriculture, including the production of red raspberry (*Rubus idaeus* L.). This study examined the impacts of nitrogen (N), water and alley management strategies in red raspberry production on NO_3^- and water loss from the root zone using passive capillary wick samplers (PCAPS) during the establishment year and the first cropping year. Irrigation regime had a significant impact on root zone losses, particularly in the second year, when, under fixed duration irrigation, more than 50% of total annual NO_3^- losses occurred during the growing season. Irrigation scheduled according to plant water demand achieved ~50% water savings, maintained adequate soil moisture and retained N in the root zone as plant available. This retention of N did not increase plant N uptake and high NO_3^- losses in response to the onset of fall rains indicated that the N-fertilizer rate of 100 kg N ha^{-1} was in excess of plant requirements. In the mineral fertilizer plots, the recommended post-harvest soil test for NO_3^- did not measure levels that indicated environmental risk, likely due to growing season leaching not accounted for by this test. The experiment was also influenced by N contributions in the irrigation water, which in fixed duration irrigation, were up to 55 kg N ha^{-1}. The use of manure resulted in greater drainage losses, nitrate losses, residual soil NO_3^- and flow-weighted nitrate concentration than mineral fertilizer plots, indicating elevated environmental risk. These effects were compounded by annual manure re-applications. Annual and perennial cover crops grown in the alleys significantly reduced nitrate leaching losses compared to alleys managed by tillage. Delivery of N by a daily fertigation strategy may better match raspberry plant N uptake than two broadcast applications. Overall, plant response to treatments was limited, suggesting that N supplied by soil, water and deposition (together, ecosystem N supply) was meeting plant N requirements and that the alternative management strategies explored are viable options to improve efficiencies in raspberry production while reducing environmental impacts.

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Acknowledgements

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Dedication

Yes, stop and smell the roses, but go even further…bend a knee for a moment.

There, feel the warmth of the sun, the soil moist between your fingers, breathe in the grace of a new day… and be thankful.

I encourage you to stop for a moment. To be still…(Psalm 46:10).

And then remind others to do the same.

Chapter 1: Introduction

An estimated 30% of Earth's freshwater supply exists as groundwater, with 25% of the Canadian population drawing from groundwater to meet their daily needs (Environment Canada, 2012). Groundwater nitrate contamination from land uses including agriculture is thus a growing concern around the globe with implications for human, animal and environmental health as well as the sustainability of agriculture. The demand on groundwater resources will increase as the earth's population continues to grow, necessitating improved understanding of land-use impacts on groundwater and the development of strategies to minimize or mitigate impacts on this precious resource. Similarly, as populations grow, so do the demands for increased productivity of the declining land base in agricultural production and increased productivity often requires increased nutrient inputs. Nitrogen is among one of the most important elements in agricultural systems, pivotal to the production of all crop plants, and required for the survival of all living things (Follett and Delgado, 2002). A surplus of N, defined from the balance between inputs from fertilizers, organic waste products, net atmospheric deposition and fixation and import of animal feed, and the outputs from the export of plant and animal products, is thus one of the best indicators of agricultural impacts on a system (Hansen et al., 2011). While agriculture related nutrient surpluses observed in the 1990's have started to decrease for many of the Organization for Economic Co-operation and Development (OECD) member countries, absolute levels of agricultural nutrient pollution remain significant (Parris, 2011). In terms of groundwater, agriculture is now the major source of pollution across many of the OECD member countries (Parris, 2011).

1.1 Groundwater nitrate and risk

1.1.1 Human and animal health

High concentrations of nitrates and nitrites in groundwater pose a health concern to humans and animals (Brady and Weil, 2008; Health Canada, 1987; Tiedemann, 2007). The toxicity of nitrate is thought to be due to its reduction to nitrite by bacteria in the body (Health Canada, 1987). Methemoglobinemia (also called "blue baby syndrome"), which affects oxygen exchange within the body, is the most common toxic effect resulting from high nitrates in drinking water, particularly in infants and young animals (Beegle et al., 2008; Health Canada, 1987). Nitrate may be converted to N-nitroso compounds which are highly toxic, are identified as carcinogenic in animals and have been linked to reproductive effects from elevated nitrate levels in water consumed during pregnancy (Brady and Weil, 2008; Health Canada, 1987). The maximum allowable concentration for nitrate-nitrogen (NO_3-N) in drinking water has been set by Canada and many countries around the world at 10 mg NO_3-N L^{-1}. In addition to human and animal health, environmental health is jeopardized when nutrient laden groundwater re-enters surface waters, promoting eutrophication and changing the biological and chemical composition of ecosystems (Hansen et al., 2011). The sustainability of all land use activities, including high value agriculture, is at risk when human, animal and environmental health is threatened.

1.1.2 Agricultural impacts: nitrogen and water management

The ammonium form of mineral nitrogen in a well-drained soil is readily converted to nitrate. This highly mobile anion is easily transported through the soil zone by downward water movement from precipitation or irrigation, facilitated by coarse-textured soils and permeable deposits (Follett and Delgado, 2002; Mitchell et al., 2003). In cropping systems, efficient N management seeks to minimize excess N and environmental impact with management decisions around rate, timing of application, N source and method of delivery all affecting N use efficiency (Meisinger et al., 2008). Power and Schepers (1989) identify that in commonly used fertilizer practices only 20-50% of nitrogen that is applied is used by the harvested crop. To minimize excess N and thereby mitigate nitrate contamination one must understand the system and improve management practices over the groundwater recharge area (Follett and Delgado, 2002). This understanding is critical as groundwater nitrate contamination can persist for decades or centuries, even if sources of contamination are eliminated (Follett and Delgado, 2002).

Over-application of manure on agricultural land has been identified as a serious threat to groundwater (Power and Schepers, 1989). However, the potential benefits of regular organic matter addition (such as manure) for long-term sustainability of a production system are numerous. Improvements to soil properties such as increased organic matter content, cation exchange capacity, porosity, infiltration rate and water retention, reduced soil bulk density, as well as improvements in ecosystem parameters such as earthworm populations and improved nutrient cycling by soil flora and fauna are well documented (Brady and Weil, 2008). In the case of manure application, retaining the benefits while mitigating the potential risks to groundwater requires careful management of application rates, methods and timing (Jeffries et al., 2008).

To better match delivery of N to crop demand an increasingly common method of fertilizer application in many crops is by dissolution and then delivery through a drip irrigation system (Haynes, 1985), herein called fertigation. The control of nutrition delivered through micro-irrigation is superior to other methods, allows for precision delivery of N and water to the plant, thereby increasing efficiency and reducing leaching losses and risks to groundwater (Bar-Yosef, 1999; Gärdenäs et al., 2005; Neilsen and Neilsen, 2002; Neilsen et al., 1998; Neilsen et al., 1999). From a production standpoint, fertigation can result in significant fertilizer savings (Haynes, 1985) and benefit crop yield by reducing fluctuations in nutrient concentrations in the soil during the growing season (Bar-Yosef, 1999).

It is well documented that water movement through the soil zone is the primary transport mechanism of dissolved chemicals (Andreini and Steenhuis, 1990) and that nitrate moves freely with percolating water (Andreini and Steenhuis, 1990; Brady and Weil, 2008; Follett and Delgado, 2002; Mulla and Strock, 2008). Research across many crops has identified the intimate link between water and nutrient management (Bar-Yosef, 1999; Neilsen and Neilsen, 2002; Neilsen et al., 2008). Nitrate leaching from agricultural land use can result from drainage losses linked to irrigation management (Mitchell et al., 2003; Mulla and Strock, 2008; Power and Schepers, 1989; Rempel et al., 2004; Tiedemann, 2007; Zebarth et al., 1997; Zebarth et al., 1998). Crucial to efficient irrigation management is the understanding that crop water demand can vary greatly day to day, over a season and with crop growth. When irrigation practices do not respond to these changes in demand, over-irrigation occurs more frequently than when water is supplied to meet plant demand (Annandale et al., 2011; Grant et al., 2009). Greenwood et al. (2010) identified that in full irrigation, where the root zone is maintained near field capacity, water is wasted through root zone drainage and environmental damage from leaching occurs. Neilsen and Neilsen (2002; 2008) reported deep drainage and nitrate leaching in the growing season due to over-supply of water in irrigated apple which increased each year with increased irrigation application. They found that N applied in apple production irrigated under a fixed regime was leached and therefore unavailable to the apple crop (Neilsen et al., 1998). Large amounts of drainage resulting from high irrigation inputs were found to result in the greatest nitrate-N leaching losses from apples planted in orchard-type lysimeter chambers (Stevenson and Neilsen, 1990). Linking drainage and nitrate-N losses are warnings that over-application of water (excessive irrigation) will result in leaching of nutrients such as nitrogen (Annandale et al., 2011; British Columbia Ministry of Agriculture and Lands, 2009), which poses risk to groundwater.

1.2 The Abbotsford Aquifer

The Abbotsford/Sumas Aquifer (herein called the Abbotsford Aquifer) is a 160 km^2 unconfined sand and gravel aquifer located in south-western British Columbia (BC) and north-western

Washington, USA (Chesnaux et al., 2007; Liebscher et al., 1992) (Figure 1.1). This aquifer supplies freshwater to growing populations of approximately 100,000 people in the Abbotsford area and 10,000 people in Washington State (Mitchell et al., 2003). The aquifer is comprised primarily of coarse glacio-fluvial deposits (Luttmerding, 1981) and lacks a protective boundary layer to safeguard it from direct percolation from the overlying soil profile (Liebscher et al., 1992). Groundwater flow in the southern part of the aquifer is generally in a southerly direction with the majority of annual recharge to the aquifer being through high annual precipitation characteristic of the coastal climate in BC (Liebscher et al., 1992). A calculated water budget (not including irrigation inputs) shows approximately 900 mm of annual recharge to the aquifer mostly from precipitation, with a water deficit in the summer months (Zebarth et al., 1998). The soil overlying the aquifer is a silty eolian soil which is productive when fertilized (Luttmerding, 1984), making it well suited for high value crops such as raspberry. The dominant soil series over the aquifer are Abbotsford and Marble Hill (Luttmerding, 1981). It is the combination of the coarse sand and gravel aquifer composition which facilitates migration of nitrate, its lack of a protective boundary layer, high winter precipitation amounts, and intensive agricultural land use that make this aquifer vulnerable to contamination (Hii, 2006; Mitchell et al., 2003). A limited understanding of the effect of land use management strategies over the aquifer on NO_3^- loading to groundwater has exacerbated the problem.

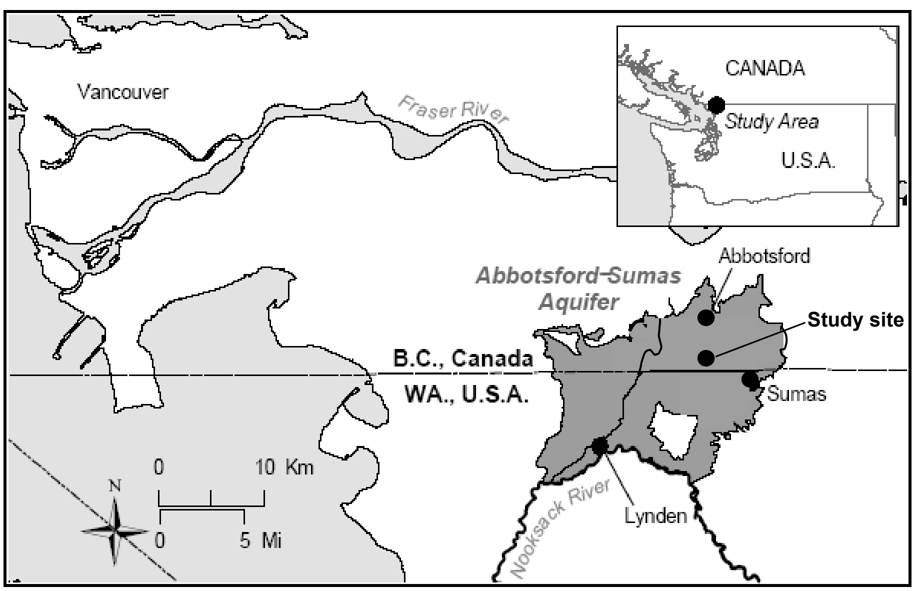

Figure 1.1: Geographical location of the Abbotsford Aquifer (modified from from Graham et al. 2006).

1.3 Land use changes: nitrogen budget and groundwater

Nitrate contamination of the Abbotsford Aquifer is primarily from intensive agricultural land use (Liebscher et al., 1992; Mitchell et al., 2003) and has increased over time in response to intensification of agricultural production (Zebarth et al., 1998). Zebarth et al. (1998) concluded that the 50% increase in surplus N (1971 to 1991) calculated from a simple N budget was due to the changes in agricultural land use rather than an increase in nitrogen inputs. Specifically, dairy and beef operations, whose feed is produced on site in a system that re-uses the animal manures produced, were replaced by poultry production using imported feed and low N removal berry crops such as red raspberry (Tiedemann, 2007; Vizcarra et al., 1997; Zebarth et al., 1998) (Figure 1.2). The intensification of agricultural production in Abbotsford and the resulting increase in N surpluses, the temperate coastal climate, high annual recharge, and the unconfined property of the aquifer, together, pose considerable risk to this groundwater resource.

Figure 1.2: Overhead view of poultry barns amidst berry production in the Abbotsford area.

Nitrate concentrations in the Abbotsford Aquifer have been monitored since the 1970's (Liebscher et al., 1992; Wassenaar, 1995). In a study by Wassenaar (1995), 54% of groundwater monitoring wells were reported to have nitrate-N concentrations greater than the Canadian drinking water guideline of 10 mg NO_3-N L^{-1}. Tiedemann (2007) found average groundwater nitrate concentrations of 14.1 to 15.1 mg NO_3-N L^{-1}, well in excess of the Canadian drinking water guideline, and with a detectable upward trend over time (December 1993 to November 2004). Poultry manure was identified as the primary source of nitrate contamination in the Abbotsford Aquifer in the early 1990's (Wassenaar, 1995; Zebarth et al., 1998). This prompted changes in poultry manure management in the Lower Fraser Valley, including its use in raspberry production. However, any changes to nutrient management practices in Fraser valley raspberry production over the past 20 years have not been accompanied by a decrease in nitrate concentration in the aquifer (Chesnaux et al., 2007; Environment Canada Pacific Yukon Region, 1990-2010; Wassenaar et al., 2006). The trends in the Environment Canada network of monitoring wells currently indicate that average groundwater nitrate concentrations in the Abbotsford Aquifer are generally stable over time and, on average, remain above the national drinking water guideline (Figure 1.3).

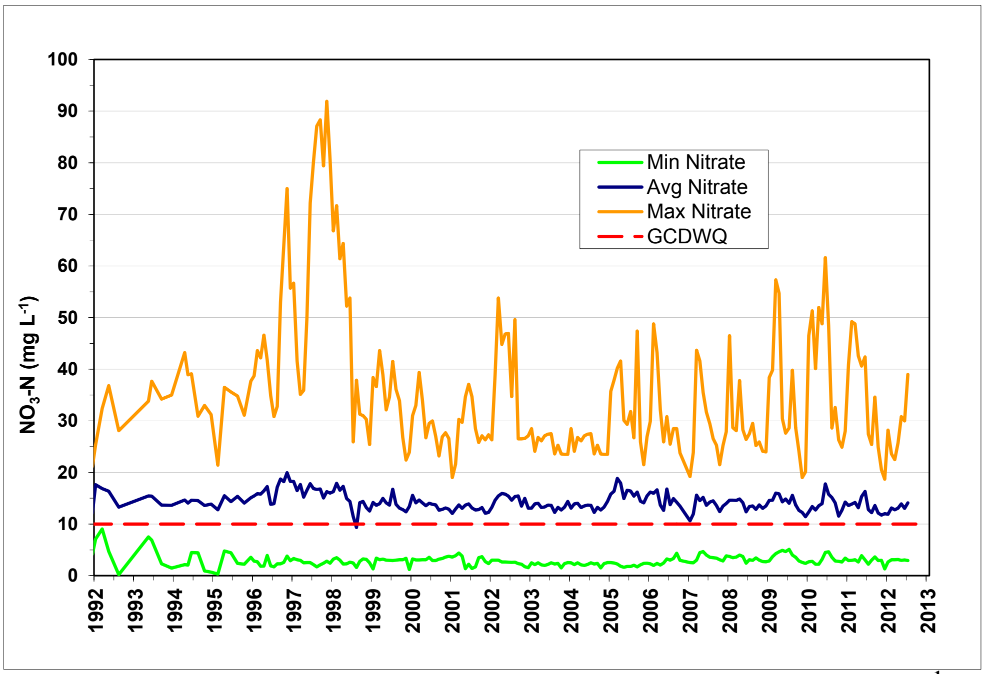

Figure 1.3: Monthly minimum, average and maxiumum nitrate-N levels (mg N L^{-1}) measured in monitoring wells over the Abbotsford Aquifer (1992-present). Guideline for Canadian Drinking Water Quality (GCDWQ) for nitrate-N identified at 10 mg N L^{-1} (Environment Canada Pacific Yukon Region, 2012).

1.4 Management strategies in red raspberry

1.4.1 Raspberry production in general

The Lower Fraser Valley is well suited for perennial red raspberry (*Rubus idaeus* L.) production, owing to its mild climate and well drained soils. It has become one of Canada's main raspberry producing regions with an estimated 1600 ha currently in production, the vast majority of which is located over the Abbotsford aquifer (Mark Sweeney personal communication, 2012; Statistics

Canada, 2011). The management of the raspberry land use system thus has the potential to influence the quality of groundwater in the Abbotsford Aquifer.

Raspberry is a perennial crop, with biennial shoots that are vegetative (primocanes) in the first year and reproductive (floricanes) in the second year. The functional root zone of a raspberry plant, in which the roots forage for water and nutrients to support growth, extends to a depth of approximately 60 cm below the soil's surface (Mark Sweeney personal communication, 2008). The raspberry system is typically managed as groups of floricanes or as solid hedge rows, trained to a post and high tensile wire system. Recommendations regarding nutrient, water, pest, soil and other management practices are available in the current Berry Production Guide provided by the British Columbia Ministry of Agriculture and Lands (British Columbia Ministry of Agriculture and Lands, 2009). Successful raspberry production requires the coordination of several key components including proper nitrogen, water and alley (between row) management to ensure profitable yields of quality fruit while minimizing environmental impacts.

1.4.2 Nitrogen management

Patterns of nitrogen uptake in raspberry vary by cultivar and year to year. In general, floricane uptake of N is rapid in spring and early summer (April to June) with maximum floricane N content occurring June to July (Kowalenko, 1994; Rempel et al., 2004). Rapid uptake of N into primocanes occurs in July and August with maximum primocane N content occurring in late summer or early fall (Kowalenko, 1994; Rempel et al., 2004). Therefore, nitrogen uptake is occurring throughout the growing season. Matching fertilizer N to raspberry plant N requirements is essential for production and decreased environmental risk (Rempel et al., 2004; Strik, 2008; Zebarth et al., 1997) as any amount of N in excess of crop requirements is at risk of being leached (Hughes-Games and Zebarth, 1999; Mitchell et al., 2003; Portela et al., 2006; Zebarth et al., 2007; Zebarth et al., 1997; Zebarth et al., 1998).

Research efforts have been made to determine the optimum N rates for raspberry crops but the perennial nature of the crop, differences among cultivars, inherent site soil fertility, nitrogen cycling within the plant and age of plantings have made this optimum N input level difficult to identify (Rempel et al., 2004; Strik, 2008). Complicating the choice of fertilizer-N application rates is the accurate estimation of N contributions to the system from other sources such as soil N mineralization, N applied in irrigation water and by atmospheric deposition (Zebarth et al., 1997). In addition, a significant challenge in raspberry production in south coastal BC is responsible manure use. Raspberry fields with a history of manure use or regular manure additions have high associated risks for nitrate leaching (Dean et al., 2000; Jeffries et al., 2008; Zebarth et al., 1997; Zebarth et al., 1998). High residual soil nitrate-N concentrations have been linked to a history of manure use in raspberry production by post-harvest soil nitrate-N (0 to 60 cm depth) measured at 225 to 670 kg N ha^{-1} (Zebarth et al., 1997) and 112 to 224 kg N ha^{-1} (Dean et al., 2000). Zebarth et al. (1998) estimated N surplus in manured fields over the Abbotsford Aquifer to be 364 kg N ha^{-1} using a budget approach. Jeffries et al. (2008) reported that in 72% of the fields surveyed that used manure, residual nitrate levels in the top 30 cm of the root zone were found to be greater than 55 ppm (equivalent to approximately 120 kg N ha^{-1}). Over the Abbotsford Aquifer, over-application of N through manure and inorganic fertilizers is known to be a significant contributor to the high nitrate concentrations in the groundwater (Hughes-Games and Zebarth, 1999; Wassenaar, 1995; Wassenaar et al., 2006).

Conventional management in raspberry production applies mineral N fertilizer on the row as a split application with the first application typically in early spring (beginning of April) followed with the second typically by mid-May (British Columbia Ministry of Agriculture and Lands, 2009). The recommended annual application rates of N from all sources range from 0 to 100 kg N ha^{-1} (British Columbia Ministry of Agriculture and Lands, 2009) (Table 1.1) and vary according to soil type, inherent soil fertility, history of organic matter application (e.g. manures), presence of alley cover crops and the results of post-harvest residual soil nitrate-N testing from the previous growing season. Fertigation strategies, though not yet commonplace in BC raspberry production, are used by some producers for smaller, supplementary applications of fertilizer-N. Earlier research has suggested limited usefulness of fertigation for N delivery to raspberry in south coastal BC (Kowalenko et al., 2000) while in raspberry production in other parts of the world, fertigation strategies have proved to be a useful tool in optimizing yield and berry quality (Gurovich, 2008).

1.4.3 Water management

The high amount of precipitation in coastal BC draining through the soil profile ensures that any residual nitrate accumulated in the soil over the growing season is lost through leaching over the rainy season (fall, winter and early spring) (British Columbia Ministry of Agriculture and Lands, 2009; Chesnaux and Allen, 2008; Hughes-Games and Zebarth, 1999; Kowalenko, 1987; Paul and Zebarth, 1997; Zebarth et al., 1997; Zebarth et al., 1998). In raspberry production in the Fraser

Valley no control over natural precipitation can be achieved, while producers can exercise full control over growing season irrigation practices.

The water deficit in the summer months in south coastal BC (Zebarth et al., 1998) means irrigation is required for profitable raspberry production (Dale, 1989). The majority of raspberry production in BC's Fraser Valley has made the transition to high efficiency drip micro-irrigation systems, with some continued overhead gun application for cooling under high temperatures. There is some variability in irrigation system design but growers typically use drip tape suspended on wire down the middle of the raspberry rows with 1.1 L h^{-1} emitters spaced approximately 40 cm apart (Rich Greig personal communication, 2009). Irrigation is applied to raspberry fields typically between June and September in response to the water deficit, with durations and frequencies fixed by each individual grower by the soil "feel method" (in-field observation and hand-texturing methods) and according to past experience. For this reason, variability in irrigation practices among growers is high (Chesnaux and Allen, 2008) making "conventional" irrigation practice difficult to define. In a typical fixed irrigation regime, watering durations may range between four to eight hours at each application with frequencies of daily or every second day (Mark Sweeney personal communication, 2009). Fixed irrigation is usually increased to match the peak demand time on either side of and during raspberry harvest, and is then tapered off at the end of the growing season as fall rains approach. Outside of this adjustment at peak demand, fixed irrigation is usually altered only in response to significant precipitation events (as determined by the individual grower, but typically precipitation > 25 mm). The BC Trickle Irrigation Manual identifies the annual water requirement for a drip irrigation system on a coarse soil in Abbotsford as 300 mm of water (Van der Gulik, 1999).

There is limited information on nitrate leaching losses from the root zone of raspberry over the growing season with some evidence from soil sampling of limited downward movement of nitrate, indicating leaching may be due to drainage stimulated by irrigation inputs (Mitchell et al., 2003; Mulla and Strock, 2008; Power and Schepers, 1989; Rempel et al., 2004; Tiedemann, 2007; Zebarth et al., 1997; Zebarth et al., 1998). The conventional fixed method of irrigating in raspberries, which is not based on quantitative measures of crop water demand or monitored by soil moisture sensors to provide feedback on irrigation practices, may increase N leaching potential. Good stewardship of water resources necessitates improving irrigation efficiency in agriculture (Greenwood et al., 2010; Jones, 2004) and one such improvement is the use of evapotranspiration based scheduled irrigation that incorporates data and information on climate, crop and field site to match water delivery to plant water demand. Studies across a variety of crops and management systems have shown that irrigation scheduling provided a means to increase water use efficiency and promote water conservation (Ganjegunte et al., 2012; Grant et al., 2009; Neilsen and Neilsen, 2002; Neilsen et al., 1998). Scheduled irrigation, which calculates expected plant water use, may be an alternative to fixed irrigation and a means to improve irrigation practices in BC raspberry production.

1.4.4 Alley management

In order to accommodate machine access to raspberry plantings, raspberry rows are widely spaced, leaving approximately 60% of the total land area to be managed as between row alleyways. The proper management of this relatively large area between rows is therefore an important consideration in the raspberry land use system. Conventionally, clean cultivation (tillage), with no N applied, is used throughout the growing season to maintain a weed and plant free alley and facilitate machine access. Tillage has some benefits including improved soil aeration, soil drying and weed control, but over the long-term destroys soil structure and causes compaction (Bowen and Freyman, 1995), impedes infiltration of water (Addiscott, 2000) and stimulates N mineralization by hastening microbial decomposition of organic matter (Brady and Weil, 2008; Power and Schepers, 1989). Addiscott (2000) identified that a large proportion of the N in a system is lost through mineralization, which is stimulated by tillage. Tillage of the fertile soils of the Lower Fraser Valley, including those between raspberry rows, has the potential to contribute N-leaching losses to the aquifer.

An alternative management strategy which is increasingly being adopted by the raspberry industry is the planting of alley cover crops. Cover crops preserve soil structure, including macropores and preferential flow pathways, all of which are involved in promoting infiltration and percolation through the soil zone (Brady and Weil, 2008). They provide some weed and pest control, promote some beneficial insects, improve field access by encouraging drainage, help aerate the root zone, reduce erosion (water and wind) and leave plant material in place for the interception of water and nutrients (British Columbia Ministry of Agriculture and Lands, 2009). Cover crops, often spring cereals, planted in the alleys following harvest, forage for N and have the potential to reduce nitrate leaching (Brandi-Dohrn et al., 1997; Power and Schepers, 1989; Rasse et al., 2000). Jeffries et al. (2008) indicated that a spring cereal planted in the alley after raspberry harvest can take up as much as 75 kg N ha^{-1}. In another study, winter rye decreased nitrate leaching over three years by 32-42% (Brandi-Dohrn et al., 1997) and by 67% compared to fallow land in a crop rotation trial (Martinez and Guirard, 1990). Grass cover was found by Stevenson and Neilsen (1990) to be the factor with the largest influence on the retention of N in the root zone of apples planted in a lysimeter system. As the land area in the alleys in raspberry production is significant, the influence of the management of these alleys can significantly impact nitrate and water movement through the soil profile and towards the aquifer.

1.5 Soil zone and plant measures

1.5.1 Soil zone monitoring

1.5.1.1 Root zone leachate monitoring

Considerable efforts have been made to monitor for nitrates in the saturated zone of the aquifer but linking water quality deep in the saturated zone to non-point sources of contamination from surface land use, such as the intensive agricultural production of raspberries, is challenging. Very little work has been done in the vadose zone directly below the functional root zone of raspberry plantings linking surface management strategies to potential nitrate loading to the aquifer. A means to accurately measure and sample unsaturated flow is required to accomplish this.

Passive capillary wick samplers have shown promise compared to other vadose zone samplers in their ability to more accurately measure total flux (volume) of soil water moving through a given area of unsaturated soil as well as enabling collection of soil water samples for quantitative measurements of soil water constituents. These samplers apply a controlled passive suction to the soil through a wick that acts as a hanging water column, typically a saturated length of fibreglass rope, to capture water moving through the profile (Boll et al., 1992; Knutson and Selker, 1996). Researchers have successfully used PCAPS to provide a continuous monitoring of the soil solution in unsaturated field conditions, deeming PCAPS superior to other sampler types (Boll et al., 1992; Gee et al., 2004; Holder et al., 1991; Knutson and Selker, 1994; Louie et al., 2000). Based on simulations by Gee et al. (2004), drainage in coarse soils (such as those in Abbotsford) can be easily monitored using wick samplers under flux rates of 1 to 10,000 mm year^{-1}. In addition to more accurate measures of drainage quantity, researchers found that solute breakthrough was largely unaffected by the wicks because constituents within the leachate were not significantly altered or adsorbed by the wicking material (Boll et al., 1992; Brandi-Dohrn et al., 1997; Holder et al., 1991; Knutson et al., 1994; Poletika et al., 1992). This allows sampling for a variety of solutes, including nitrate, making PCAPS a valuable tool for collecting soil solution and assessing nitrate losses (Brahy et al., 2002).

In raspberry production, it is valuable to monitor the impacts on root zone losses from inputs such as nutrient and irrigation applications, and other management activities, such as tillage or cover crop production in the alley, over time and as a function of root zone transport processes. Drainage and nitrate losses can be summarized over defined sampling intervals or time periods, for example, seasonally or annually. Monitoring the timing of root zone losses can be useful to identify the most effective periods in which to undertake or alter specific management strategies to maximize production efficiency and minimize losses.

Dissolved nitrate is carried downwards by infiltrating water, and therefore, monitoring losses over time is complemented by plots of flow-weighted nitrate concentration (total mass of nitrate divided by total volume of drainage water) against cumulative drainage losses, also known as a (solute) breakthrough curve, which tracks the progress of nitrate movement through the root zone as a function of drainage volume (Figure 1.4). If solute movement through the soil zone is by classical soil transport mechanisms described by Richards equation and the advection dispersion equation, then the breakthrough curve takes on a Gaussian form and peaks at approximately one pore volume of drainage water. This is the amount of water contained within the volume of soil between the input and the depth of monitoring and can be estimated from the mean volumetric water content of the soil multiplied by that given soil volume. It is the cumulative drainage amount required to replace the resident soil water, and therefore, under ideal circumstances, represents the mean velocity of the soil water at which the center of mass of the solute could be expected to progress.

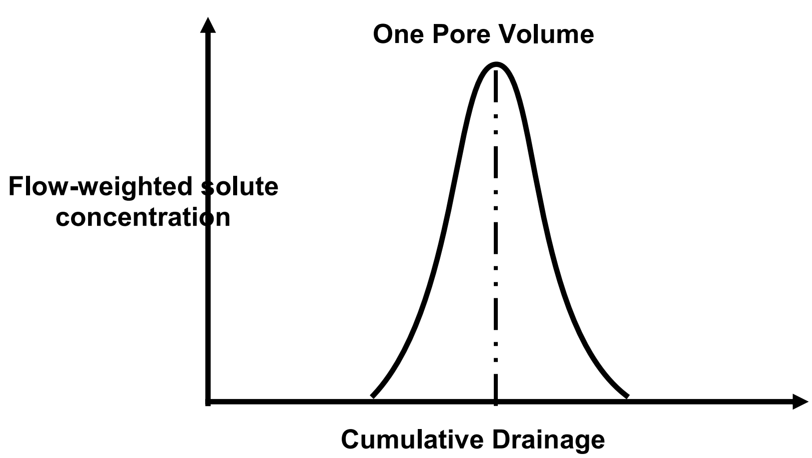

Figure 1.4: Solute breakthrough curve observed at a fixed observation depth.

Some of the nitrate mass will move faster than the average soil water velocity, and some will move slower, due to chemical diffusion and mechanical dispersion. The result is a broadening of the peak on the breakthrough curve that is a function of the range of velocities at which water carrying the solute moves through the soil matrix (Andreini and Steenhuis, 1990) to the PCAP sampler. Several mechanisms can lead to variations from the simple description of transport described above. Additional peaks on a breakthrough curve at cumulative drainage volumes less than or greater than the first pore volume or a significant skew (referred to as tailing) to the breakthrough curve identify other transport processes or mechanisms at work. These may include preferential flow, which carries water (solute laden or fresh) through the soil faster than the average speed of the soil water, down travel paths that bypass the bulk of the soil matrix (such as macropores), or flow that has been retarded (slowed) by longer travel times or pathways through the soil. Preferential flow in the unsaturated zone is the rule, rather than the exception (Flury et al., 1994). The movement of nitrate out of the raspberry root zone is further complicated by processes that can add (e.g. natural mineralization) or remove (e.g. plant uptake) dissolved nitrate, and therefore, nitrate movement out of the root zone as a function of both time and cumulative drainage are important to understanding the leaching losses from this system.

Though many researchers confirm the ability of PCAPS to accurately measure drainage over a range of fluxes (Boll et al., 1992; Brahy et al., 2002; Gee et al., 2002; Gee et al., 2004) other studies warn that unmatched suction in the wick and soil material could lead to unrepresentative sampling of recharge (Brandi-Dohrn et al., 1996a; Holder et al., 1991; Rimmer et al., 1995). Unrepresentative sampling of drainage moving through the root zone could be caused by disturbance to native soil matric suction due to the presence of the PCAP samplers. Differences in soil water potentials between the locations of the samplers, and native soil without samplers, could generate water potential gradients that influence the direction and magnitude of water flow. If soil has a higher water potential at the PCAP, a gradient away from the PCAP exists, which might be evidence that soil water is being under-sampled (divergent flow). Conversely, soil with a lower water potential at the PCAP might indicate oversampling of the soil water (convergent flow). Water potential gradients may be influenced by PCAP instrumentation as well as raspberry management and timing during the season.

Leachate collection efficiency, the ratio of expected collection volume from a water budget (water inputs – water losses) compared to measured collection volume from sampler data, can be used to monitor the accuracy with which a sampler is measuring drainage through the soil zone.

Other researchers have found drainage volumes measured by PCAPS to be significantly correlated to percolation estimated from a water balance (Brandi-Dohrn et al., 1996a; Gee et al., 2004; Louie et al., 2000; Zhu et al., 2002).

1.5.1.2 Soil water monitoring

Quantitative measures of soil moisture are essential as a means to monitor and provide feedback on the soil moisture status effects of managements imposed. A variety of sensors can be used to inform and monitor irrigation scheduling decisions (Ganjegunte et al., 2012). Volumetric water content of a soil can be inferred by sensors which monitor a soil's dielectric constant as a function of its water content. The tension with which water is held by soil, or soil water potential, can be measured by tensiometers or other soil water potential sensors and used to infer soil-water availability to plants. In raspberry production, irrigation management should be evaluated by systematic monitoring of soil moisture to ensure that it has been maintained at levels which provide available water to plants throughout the growing season.

1.5.1.3 Soil sampling

A variety of soil sampling strategies in the raspberry production system have been used to quantify the amount of residual N in the soil zone over time and in response to various management strategies. The sampling time that receives the most attention by producers is the post-harvest soil test taken between the middle of August and the middle of September each year. In this test, soil is sampled in the center of the raspberry row and in the center of the fertilizer strip over the 0 to 30 cm depth increment. A composite sample is formed from multiple locations across the field and tested for soil nitrate-N concentration. This test for residual (i.e., post - harvest) soil nitrate can serve as a "report card" for determining how well current year N inputs were matched to plant requirements, thereby guiding next season's fertilizer application rates (British Columbia Ministry of Agriculture and Lands, 2009; Dean et al., 2000; Hughes-Games and Zebarth, 1999; Zebarth et al., 1997) (Table 1.1). Some research indicates that many raspberry growers are producing in an environmentally sound manner and are not leaving significant amounts (more than approximately 70 kg N ha^{-1}) of residual soil nitrate (as determined by the post-harvest soil test) at risk of being leached (Jeffries et al., 2008). However, in other research, residual soil nitrate levels determined by post-harvest soil testing and the high groundwater nitrate concentrations in the Abbotsford Aquifer suggest that many raspberry fields have excess nitrogen due to application rates beyond plant requirements (Dean et al., 2000; Zebarth et al., 1997, 1998 and 2007).

Table 1.1: Post-harvest soil nitrate-N concentrations (0 to 30 cm) in raspberry production and their interpretation, assessment of leaching risk and recommended subsequent N application rates for the following growing season (British Columbia Ministry of Agriculture and Lands, 2009; Hughes-Games and Zebarth, 1999).

Post-harvest nitrate-N concentration 0 to 30 cm (kg N ha^{-1})	Interpretation	Discussion and following year N rate recommendations (N from all sources)
More than 120	High to very high soil N	-significant risk of nitrate leaching. Fertilizer and manure applications are well in excess of crop requirement. -nitrogen application (all sources) 0-25 kg N ha^{-1}.
75 to 120	Low to moderate soil N	-some risk of nitrate leaching. Fertilizer and manure applications are above crop requirement. -nitrogen application (all sources) 25-50 kg N ha^{-1}.
Less than 75	Low to very low soil N	-minimal risk to the environment from nitrate leaching. -nitrogen application (all sources) 50-100 kg N ha^{-1}.

1.5.2 Plant response

The impacts of management strategies on raspberry plant performance can be measured through plant nutrient status (N content in raspberry plant components, such as leaf or cane tissue), growth and vigour (cane diameter and length) as well as yield. Previous research in raspberry indicates minimal and inconsistent plant response to imposed N-fertility treatments. Over a single year, increasing N fertilizer rates increased crop N status in less than half of trials conducted by Zebarth et al. (2007) in the Lower Fraser Valley, with little effect on vigour or yield indices, while a trend toward lower yields was observed over two years where no N had been applied (Rempel et al., 2004) and small yield increases measured over four years as N rate increased (Kowalenko, 1981). Fertigation strategies in raspberry over a five year period were found to benefit yield (Gurovich, 2008) and, in apple, reduce fertilizer-N inputs without effect on plant N status (Neilsen et al., 1999) while Kowalenko et al. (2000) found no benefit to plant performance from fertigation. Similarly, the reported effects on raspberry plant performance when cover crops are grown in the alleys are mixed and depend on the choice and management of the cover crop. A review of early work on irrigation scheduling strategies, over a wide range of crops, identified significant water savings without impacting yield (Annandale et al., 2011).

1.6 Research objective

The objective of this study was to quantify the effects of different nitrogen, water and alley management strategies on the magnitude and timing of nitrate and water loss from the root zone, and on crop performance, in perennial red raspberry. A planting of 'Saanich' red raspberry (*Rubus idaeus* L.) was established in a soil that was representative of that used for berry production over the aquifer, and N, water and alley management treatments were replicated in a randomized complete block design within this planting. The objective was achieved by measuring leachate, collected by passive capillary wick samplers designed to measure total water and nitrogen flux exiting the functional root zone and through soil instrumentation and soil and plant sampling strategies. The reporting period included the establishment year (2009-2010) and the first production year (2010-2011).

Chapter 2: Materials and methods

2.1 Experimental design

An experiment in 'Saanich' red raspberry (*Rubus idaeus* L.) was established in a randomized complete block design with eight treatments (Table 2.1) and four replications (blocks) to test the management effects of interest. Mean soil NO_3-N content to 30 cm was measured to be 24 mg N kg^{-1} dry soil in a composite sample taken on August 12, 2008. Based on this, and in consultation with scientists, berry specialists and the BC Berry Production Guide (British Columbia Ministry of Agriculture and Lands, 2009) the experimental site was identified as a low-fertility site that would require annual N applications of 100 kg N ha^{-1} to replicate industry practice in a similar field. The effects of N rate were investigated through applications of 0, 50 and 100 kg N ha^{-1}. The 0N treatment allowed assessment of ecosystem N supply from soil N mineralization, atmospheric deposition and irrigation water. The Fertigated + Scheduled treatment (N rate of 50 kg N ha^{-1}) investigated the ability of six weeks of daily fertigation to better match N supply to plant N requirements. Poultry broiler manure was applied to deliver 100 kg plant-available nitrogen (PAN) ha^{-1}, assuming 33% of total N was available in the year of application (British Columbia Ministry of Agriculture and Lands, 2009), to investigate the effect of N source and compare manure (organic) and fertilizer (inorganic) N sources at the same rate. The effects of irrigation type were compared through fixed and scheduled irrigation. The effects of perennial (grass) and annual (fall seeded spring barley) cover crops planted in the alley were compared to standard clean cultivation (tillage).

Table 2.1: Nitrogen, irrigation and alley management treatments in the Saanich raspberry trial.

Treatment	Description	Nitrogen[a] kg N ha^{-1}	Irrigation[b]	Alley[c]
1	0N	0	Fixed	Clean cultivated
2	50N	50	Fixed	Clean cultivated
3	100N[d]	100	Fixed	Clean cultivated
4	Manure	100[e]	Fixed	Clean cultivated
5	Perennial cover	100	Fixed	Perennial cover crop
6	Barley cover	100	Fixed	Barley cover crop
7	Scheduled	100	Scheduled	Clean cultivated
8	Fertigated + Scheduled	50[f]	Scheduled	Clean cultivated

[a]Nitrogen applied as a split application of urea (46-0-0) unless otherwise stated
[b]Irrigation regime determined by replicating irrigation practices of leading berry producers in the region (Fixed) or scheduled based on daily evaporative demand as determined by atmometer-measured evapotranspiration (Scheduled)
[c]Alley clean cultivated, planted with perennial grass cover or fall seeded with barley
[d]Treatment 3, 100N, is current industry practice for nitrogen, irrigation and alley management
[e]Nitrogen applied in a single annual application as poultry broiler manure to supply 100 kg PAN ha^{-1} in the year of application, assuming 33% of total N was available in the year of application.
[f]Nitrogen applied as dissolved calcium nitrate through 10 minutes daily fertilizer injection through irrigation line

2.2 Study site

The Clearbrook Substation of Agriculture and Agri-Food Canada is located at 510 Clearbrook Rd., Abbotsford, BC (Lat. 49° 0.702' N and Long. 122° 20.097'W) in the Fraser Valley and is located over the unconfined Abbotsford Aquifer. It is surrounded by a mixture of agricultural, industrial and municipal lands. The 1971-2000 average annual precipitation measured at the Abbotsford Airport Environment Canada Weather station nearby was 1573 mm, most of which fell as rain between October and April each winter (Environment Canada, 2011). Average monthly temperatures over the same period ranged from a daily minimum of -0.6 ºC in January to a daily maximum of 23.8 ºC in August (Environment Canada, 2011).

Based on the Canadian soil classification system, soils at the experimental site belong to the Marble Hill series and are classified as Orthic Humo-Ferric Podzols and were developed on 20 to 50 cm of medium-textured eolian deposits overlying coarse, gravelly glaciofluvial deposits (Luttmerding, 1981). The soils are well drained and productive for most agricultural crops.

2.2.1 Plot history

Field history was researched prior to the establishment of the current research trial (Table 2.2). For the four years prior to the establishment of the current research trial the field was unplanted and received no managed nutrient inputs.

Table 2.2: Research plot history, Clearbrook Substation (Chaim Kempler personal communication, 2007).

Year(s)	Details
1986-1994	Research field left unplanted prior to incorporation into Agriculture and Agri-Food Canada's Berry Breeding Program
1995-1998	Strawberry production managed under BC Production Guide[a] practices
1998 - 2000	Field left unplanted
2001	In preparation for raspberry planting, poultry manure (broiler) incorporated into the soil at an estimated rate of 211 kg plant available nitrogen ha^{-1}.
2001 - 2004	Raspberry production managed under BC Production Guide[a] practices
2004 - 2008	Field left unplanted
2008 - present	Current research trial in raspberry production

[a]Industry management practices as per BC Berry Production Guide practices at the time

2.2.2 Soil properties

Soil profiles (Figure 2.1) were characterized prior to establishing the research plots using samples from two 0.75 m deep soil pits dug in different locations in the field.

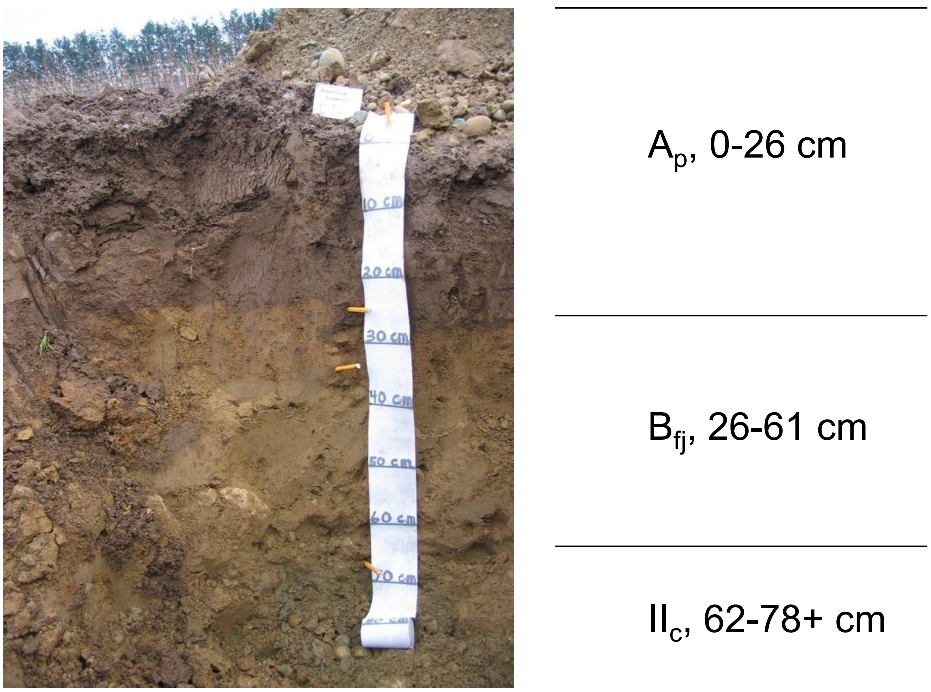

Figure 2.1: Soil profile with horizons identified, Clearbrook Substation.

Basic soil properties tests (dry bulk density (BD), soil pH and electroconductivity (EC), soil organic matter (OM) content and hand texturing) were carried out on all horizons (Table 2.3).

Table 2.3: General soil properties and soil characterization in research field.

Horizon	Depth (cm)	Dry BD[a] ($g\ cm^{-3}$)	pH[b]	EC[b] ($mS\ cm^{-1}$)	OM[c] (%)	Texture
A_p	0-26	1.18	6.0	0.13	7.4	Loam
B_{fj}	26-61	1.27	6.2	0.042	3.2	Loam
II_c	62-78+	1.80	6.3	0.030	1.3	Sand to gravelly sand

[a]using brass cores ~137 cm^3
[b]pH and EC determined on 1:2 by mass soil to water extract
[c]loss on ignition

2.3 Research plot establishment

2.3.1 Planting and field layout

'Saanich', a floricane fruiting red raspberry cultivar developed by the breeding program at the Pacific Agri-Food Research Centre of Agriculture and Agri-Food Canada (Agassiz, BC) was planted on April 24, 2008. An aliquot of roots was spread evenly in a planting trench 10-15 cm deep along the length of each of four 64 m rows. These four experimental rows were managed as hedge rows and were separated from each other by guard rows of mixed varieties of raspberry cultivars used by the PARC Berry Breeding Program (Figure 2.2).

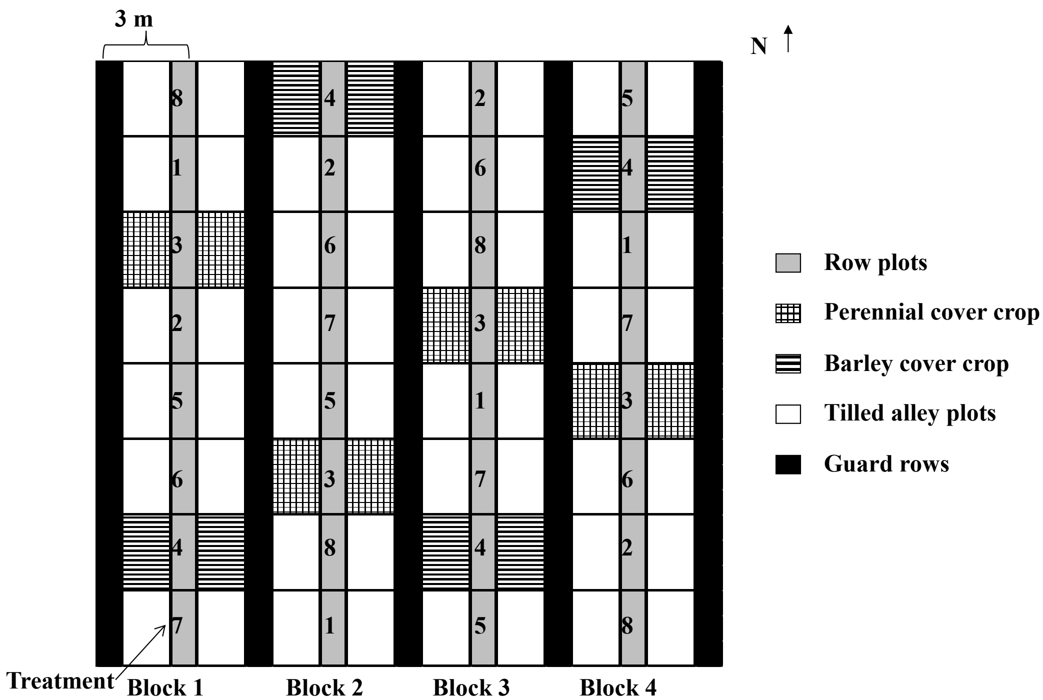

Figure 2.2: Experimental plot layout.

The distance between the centers of adjacent rows was 3 m which was in accordance with industry practice to allow adequate space for machine access (tractors, rototillers, spray equipment) through the alleys. Posts and high tensile wires were installed according to industry practice to provide structure for the raspberry system and its plant training, irrigation and management requirements (Figure 2.3). The experimental unit was a plot, which was the combination of an 8 m long by 1.2 m wide section of row management (with the raspberry hedge row centered on the 1.2 m width) and the two 8 m long by 1.8 m wide alleys managed (the same) on either side.

Figure 2.3: Posts and wires installed for raspberry management requirements.

2.3.2 Irrigation design

Irrigation water was supplied from an on-site well and delivered through a drip micro-irrigation system that employed irrigation control valves, polyvinyl chloride (PVC) header lines, 25 mm flexible polyethylene drip line and 2 L h^{-1} Toro pressure compensating drip emitters. A polyethylene drip line with emitters installed at standard 46 cm spacing was suspended on a high tensile support wire running down the center of each raspberry row at a height of 30 cm above the soil surface.

2.3.3 Crop establishment year

The 2008 growing season was used to establish a healthy, uniform hedge row by following BC Berry Production Guide (British Columbia Ministry of Agriculture and Lands, 2009) practices for crop, nutrient, soil, and pest management. All plots received an industry standard spring application of 18-9-9 + micronutrients fertilizer ('Standard Blueberry Blend', Table 2.4, Terralink Horticulture Inc., Abbotsford, BC) to supply 100 kg N ha^{-1} over the row area.

Table 2.4: Nutrient analysis of 'Standard Blueberry Blend' applied to all plots in 2008.

Guaranteed minimum analysis	%
Total Nitrogen (N)	18
Available Phosphoric Acid (P_2O_5)	9
Soluble Potash (K_2O)	9
Sulphur (S)	12
Magnesium (Mg)	4
Boron (B)	0.2
Zinc (Zn)	0.2

Irrigation during the 2008 growing season was delivered as required by manually turning on irrigation valves and applying uniform irrigation to all plots. The newly planted crop was maintained with a well-watered status over the 2008 growing season, as determined by field observation of soil moisture content on the row. All alleys were clean cultivated to provide weed control as required.

2.4 Treatments imposed

2.4.1 Nutrient management

All granular fertilizer applications and manure applications were accomplished by hand-broadcasting the nutrient source uniformly over the 8 m x 1.2 m raspberry row area in each plot. All applications were surface applied and poultry manure was spread with light raking. In 2009 and 2010, nitrogen was applied as a split application of urea (46-0-0) in early and late spring to achieve application rate targets and timings (Table 2.5). In 2009, the split applications were made seven weeks apart which was reduced to four weeks in 2010 to more accurately reproduce current industry practice. The required application volume of poultry manure for each plot was determined following annual laboratory analysis of fresh poultry broiler manure for total N and bulk density and assumed that 33% of the total N was available in the year of application (British Columbia Ministry of Agriculture and Lands, 2009). In 2009, broiler manure % N as wet weight was 3.3% and required an application of 68 L wet manure per plot to achieve 100 kg PAN ha^{-1} in the year of application. In 2010, broiler manure % N as wet weight was 4.0% and required an application of 63 L wet manure per plot. Treatment 8 (Fertigated + Scheduled) N applications were delivered as dissolved calcium nitrate ($Ca(NO_3)_2$) by injection through the irrigation line. The weekly amount of $Ca(NO_3)_2$ (516 g) was dissolved in approximately 50 L of water. This solution was then injected directly into the irrigation line at a rate of 0.6 L $minute^{-1}$ for 10 minutes each day and delivered to all the fertigated plots (four total) using irrigation water as the carrier. In the 2009 growing season, fertilizer injection began mid-way between the two split applications; however, in 2010, the beginning of the six weeks of fertilizer injection was matched with the timing of the first split N application. Injection into the irrigation line was accomplished using a Jaeco AgriFram (Jaeco Fluid Systems, Malvern, PA) injection pump. A Campbell Scientific CR10X datalogger (Campbell Scientific Corp., Edmonton, AB) was used to control the daily fertilizer injection cycle.

Annual split applications of P, K and micronutrients (as 0-20-20 + micros, Evergrow 'Post harvest blueberry' blend, Terralink Horticulture Inc., Abbotsford, BC) were hand-broadcast over the 8 m x 1.2 m raspberry row area in each plot to meet crop requirements as identified in the BC Berry Production Guide (British Columbia Ministry of Agriculture and Lands, 2009).

Table 2.5: Nutrient application information, 2009 and 2010.

Nutrient source, rate	Treatment(s)	2009 application dates		2010 application dates	
0-20-20 + micros[a]	All	May 5	June 2	April 6	May 6
46-0-0, 100N[b]	3, 5, 6 and 7	April 9	June 2	April 6	May 6
46-0-0, 50N[c]	2	April 9	June 2	April 6	May 6
Manure, 100N[d]	4	April 9		April 6	
15.5-0-0, 50N[e]	8	May 13 to June 21		April 6 to May 25	

[a]All experimental plots received 300 g 0-20-20 + micronutrients blend applied on the raspberry row
[b]261 g plot^{-1} urea at each application date
[c]130 g plot^{-1} urea at each application date
[d]Nitrogen applied in single annual application as poultry broiler manure based on manure analysis and assuming 33% of the total N was available in the year of application
[e]For each of 6 weeks, 516 g plot^{-1} calcium nitrate was dissolved in water and delivered by 10 minutes daily fertilizer injection through the irrigation line

2.4.2 Irrigation management

The dates for regular irrigation start up and shutdown were chosen based on general observations of plant physiological stage, climate, soil moisture status and in consultation with leading raspberry producers in the Abbotsford area. In 2008, the same amount of irrigation was applied to all experimental plots and delivered as required. In 2009, the irrigation season began June 11 and carried through until October 7 and in 2010 began June 14 and ended September 7. Overall water demand was lower in 2009 because it was an establishment year for the crop (no berry-producing floricanes present). The 2009 fixed irrigation regime delivered four hours of water every second day which amounted to 5.6 mm of water applied per field hectare each irrigation cycle. In 2010, the first cropping year, the fixed irrigation regime applied four hours of water every second day which was increased (to replicate current grower practice) to six hours every second day at peak demand times. At peak demand in 2010, 8.4 mm of water per field hectare was delivered during each irrigation cycle. Following grower practice, fixed irrigation was disabled for one or two cycles after significant rainfall events.

The scheduled irrigation regime used a Model E ETgage evapotranspiration simulator (ETgage Co., Loveland, CO) with a #54 canvas cover (designed for agricultural crops) to measure daily evaporative demand in millimetres. The ETgage atmometer was installed at the south end of the experimental plots according to manufacturer's specifications. The daily ET accumulated up to midnight each day minus any effective precipitation (precipitation > 5 mm) was used in combination with a daily raspberry crop coefficient calculation, crop specifications (maturity and planted area factors) and irrigation design specifications (flow rate factor) to calculate a required irrigation duration for the coming growing day. The daily scheduled irrigation regime was thus a precision replacement of water used/lost by the raspberry system during the previous growing day. Irrigation control and monitoring was accomplished using a Campbell Scientific CR10X datalogger interfaced to the appropriate peripheral devices.

2.4.3 Alley management

On September 10, 2008 Treatment 5 and 6 alleys were tilled in preparation for the perennial grass mix and barley cover crop seeding. The perennial cover seed (Richardson Seed's 'Alleyway blend', Terralink Horticulture Inc., Abbotsford, BC) was a mixture of 'Keystone 2' perennial ryegrass and 'Bridgeport II' chewings fescue. The perennial cover was hand seeded at a rate of 44.4 kg ha^{-1}. The barley cover crop (Terralink's 'Common Barley') was hand seeded at 174 kg ha^{-1}. The barley cover was re-seeded at rates of 348 kg ha^{-1} on September 3, 2009 and September 7, 2010.

Ideally, the annual barley cover provides its management benefits in fall and early winter and then suffers over-winter kill. Winter kill was not complete in spring 2009 and 2010 and the barley required a routine spring herbicide application with glyphosate. The barley cover crop stubble was left in place in the alley in 2009 until re-seeding in the fall. Following spring herbicide application in 2010, the barley stubble was incorporated by roto-tilling. An early winter freeze the week of November 20-27, 2011 resulted in premature winter kill of the barley cover crop.

In the remaining alleys, tillage to a 25 cm depth with a tractor-mounted roto-tiller occurred on April 13, May 20, June 30 and August 20 in 2009 and March 31, May 14, August 17 and September 11 in 2010.

2.4.4 Additional management practices

Production, maintenance and pest management activities in the raspberry planting were standardized across treatments according to the BC Berry Production Guide (British Columbia Ministry of Agriculture and Lands, 2009). In 2010, plots were pruned to a common density of 48 canes per plot but in 2011 all viable canes were retained. Cane prunings each year were left in the alleys and mowed in the spring to facilitate breakdown and return of the organic matter to the raspberry system. Primocane growth was not suppressed in this experiment.

2.5 Instrumentation

2.5.1 PCAP design and installation

Passive capillary wick samplers were custom designed to intercept water and N moving past the raspberry crop and beyond the raspberry plant's functional root zone.

2.5.1.1 Sampler design and construction

The PCAPS sampled pore water using the capillary potential of fibreglass wicks (Knutson and Selker, 1994) to exert passive suction on the soil at the top of the PCAP instrument. The sampling suctions of the wicks were matched to the soil into which the PCAP samplers were installed using Knutson and Selker's (1994) wick matching protocol which accounted for properties and derived parameters of both the wick material and the soil in the plots over a range of fluxes. The hanging wick length for the samplers was determined to be 40 cm. The wick construction material was Intertex Textiles #10 – 863KR089 2.5 cm diameter medium density braided fibreglass rope (Intertex Textiles Inc., Oakville, ON).

The fibreglass rope was cut into pieces and the outer casing removed to expose and unravel the inner strands of fibreglass. This was followed by a trimming of both the intact rope and unravelled strands to their target lengths. The wicks were placed in a muffle furnace at 400 °C for four hours to clean them of any impurities (Knutson et al., 1994).

Each PCAP lid (60 cm x 60 cm) was sectioned into four equal quadrants. A 3.2 cm diameter hole at the center of each quadrant was drilled to accommodate a single wick. The hanging length was passed through the lid leaving the unravelled tails to be laid flat, evenly spaced within the quadrant. The end of each tail strand was secured to the PCAP lid using a hot glue gun. Each completed PCAP lid held four wicks (Figure 2.4).

a) b)

Figure 2.4: a) Top view of PCAP lid with wick tails secured. b) Hanging wick lengths inside the sampler collection vessel with internal support pipe.

The PCAP sampler consisted of a large 150 L Rubbermaid © Brute #3536 (Rubbermaid Commercial Products, Mississauga, ON) low density polyethylene collection vessel and lid with dimensions 0.8 m x 0.6 m x 0.6 m and 3.7 mm wall thickness. The collection vessel was tall enough that large collection volumes could accumulate and the full wick length would not contact the drainage water. The container was fitted inside with a 15 cm diameter PVC support pipe placed in the center to help support the PCAP lid under the weight of the soil overhead once buried. The collection vessel lid was sealed upside down to the container body with bolts in the corners and gasket material between the lid and container body. The upside down lid provided a continuous 3.8 cm lip around the top of the sampler. Holes were drilled through the walls of the collection vessel through which two 1.3 cm and two 0.5 cm diameter vinyl sampling tubes were passed and glued to the bottom of adjacent corners in each sampler. The sampling lines allowed sampling from the soil surface and were housed in PVC conduit (Figure 2.5).

Figure 2.5: PCAP samplers and sample line conduit assemblies.

2.5.1.2 Sampler installation

In the experimental field, 32 large holes (2.2 m long x 0.9 m wide x 1.3 m deep) were excavated by soil horizon with a backhoe. Each excavation was designed to house a pair of PCAP samplers, one which was located with its inside edge directly under the drip line centered on the raspberry row management system (Row PCAP) and the other under the associated alley management (Alley PCAP) (Figure 2.6). The target horizon for the soil/wick interface was the B_{fj} whose horizon midpoint (based on soil pits) was located at a depth of approximately 50 to 55 cm below soil surface. This is at the bottom of the functional root zone of the raspberry crop (Mark Sweeney personal communication, 2008) and the depth at which transition to the coarse gravelly aquifer material was observed. PCAPS were levelled and aligned in the hole and sampling line conduits were positioned. The soil around the samplers was backfilled (by hand) by horizon. Proper wick and soil contact is crucial to proper instrument function (Boll et al., 1992) and to that end, sieved soil (0.5 cm mesh) from the native soil horizon (Bfj) was firmly pressed on the lid surface to a depth of 5 cm. As a growth inhibitor to invading raspberry plant roots, Biobarrier Root Control System ® (Reemay, Inc., Old Hickory, TN) geotextile fabric with nodules containing slow release trifluralin was cut into strips 70 cm long x 2.5 cm wide and placed 2 cm apart on top of each PCAP prior to refilling the remaining soil over top the samplers. Trifluralin has an EPA rating of "practically nontoxic", has low water solubility, adsorbs to soil and does not leach to groundwater (Hort Enterprises, 2012). The field was re-levelled after PCAPS installation with a roto-tiller. Following PCAP installation April 7-11, 2008, the subsequent 2008 growing season and 2008/2009 over-winter rainy season provided settling time for the samplers and soil. No leachate data from this settling time period was reported on. Prior to the start of data collection following the settling period, the soil surface over top of the samplers was visually checked for level and native soil added as required.

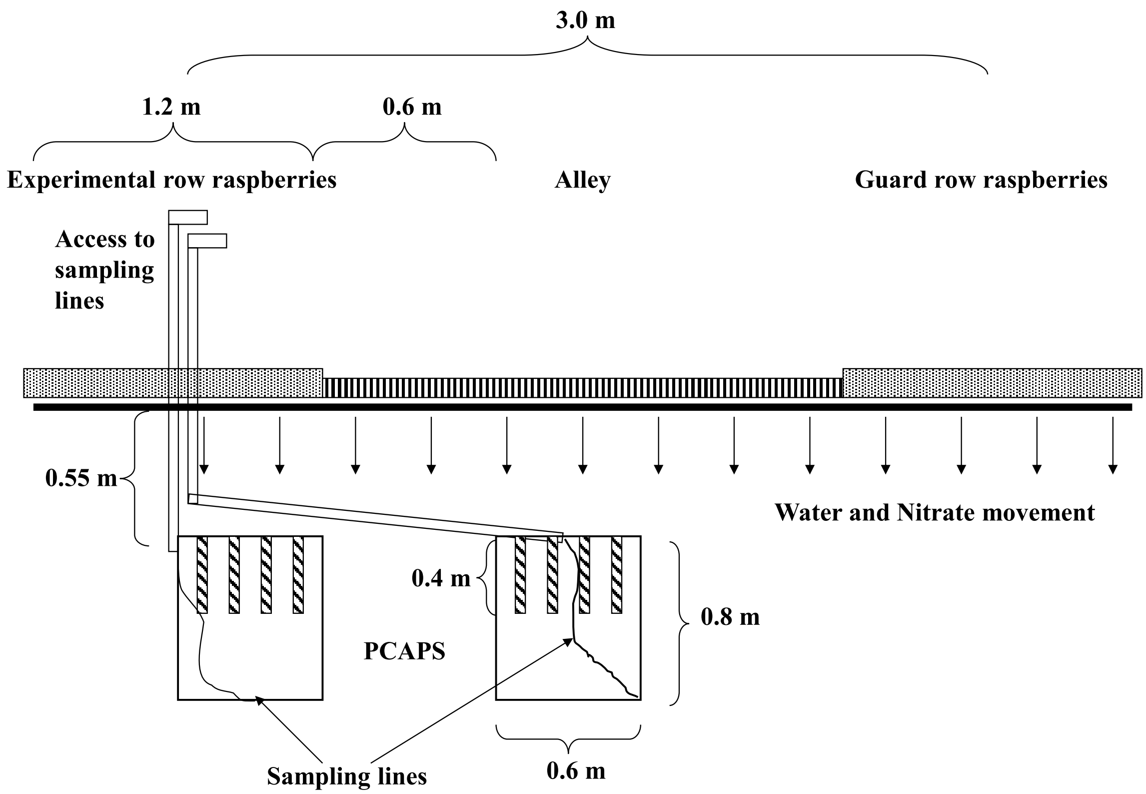

Figure 2.6: PCAP sampler installation sites under raspberry row management and associated alley management.

2.5.2 Control and data recording

A Campbell Scientific CR10X datalogger interfaced to peripheral control devices and sensors was used to control on-site irrigation and fertilizer injection, and record climate and soil sensor data. On-demand remote communication through a cellular modem service allowed careful oversight and coordination of activities. All equipment was powered with solar charged 12V deep cycle batteries.

2.5.3 Soil and climate sensors

In November of 2008, Campbell Scientific CS616 Water Content Reflectometers (WCR) were installed 30 cm from the drip line and approximately 1 m away from the row PCAP location (Figure 2.7) in the first three replicates of the 100N and Perennial treatments (both fixed irrigation) and the Scheduled and Fertigated + Scheduled treatments (both scheduled irrigation). Sensors were installed vertically and provided continuous monitoring of the soil's volumetric water content integrated over the 0 to 30 cm installation depth.

In April 2010, the first three replicates of the 100N and Scheduled plots were further instrumented to provide continuous monitoring of the soil water potential both at the edge of the PCAP instrumentation (sensor site #1) and in bulk soil on the plot undisturbed by the PCAP instrumentation (sensor site #2) (Figure 2.7). Soil water potential instrumentation included 60 cm Jet Fill tensiometers (Soilmoisture Corp., Santa Barbara, CA) and Decagon MPS-1 dielectric water potential sensors (Decagon Devices Inc., Pullman, WA). One tensiometer and one MPS-1 were installed at two sites in each plot: #1) 30 cm from the drip line at the edge of the row PCAP sampler, and #2) 30 cm from the drip line approximately 1 m away from the sampler (Figure 2.7). The tensiometers were installed at the same depth as the PCAP sampler lid (50-55 cm) and were interfaced with GT3-15 tensiometer transducers (ICT International Pty, Ltd., NSW, Australia) to measure soil water potential. These were controlled and logged with Campbell Scientific CR10X dataloggers. The Decagon MPS-1 sensors were individually calibrated in tempe cells containing diatomaceous earth over suctions of 0 to 400 kPa prior to installation and logged with Decagon EM50 loggers once in the field.

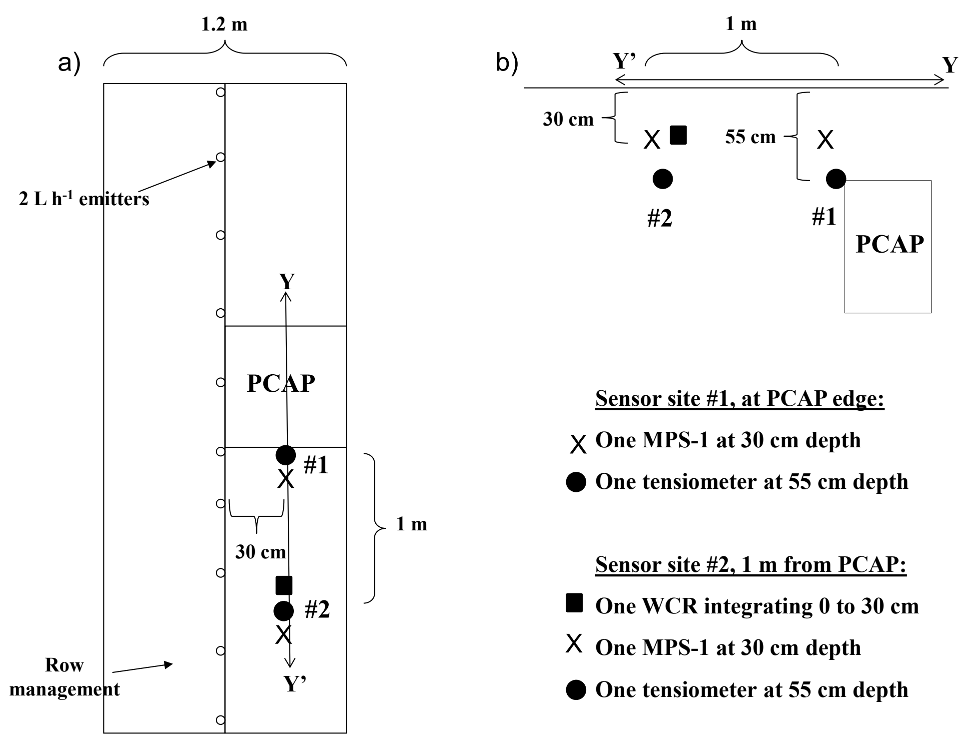

Figure 2.7: Sensor installation sites on the raspberry row: a) overhead view and b) cross-section view.

A tipping bucket rain gauge (Model 3525R, Spectrum Technologies, Inc., Plainfield, IL) was used to record daily on-site rainfall.

2.6 Sampling and analysis

2.6.1 PCAP sampling and water analysis

The PCAPS were sampled bi-weekly over the monitoring period (Table 2.6). The first sampling times in the 2009/2010 and 2010/2011 PCAP sampling years were two weeks after the initial spring applications of manure and fertilizer treatments to the experimental plots. A PCAP sampling year was comprised of all subsequent bi-weekly sampling times over the growing and rainy seasons through to the following April. There were a total of 26 sampling times in 2009/2010 and 27 in 2010/2011. The growing season in each year was represented by the first 13 sampling events, and included approximately a five month period (early April to late September) (Table 2.7). The remainder of the year is referred to as the rainy season.

Table 2.6: PCAP sampling dates for the 2009/2010 and 2010/2011 sampling years.

Date[a]	Sampling	Date[a]	Sampling
April 21/09	1	April 23/10	1
May 6/09	2	May 4/10	2
May 20/09	3	May 17/10	3
June 3/09	4	June 1/10	4
June 16/09	5	June 14/10	5
June 29/09	6	June 28/10	6
July 12/09	7	July 12/10	7
July 29/09	8	July 28/10	8
August 12/09	9	August 10/10	9
August 26/09	10	August 23/10	10
September 9/09	11	September 1/10	11
September 21/09	12	September 14/10	12
October 8/09	13	September 28/10	13
October 19/09	14	October 12/10	14
November 4/09	15	October 26/10	15
November 16/09	16	November 9/10	16
November 30/09	17	November 27/10	17
December 16/09	18	December 6/10	18
December 29/09	19	December 21/10	19
January 12/10	20	January 4/11	20
January 25/10	21	January 17/11	21
February 8/10	22	January 30/11	22
February 22/10	23	February 15/11	23
March 8/10	24	February 28/11	24
March 22/10	25	March 14/11	25
April 5/10	26	March 28/11	26
		April 11/11	27

[a]Length of time to complete each PCAP sampling varied from 1-3 days depending on collection volumes; the start date of each sampling time period is given here

Table 2.7: PCAP sampling seasons and associated sampling times.

2009/2010 PCAP year			2010/2011 PCAP year		
Date	**Season**	**Samplings**	**Date**	**Season**	**Samplings**
April 6/09 to October 8/09	Growing	1-13[a]	April 6/10 to September 29/10	Growing	1-13[b]
October 9/09 to April 5/10	Rainy	14-26	September 30/10 to April 11/11	Rainy	14-27
April 6/09 to April 5/10	Annual	1-26	April 6/10 to April 11/11	Annual	1-27

[a]PCAP sampling times 5-13 in the 2009 growing season were within the irrigation season
[b]PCAP sampling times 6-12 in the 2010 growing season were within the irrigation season

Bi-weekly sampling was accomplished using a sampling cart fitted with a Welch dry vacuum pump (Model 2585B-50, Gardner Denver Welch Vacuum Technology, Inc., Niles, IL), vacuum manifold and suction lines and volume calibrated collection vessels (Figure 2.8). At each sampling time, individual PCAP sampling lines were hooked to the vacuum manifold and all drainage water present in the PCAP sampler was pumped out. Total drainage volume was recorded using the calibrated collection vessels and a subsample of the leachate was collected in a 250 mL high density polyethylene Nalgene™ sample bottle. Samples were placed in a cooler and then transported to frozen storage where they were held until analysis. Once volume was measured and the subsample collected, leachate was discarded in adjoining alleys away from the locations of PCAP samplers.

Figure 2.8: PCAP sampling cart.

The PCAP samples were thawed immediately prior to analysis and analyzed colorimetrically by a segmented flow analyzer (SFA, Model 305D, Astoria Pacific International, Clackamas, OR) and manufacturer's procedures for the determination of nitrate-N and ammonium-N. Ammonium-N was determined by mixing with an alkaline complexing reagent to liberate ammonia gas which was diffused through a Teflon^{TM} membrane and reacted to create indophenol blue. Nitrate-N was determined as an azo dye following reduction of nitrate to nitrite by cadmium metal.

Over the 2009 and 2010 growing seasons irrigation water samples were taken from a hose bib installed on the irrigation headworks at the south end of the experimental rows. Water was sampled on a weekly or bi-weekly basis with focus on the time periods of the growing seasons during which irrigation was being applied. Samples were handled according to the sampling and analysis protocols used for the PCAP water samples.

2.6.2 Soil sampling and analysis

Soil was sampled from the raspberry row in the experimental plots of all eight treatments, and from the alleys of the 100N, Perennial cover and Barley cover treatments (Table 2.8).

Table 2.8: Soil sampling dates and timings for the 0-15 and 15-30 cm depth increments in 2009 and 2010.

Date	Timing
April 3, 2009	Pre-nutrient application
June 29, 2009	First berry ripening
August 19, 2009	Post-harvest
September 28, 2009	Prior to fall rains
March 24, 2010	Pre-nutrient application
June 30, 2010	First berry ripening
August 17, 2010	Post-harvest
September 30, 2010	Prior to fall rains

The 0-15 and 15-30 cm depth increments were sampled using a 2.5 cm Oakfield soil probe. On the row, two cores at distances of 10, 30 and 50 cm from the drip line were taken to form a six core composite sample for the 0-15 and 15-30 cm depth increments (Figure 2.9). Soil was mixed and then subsampled. The remaining soil was replaced by horizon and the holes were crushed in to reduce potential for preferential flow at these sampling locations. The sampling locations (distance from the drip line) along the plot length were systematically rotated for each new sampling date to ensure a representative sample. Soil samples were kept frozen until extraction and analysis. Soils were extracted for nitrate-N and ammonium-N with 2M KCl using a 1:5 soil to extractant ratio and a one hour shaking time (Zebarth et al., 1996) and analyzed colorimetrically by SFA as described above.

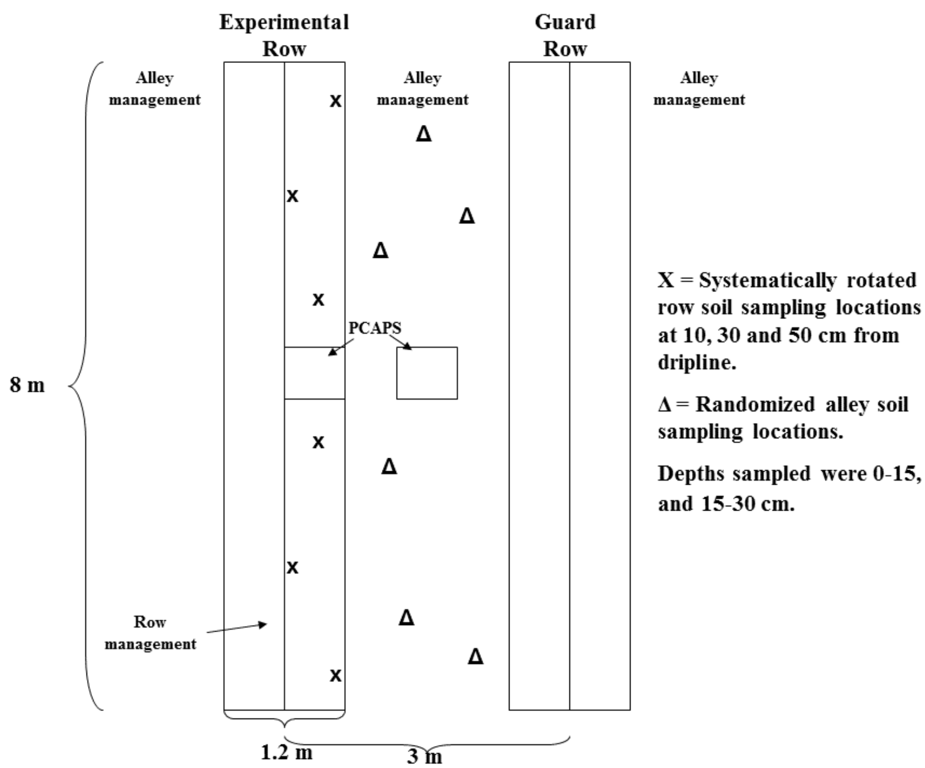

Figure 2.9: Soil sampling locations on the row and in the alley.

2.6.3 Plant sampling and analysis

Primocane leaves were sampled for nitrogen concentration on September 29, 2009 and September 21, 2010. The 2009 sampling included all leaves and petioles from five sampled primocanes randomly chosen from each experimental plot. In 2010, one fully expanded leaf plus petiole was sampled from 16 randomly selected primocanes along the length of each plot. Sampled leaf and petiole tissue was air dried followed by oven drying at 65 ºC for 24-36 hours and ground in a stainless steel Wiley mill (A.H. Thomas Co., Philadelphia, PA). Leaf total N concentration was determined using a combustion analyzer (model FP-528; LECO, St. Joseph, MI).

Ten dormant primocanes were randomly sampled along the length of each plot on December 15, 2009 and January 11, 2010. Primocane diameters were measured at 30 cm from the soil surface and individual cane lengths were recorded. Primocane tissue was air dried then oven dried for 24-36 hours and ground to pass a 2 mm screen in a cutting mill (Retsch Inc., Newtown, PA). Cane total N concentration was determined by LECO combustion analysis as described above. Following the 2010 primocane sampling and pruning, the number of viable canes left on each plot as next season's floricanes was recorded.

At first berry ripening in 2010 (week of June 25 to 30), six floricanes were sampled from each plot. Cane diameters were recorded at 30 cm above the soil surface. From the six floricanes, individual counts of the number of fruiting structures (berries or flowers) on the laterals and the number of laterals (branches off the main stem) were made. The laterals, leaves and fruiting structures (together, the lateral components) were separated from the main stem. The main stem and lateral components were handled separately and were dried, ground and analyzed for total N concentration as described above.

In 2010, all ripe berries from 12 canes on each plot were harvested weekly. Total yield on the 12 canes was recorded and a random subsample of 50 berries at each harvest time was weighed for the determination of mean berry weight.

2.6.4 Statistical analysis

All PCAP, soil and plant data collected were tested for the assumptions of normality, independence of samples, equality of variance and linearity of data using diagnostic plots within R statistical software. Based on these plots, a $\log_{10}$ transformation was performed on the PCAP nitrate-N data only. The individual *apriori* contrasts of interest (Table 2.9) were tested within the PROC GLM package in SAS statistical software (SAS Institute Inc., 2002-2008) with Treatment and Block as fixed main effects. The number of contrasts was limited to seven. The single degree-of-freedom contrasts were used to test for the effects of N rate (linear and quadratic), N source (manure vs mineral fertilizer), alley perennial cover crop (perennial cover crop vs clean cultivated), alley annual cover crop (barley cover vs clean cultivated), irrigation management (fixed vs scheduled) and N application method (50N vs Fertigated + Scheduled) and were interpreted from the model output with p values < 0.05 considered as significant. The PCAP data were analyzed separately by row and alley locations. The PCAP data were expressed on a per hectare of land under row or alley management basis. The PCAP data were also combined as management totals, area-weighted across the row and alley locations. The soil mineral N data were also analyzed separately by row and alley locations.

Table 2.9: Individual *apriori* contrasts used in statistical analyses.

Contrasted treatments[a]	Contrasted treatments[a]	Effect	Significance
1 and 3[b]	0N and 100N[b]	N rate (linear)	L
1, 2 and 3	0N and 50N and 100N	N rate (quadratic)	Q
4 and 3	Manure and 100N	N source	M
5 and 3	Perennial cover and 100N	Perennial cover	P
6 and 3	Barley cover and 100N	Barley cover	B
7 and 3	Scheduled and 100N	Scheduled	S
2 and 8	50N and Fertigated + Scheduled	Fertigated + Scheduled	F

[a]Using CONTRAST statement within PROC GLM in SAS statistical software
[b]Treatment 3, 100N, is the current industry practice for N, irrigation and alley management against which most other treatments were contrasted

Chapter 3: Results

3.1 Experimental site climate

The monthly total precipitation values, almost all of which fell as rain, over the 2009 to 2011 reporting period were, on average, 94% of the 30 year long-term monthly averages (Environment Canada, 2011) (Table 3.1). Mean monthly temperatures were, on average, higher by less than 0.5 ºC compared to the 1971-2000 climate normals (Environment Canada, 2011). Overall, conditions were a little drier and warmer, but close to the long-term means over the reporting period.

Table 3.1: Monthly precipitation and mean monthly air temperature at the Abbotsford Airport (~1 km from experimental site) 2009 to 2011 compared to 30 year (1971-2000) climate normal (Environment Canada, 2011).

	Mean Monthly Precipitation (mm)[a]				Mean Monthly Air Temperature (ºC)[a]			
Month	**2009**	**2010**	**2011**	**30 year average[b]**	**2009**	**2010**	**2011**	**30 year average[b]**
January	223	199	328	198	2.1	7.0	3.7	2.6
February	69	129	88	160	4.1	7.7	3.1	4.7
March	127	120	151	146	4.8	8.1	7.3	6.8
April	91	94	164	120	9.6	10.0	7.7	9.5
May	122	150	135	99	13.1	12.0	11.8	12.5
June	15	51	49	79	17.5	15.0	15.6	15.1
July	39	1	75	50	20.4	18.3	17.4	17.5
August	59	59	16	49	18.4	18.6	18.5	17.7
September	58	192	91	76	16.6	16.1	17.2	15
October	206	109	107	145	10.0	11.9	10.5	10.2
November	296	160	166	241	7.3	4.8	4.9	5.7
December	84	232	92	209	1.0	4.5	3.3	2.8
Annual total	1389	1496	1462	1573				

[a]Data from Environment Canada's National Climate Data and Information Archive for Abbotsford A. ID 1100030
[b]Climate Normals 1971-2000 for Abbotsford A. ID 110003

Precipitation amounts were high in the shoulder seasons, the time periods on either side of the growing seasons, and in the over-winter rainy seasons (Figures 3.1 and 3.2). In general, Penman-Montieth reference evapotranspiration (ET_o, which is for a grass reference crop) (Allen et al., 1998; Stephanie Tam personal communication, 2012) exceeded precipitation during late spring to early fall during which time irrigation was applied in response to the water deficit.

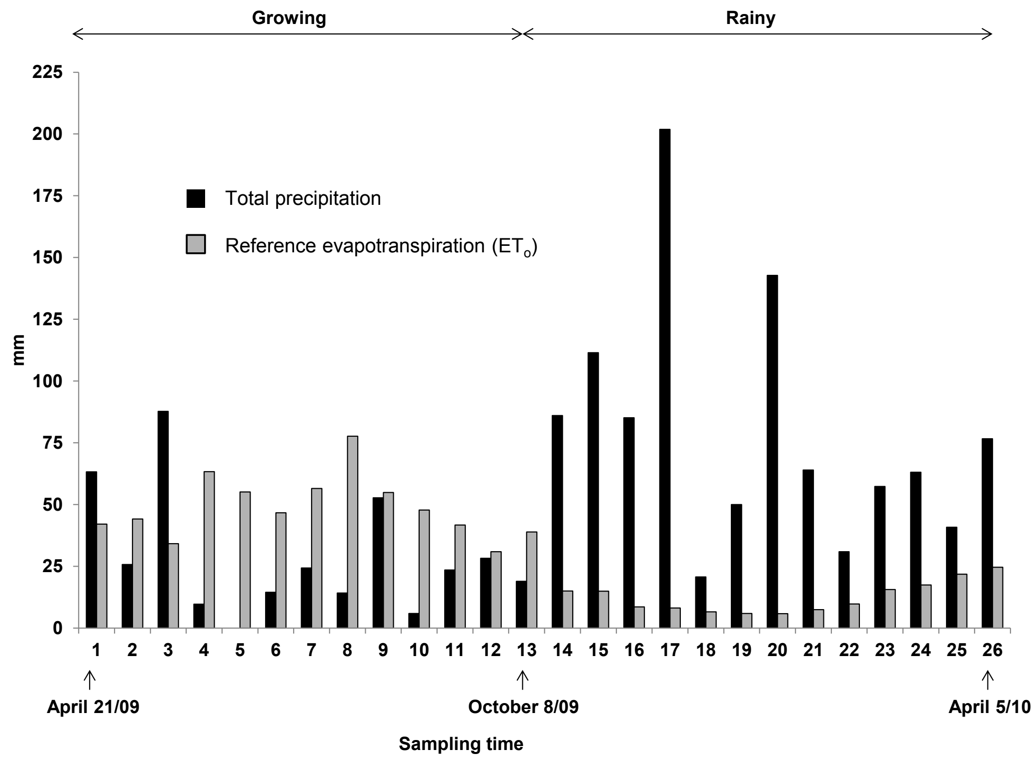

Figure 3.1: Precipitation and Penman-Montieth reference evapotranspiration (ET_o) over each two-week PCAP sampling interval, 2009/2010.

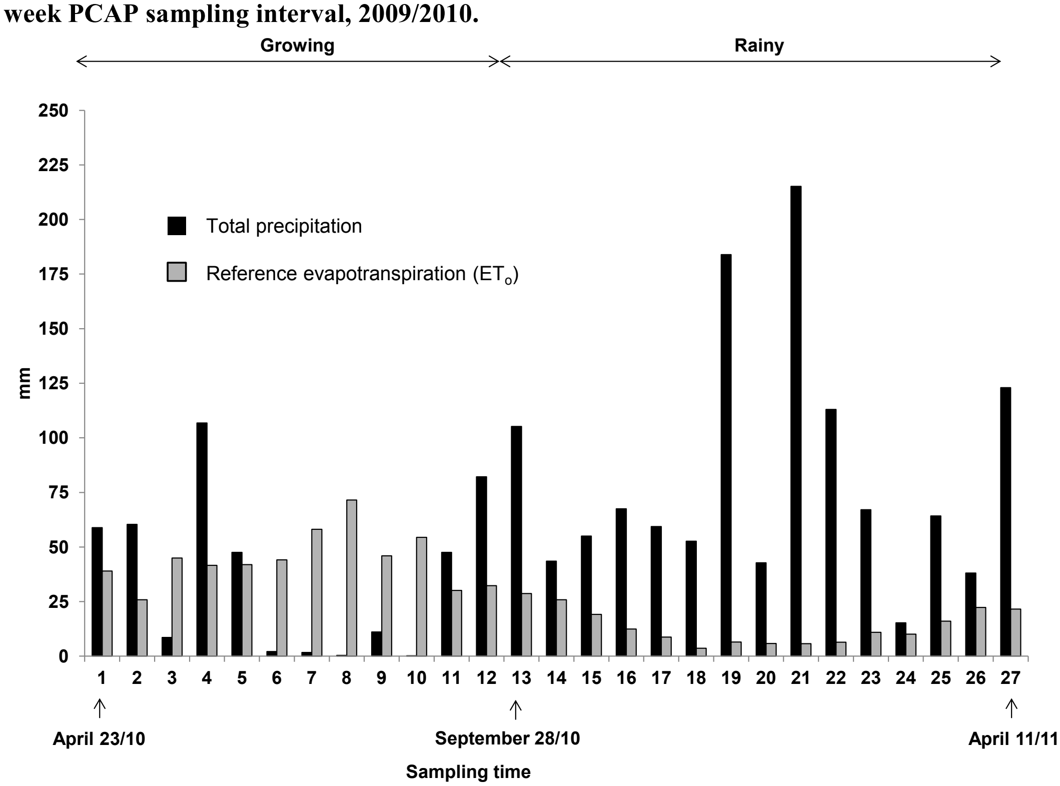

Figure 3.2: Precipitation and Penman-Montieth reference evapotranspiration (ET_o) over each two-week PCAP sampling interval, 2010/2011.

3.2 Water management

3.2.1 Irrigation applied

In 2009, treatments under the fixed irrigation regime received a total of 285 mm of applied irrigation per field hectare while those under scheduled irrigation received 152 mm of applied irrigation per field hectare (Table 3.2). As the raspberry plants moved into production in 2010, fixed irrigation was increased by 11% from 2009 levels to 320 mm of applied irrigation; this better matched current reported grower practice and recommended irrigation rates for a coarse soil in the Abbotsford area (Van der Gulik, 1999). Therefore, irrigation scheduling resulted in water savings of 46% and 51% for 2009 and 2010, respectively. The four percent increase in the amount of irrigation water applied in the scheduled regime between 2009 and 2010 was the result of an increased crop maturity factor in the scheduled irrigation calculation as well as measured ET_o differences during the irrigation season between the two years.

Table 3.2: Expected raspberry crop water use, irrigation water applied in each year under fixed and scheduled irrigation and the percentage increase in watering from 2009 to 2010.

Irrigation treatment	Expected crop water use (mm)[a] 2009	Expected crop water use (mm)[a] 2010	Irrigation water applied ($mm\ ha^{-1}$)[b] 2009	Irrigation water applied ($mm\ ha^{-1}$)[b] 2010	Application increase 2009 to 2010 (%)
Fixed	319	281	285	320	11
Scheduled	319	281	152	158	4

[a]calculated from daily atmometer measured ET multiplied by the raspberry crop coefficient
[b]water applied through irrigation system, not including precipitation

3.2.1.1 Nitrogen applied through irrigation water

Thirteen irrigation water samples were collected over the 2009 and 2010 growing seasons. Nitrate-N concentration in all but one of the samples collected (a single sample measured 25 mg NO_3-N L^{-1}) measured between 15 to 18 mg NO_3-N L^{-1} and averaged 17 mg NO_3-N L^{-1} overall. The calculated N application rate through irrigation water alone in the 2009 growing season was 49 and 26 kg N field ha^{-1} under fixed and scheduled irrigation, respectively. In comparison, N applied through irrigation water in 2010 increased to 55 and 27 kg N field ha^{-1} in the fixed and scheduled irrigation regimes, respectively.

3.2.2 Irrigation effects on soil moisture status

3.2.2.1 Soil water potential

For a loam soil, 80 to 85% of the soil water is plant available at a soil water potential of approximately -35 kPa (Van der Gulik, 1999). Based on this, both irrigation regimes maintained soil water potentials at levels that provided the raspberry plants with readily available water even during the peak water demand periods of the summer (Figure 3.3). Fixed irrigation maintained soil water potentials measured at both 30 cm (by MPS-1 sensors) and 55 cm (by tensiometers) depths at higher potentials (wetter) than scheduled irrigation. The potentials recorded at 30 cm by the MPS-1 sensors were higher than the tensiometers as they were recorded higher up in the soil profile and therefore closer to the point sources of irrigation (the emitters). Soil water potential cycled in response to irrigation events and subsequent soil drying. During calibration of the MPS-1 probes in the laboratory, sensor response was only consistent at water potentials lower than -15 kPa. This limited the usefulness of this particular sensor for monitoring soil water potentials in the upper 30 cm of the soil profile under the current irrigation regimes.

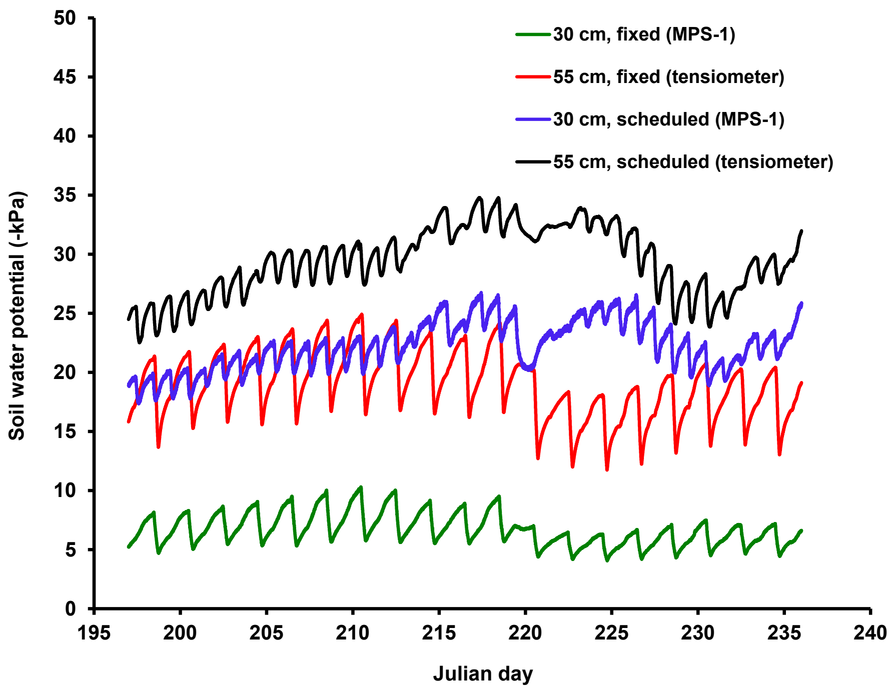

Figure 3.3: Soil water potential measured under fixed (100N, Treatment 3) and scheduled (Scheduled, Treatment 7) irrigation regimes for the high water demand period of July 16, 2010 (Julian day 197) to August 23, 2010 (Julian day 235) measured by MPS-1 sensors (at 30 cm depth) and tensiometers (at 55 cm depth).

Over the 2010 soil water potential monitoring period, water potential at 55 cm in those treatments under scheduled irrigation averaged -18.6 kPa which was 20% dryer than in the treatments under fixed irrigation, which averaged -14.9 kPa (Table 3.3). In the pre-irrigation season, potentials under the two regimes were closely matched. Differences in soil water potential between the treatments were observed during the irrigation season (Julian days 165-250), with the scheduled treatments averaging -24.3 kPa which was 33% lower (dryer soil) than those treatments under fixed irrigation. As the irrigation season ended and the cooler, wetter weather of the fall arrived, the water potential in treatments in both irrigation regimes became closely matched at -13.2 and -12.6 kPa, respectively.

3.2.2.2 Soil volumetric water content

The VWC during winter was similar across treatments and within the natural variability expected from soil texture differences among locations. The VWC of the soil in the treatments under fixed irrigation was higher than for scheduled irrigation during both the 2009 and 2010 irrigation seasons (Figure 3.4). Soil VWC varied in response to irrigation, increasing as irrigation cycles began and decreasing during subsequent drying periods. This cycling was most pronounced in the treatments watered on the fixed irrigation regime.

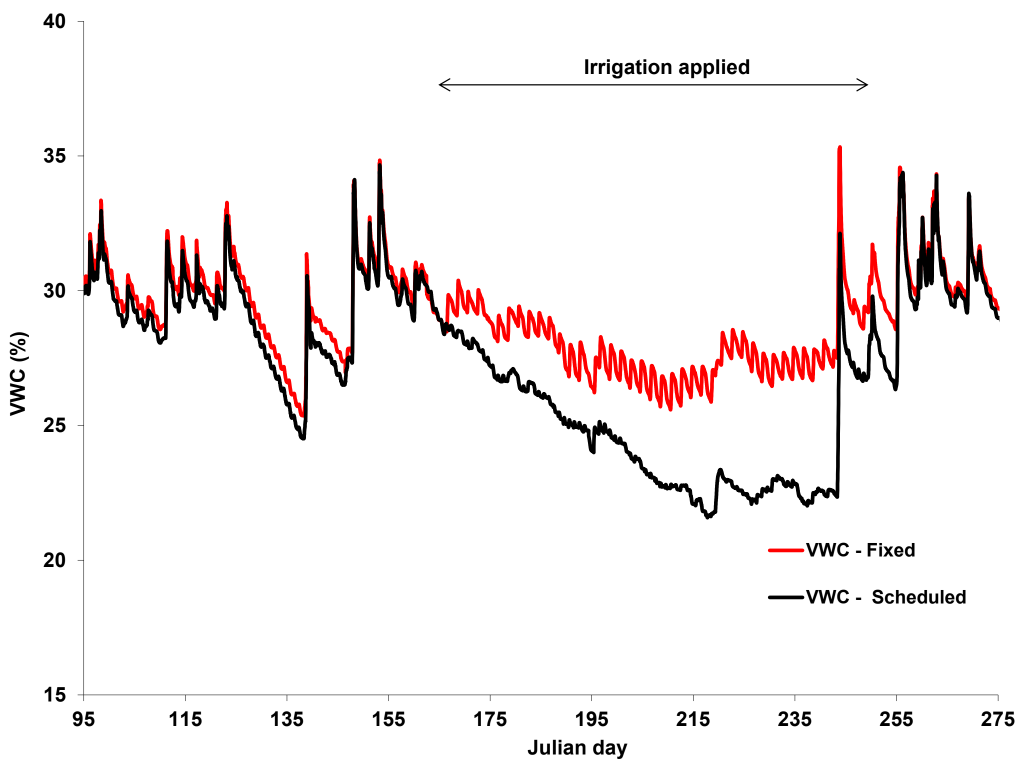

Figure 3.4: Mean % volumetric water content of soil (integrated 0 to 30 cm) under the fixed and scheduled irrigation regimes over the 2010 growing season (Julian day 96 to 272), measured by water content reflectometers. Irrigation in 2010 applied June 14 to September 7 (Julian day 165 to 250).

Over the irrigation season in 2009 (June 10 to October 8), soil VWC under fixed irrigation averaged 24.3% while that in soil under scheduled irrigation averaged 18.3%. In the 2010 irrigation season (June 14 to September 7), soil VWC averaged 27.9% under fixed irrigation and 24.7% under scheduled irrigation. Outside of the irrigation seasons, soil VWC between the two regimes were similar as a result of uniform recharge to the soil profile by precipitation events, cooler temperatures and lower plant water demand.

3.3 Passive capillary wick samplers

3.3.1 Soil water potential gradients due to PCAP instrumentation

Soil water potential gradients were calculated from soil water potentials measured by tensiometers at the PCAP edge minus soil water potentials measured by tensiometers 1 m away in undisturbed locations within a plot (Figure 3.5a). Soil water potential gradients varied slightly in response to irrigation regime and the period of the growing season in which the water potential readings were recorded (Figure 3.5b). Under both the fixed and scheduled irrigation regimes time periods were identified during which soil water potential was lower in undisturbed soil than at the edge of the PCAP instrumentation. This created a water potential gradient away from the samplers and may be an indication of conditions during which soil water flow avoided the samplers (divergent flow) and may have been under-sampled. At irrigation start times, around midway through each Julian day for scheduled and every second day for fixed irrigation, the magnitude of the gradient started to decrease as soil in a plot became more uniformly wetted. During some irrigation cycles, the direction of the water potential gradient reversed, indicating flow would occur towards the sampler; however, these periods of potential convergent flow and over-sampling did not persist for long following the end of the irrigation cycles. Similar water potential gradients were observed under both irrigation regimes. Overall, gradients under both irrigation regimes indicated more time periods of possible divergent than convergent flow.

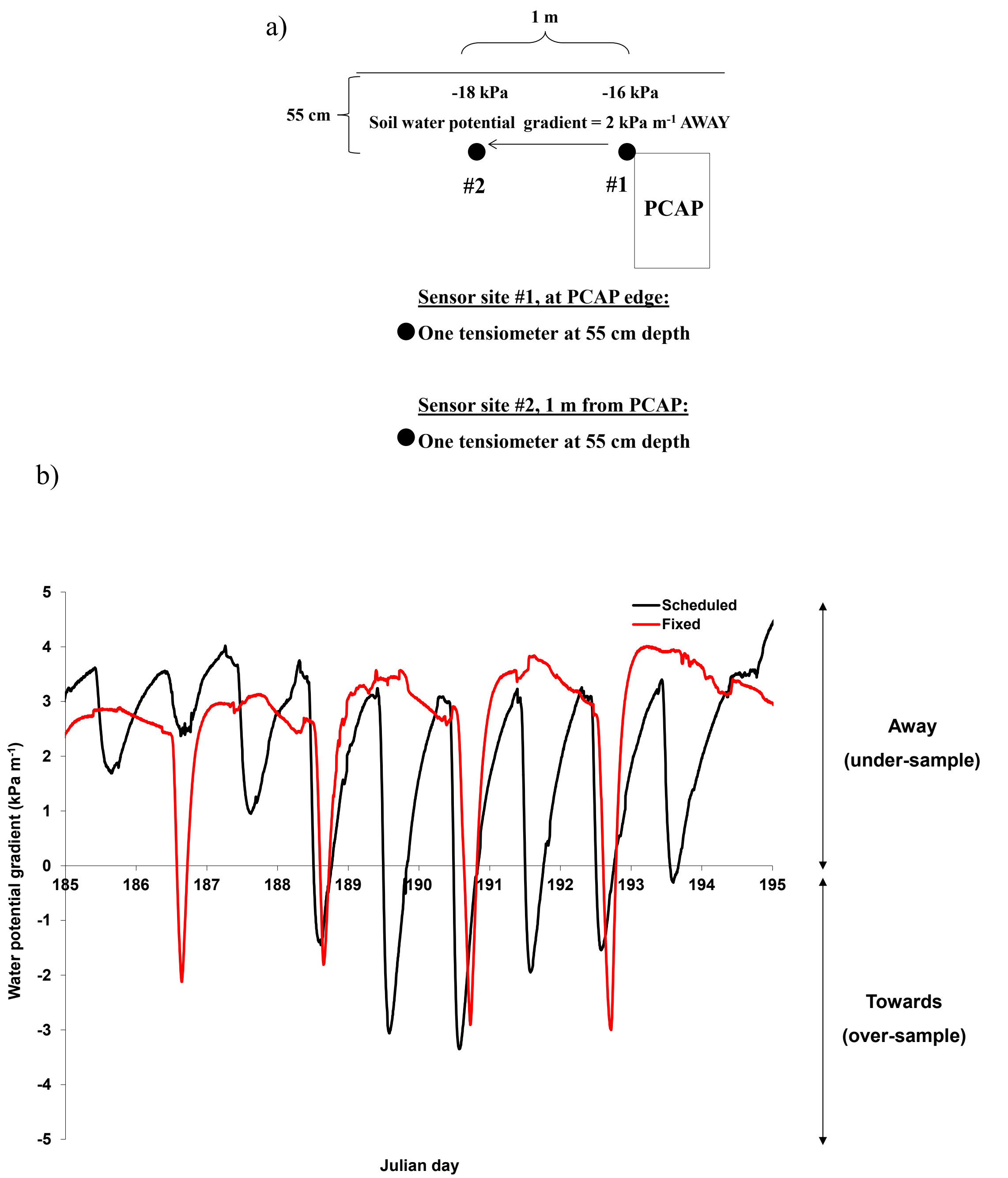

Figure 3.5: a) Soil water potential gradient (differences in soil water potential at PCAP edge relative to soil water potential in undisturbed soil 1m away) at two tensiometer monitoring locations (55 cm depth) within a plot b) Magnitude and direction of water potential gradient under fixed (100N, Treatment 3) and scheduled (Scheduled, Treatment 7) irrigation regimes during a portion of the 2010 soil water potential monitoring period.

Calculated water potential gradients over the full monitoring period had a time-averaged magnitude of 1.7 and 1.5 kPa m^{-1} for the fixed and scheduled treatments, respectively (Table 3.3). The lateral potential gradients measured for both irrigation regimes were very close in magnitude for the pre-irrigation season and differed only slightly during the irrigation and post-irrigation time periods. In all time periods and for both irrigation regimes, the overall direction of the potential gradient was away from the PCAP instrumentation and the magnitudes of the potential gradients calculated from the tensiometer data were less than ~2 kPa.

Table 3.3: Time-averaged soil water potential and water potential gradient relative to the PCAP sampler during 2010.

Timing[a]	Julian Day	Suction (kPa)[b]		Water potential gradient (kPa m^{-1})[c]	
		Fixed	Scheduled	Fixed	Scheduled
Full period	120-323	-14.9	-18.6	1.7	1.5
Pre-irrigation	120-164	-15.8	-15.3	1.2	1.1
Irrigation	165-250	-16.2	-24.3	2.4	2.1
Post-irrigation	251-323	-13.2	-12.6	1.1	0.6

[a]Full period = April 30 to November 19, 2010; Pre-irrigation = April 30 to June 13, 2010; Irrigation = June 14 to September 7, 2010; Post-irrigation = September 8 to November 19, 2010.
[b]Treatment means of both tensiometer locations within plots
[c]Tensiometer soil water potential at the PCAP edge minus the tensiometer soil water potential in undisturbed soil on the same plot over a 1m distance. Direction of gradient is indicated by the sign. A positive water potential gradient indicates a direction away from the PCAP sampler.

3.3.2 Drainage and nitrate-N losses measured by PCAPS, 2009/2010

3.3.2.1 Drainage and nitrate-N losses measured in the row, 2009/2010

Growing season drainage losses in 2009/2010 ranged from 39 to 161 mm. In April and May, prior to the start of irrigation, drainage losses resulted from spring precipitation at times when plant and evaporative demands were low and soil moisture content high from the preceding winter rainy period (Table 3.1 and sampling times 1-3 in Figure 3.1). Drainage losses over the majority of the growing season were generally low (Figure 3.6) with somewhat elevated losses observed during the latter portion of the irrigation season (sampling times 8-12) likely due to decreasing plant water demand and increased precipitation inputs (Figure 3.1). A marked increase in drainage losses occurred in October when plant and evaporative demands had decreased and the arrival of fall rains began soil recharge. Rainy season losses were less variable and ranged from 549 to 774 mm. Drainage losses in the row were measureable throughout the rainy season and varied with the precipitation amount in the sampling period. Annually, drainage losses ranged from 639 to 854 mm.

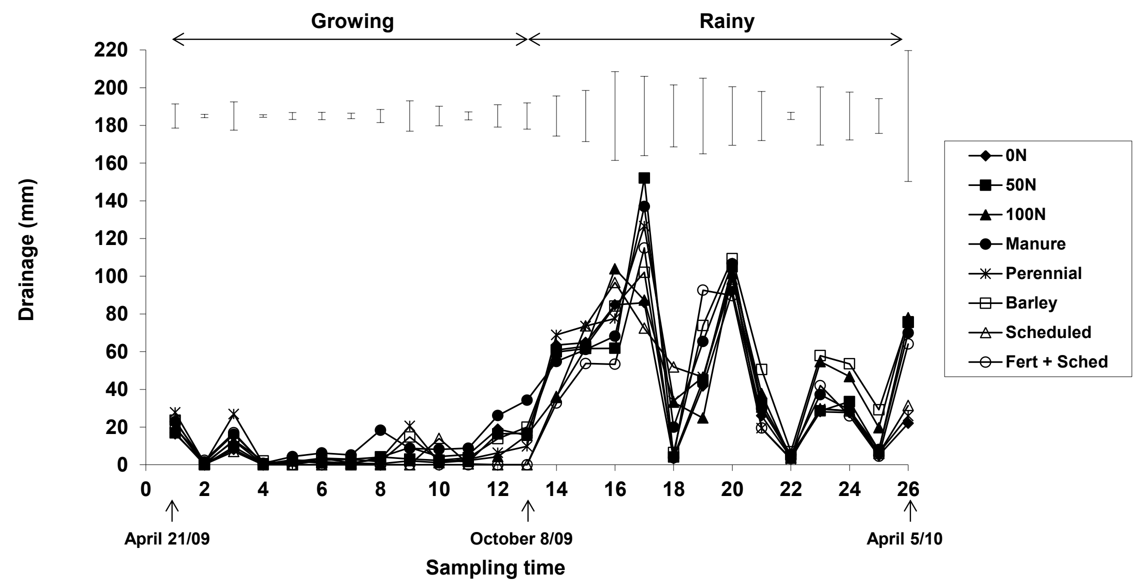

Figure 3.6: Drainage losses in the raspberry row in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.4 and 3.5. Error bars represent +/- 1 SE.

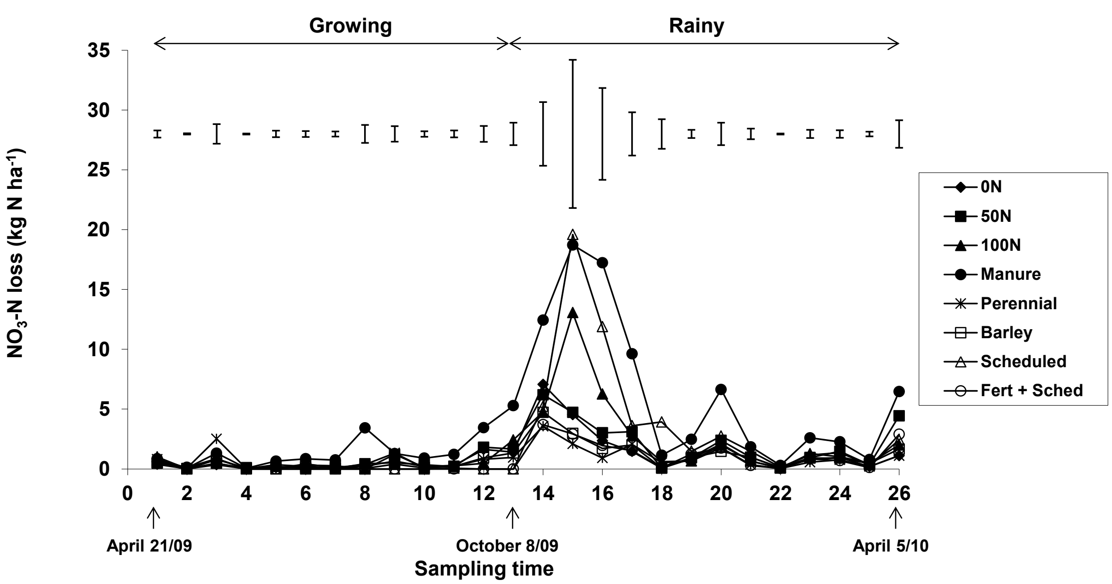

Figure 3.7: Nitrate-N losses in the raspberry row in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.4 and 3.5. Error bars represent +/- 1 SE.

In the 2009/2010 PCAP year, four individual sampling times during the growing season showed significantly higher drainage under the Manure treatment than the 100N treatment in the row (Table 3.4). Outside of this effect of N source there were few individual sampling times that showed significant treatment effects on drainage in the row. Over the growing and rainy seasons and annually, no significant treatment effects on drainage were measured, though the Manure treatment trended toward higher drainage and the plots under the scheduled irrigation regime toward the lowest drainage (Table 3.5).

Table 3.4: Number of times and the individual sampling events that PCAP samplers in the raspberry row measured significant ($p<0.05$) N, irrigation and alley treatment effects on drainage and nitrate-N losses, 2009/2010.

Effect	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	No. times	Sampling(s)	No. times	Sampling(s)
N rate (L)	0		2	9,12
N rate (Q)	1	17	1	26
Manure (M)	4	7,8,11,12	7	8,12,19,20,23,24,26
Perennial cover (P)	1	14	2	16,21
Barley cover (B)	0		1	12
Scheduled (S)	0		3	13,18,19
Fertigated + Sched (F)	0		4	5,9,12,13

Table 3.5: Drainage and nitrate-N losses in the raspberry row measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2009/2010.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	91	549	640	6	22	28
50N	75	672	747	6	29	35
100N	65	689	754	6	36	42
Manure	161	692	854	20	83	103
Perennial cover	105	641	746	8	15	22
Barley cover	101	774	875	6	19	25
Scheduled	42	605	647	2	55	57
Fertigated + Sched	39	600	639	2	18	20
SE	35	151	168	4	14	16
Significance[b]	ns	ns	ns	ns	ns	M

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

Nitrate-N losses in the row during the 2009 growing season were low (2 to 20 kg N ha^{-1}). The arrival of fall rains, which resulted in increased drainage losses, also resulted in the flushing of nitrate from the root zone and thereby, increased nitrate-N losses in the row (Figure 3.7). The Manure treatment significantly increased nitrate-N losses in the row compared to the 100N treatment at seven sampling times (Table 3.4), mainly in the rainy season, leading to a significant effect of this treatment over the year. Annual nitrate-N loss under the Manure treatment was 103 kg N ha^{-1}, two times that of the conventional 100N management which lost 42 kg N ha^{-1}.

In 2009/2010 there was a significant effect of the Manure treatment on ammonium loss in the row over the growing season and annually (data not shown). However, annual losses in the row measured by the PCAPS were less than 0.4 kg NH_4-N ha^{-1} for all treatments and were therefore not considered a major source of N loss from the root zone.

In 2009/2010, the row PCAP samplers under treatments that were irrigated on a fixed schedule collected, on average, 13% of their total annual drainage losses during the growing season and the remaining 87% of annual drainage losses during the rainy season (Table 3.6). The PCAPS under treatments with scheduled irrigation collected only 6% of their annual drainage losses during the growing season. Nitrate-N losses under fixed and scheduled irrigation in the growing season were 22 and 6%, respectively, of annual totals.

Table 3.6: Percentage of annual drainage and nitrate-N losses that occurred in the raspberry row in the growing and rainy seasons, 2009/2010, as influenced by N, irrigation and alley management treatments.

Treatment	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	% of annual losses			
	Growing	Rainy	Growing	Rainy
0N	14	86	20	80
50N	10	90	18	82
100N	9	91	14	86
Manure	19	81	20	80
Perennial cover	14	86	35	65
Barley cover	12	88	23	77
Scheduled	6	94	3	97
Fertigated + Sched	6	94	8	92

3.3.2.2 Drainage and nitrate-N losses measured in the alley, 2009/2010

Growing season drainage losses in the alley in 2009/2010 ranged from 29 to 66 mm. As observed in the row, losses in April and May were driven by precipitation events and were followed by little to no drainage losses until the beginning of the rainy season, at which time losses increased dramatically in response to precipitation inputs (Figures 3.1 and 3.8). Rainy season losses ranged from 469 to 692 mm and total annual drainage in the alleys from 498 to 751 mm.

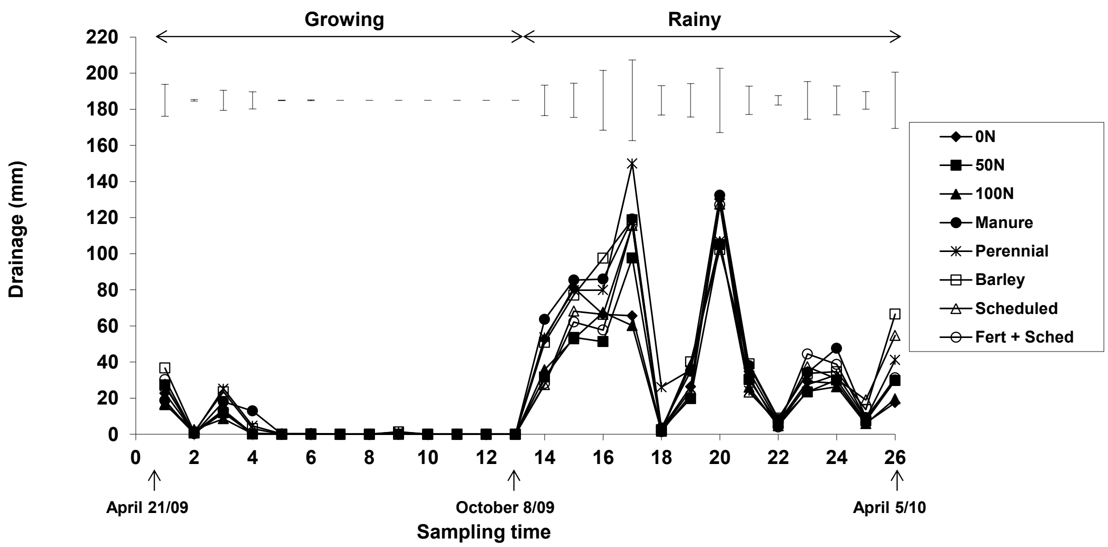

Figure 3.8: Drainage losses in the alley 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.7 and 3.8. Error bars represent +/- 1 SE.

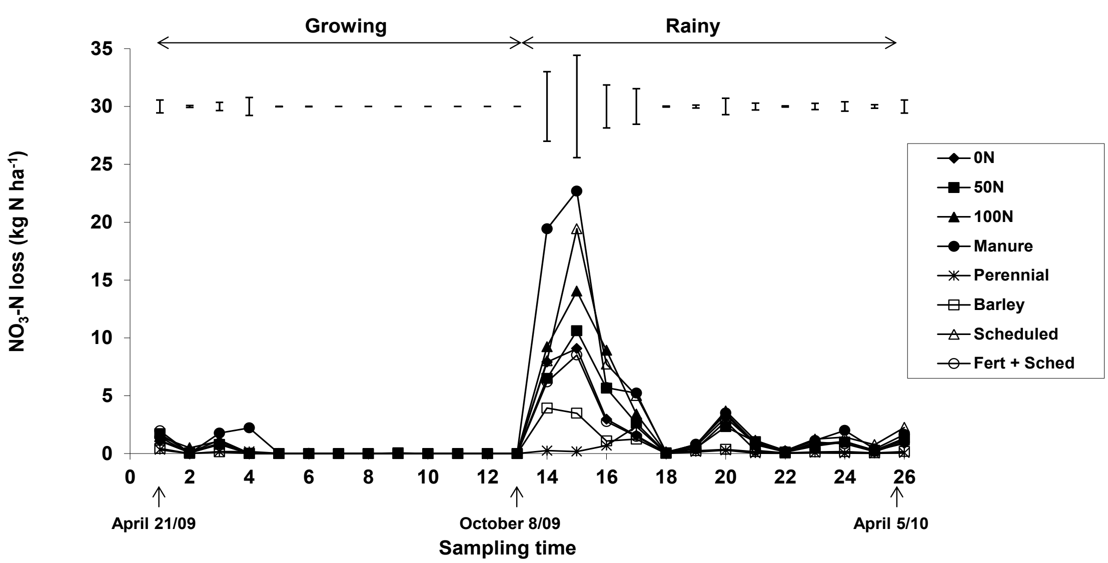

Figure 3.9: Nitrate-N losses in the alley in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.7 and 3.8. Error bars represent +/- 1 SE.

The Manure treatment increased drainage losses compared to the 100N treatment in 2009/2010 in three individual sampling times and the Perennial treatment increased losses in four sampling times compared to the 100N treatment (Table 3.7). These effects were not significant over the growing or rainy seasons or annually (Table 3.8). However, for the Perennial treatment, these significant sampling times and the magnitude of the rainy season drainage losses in the alleys planted with a perennial cover crop suggest a possible soil structure effect which could be increasing drainage losses from land planted in vegetative cover.

Table 3.7: Number of times and the individual sampling events, that PCAP samplers in the alley measured significant ($p<0.05$) N, irrigation and alley treatment effects on drainage and nitrate-N losses, 2009/2010.

Effect	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	No. times	Sampling(s)	No. times	Sampling(s)
N rate (L)	2	2,15	1	16
N rate (Q)	0		0	
Manure (M)	3	2,14,15	0	
Perennial cover (P)	4	2,3,17,18	11	1,3,14,15,19-21,23-26
Barley cover (B)	1	26	11	1,3,15,18,19-21,23-26
Scheduled (S)	1	2	0	
Fertigated + Sched (F)	0		0	

Table 3.8: Drainage and nitrate-N losses in the alley measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2009/2010.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	37	548	585	2	29	31
50N	40	489	529	3	33	35
100N	29	469	498	3	44	47
Manure	50	692	742	5	64	69
Perennial cover	59	672	731	1	4	5
Barley cover	66	685	751	1	11	12
Scheduled	31	603	634	2	52	54
Fertigated + Sched	44	573	617	3	26	28
SE	14	90	99	1	11	11
Significance	ns	ns	ns	P, B	P, B	P, B

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

The nitrate-N losses in the alleys in 2009/2010 were generally low in spring and negligible over the majority of the growing season (Figure 3.9), ranging between 1 to 5 kg N ha^{-1}. Nitrate-N losses increased dramatically with increased drainage at the onset of the rainy season, ranging between 4 and 64 kg N ha^{-1}. Rainy season losses were lowest under alleys planted with cover crops which could take up excess nitrate-N in the root zone, and were measured at 4 and 11 kg N ha^{-1} under perennial and barley covers, respectively. Total annual nitrate-N losses in the alleys ranged from 5 to 69 kg N ha^{-1}.

In 11 out of 26 individual sampling times in 2009/2010, the effects of perennial and barley cover crops on nitrate-N loss in the alleys were significant, suggesting they foraged effectively for nitrate in the root zone (Table 3.7). Compared to the tilled alleys of the 100N treatment, growing season nitrate-N losses in the alley were low (1 kg N ha^{-1}) for both Perennial and Barley treatments. These effects were significant over the growing season (Table 3.8). The majority of the individual samplings times in which cover crops reduced nitrate-N losses occurred in the rainy season, leading to a significant effect over the entire rainy season. The cover crop effects were also significant annually. Total annual nitrate-N losses in the alleys under tillage averaged 44 kg N ha^{-1} compared to only 8 kg N ha^{-1} under cover crops, which amounted to an 82% decrease in leaching losses over the year compared to tillage. There were few significant treatment effects on ammonium-N losses in the alley and losses were less than 0.20 kg N ha^{-1} for all treatments (data not shown).

The alley PCAPS in 2009/2010 collected 93% of their annual drainage losses and 92% of their annual nitrate-N losses during the rainy season with the remainder collected during the growing season.

3.3.3 Drainage and nitrate-N losses measured by PCAPS, 2010/2011

3.3.3.1 Drainage and nitrate-N losses measured in the row, 2010/2011

In contrast to 2009/2010, there were consistent drainage losses in the 2010 growing season measured in the row under all treatments irrigated on the fixed regime (Figure 3.10). Under fixed irrigation, drainage losses in the row in the growing season ranged from 310 mm to 548 mm. Over the growing season, the treatments irrigated on the scheduled regime had measured drainage losses ranging from 72 to 109 mm, the majority of which occurred during April/May and September/October in response to precipitation inputs (Table 3.1, Figure 3.2). Over much of the growing season, treatment plots under the scheduled irrigation regime had no drainage losses. Drainage losses in the rainy season under all managements in the row were driven by precipitation inputs, averaged 737 mm and followed a similar pattern across all treatments for the remainder of the sampling year. Annual drainage losses in the row ranged from 761 to 1356 mm.

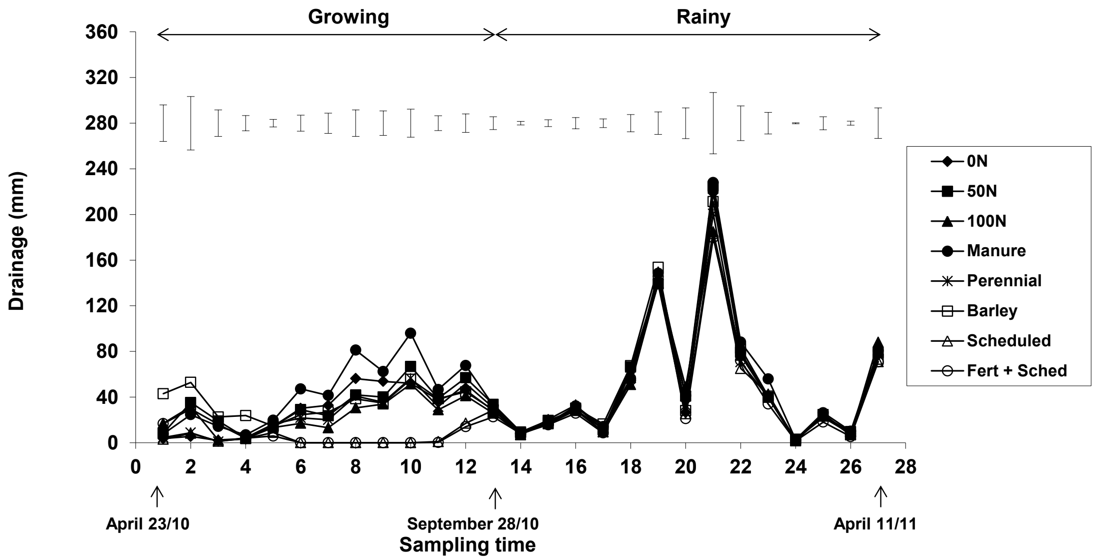

Figure 3.10: Drainage losses in the raspberry row in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.9 and 3.10. Error bars represent +/- 1 SE.

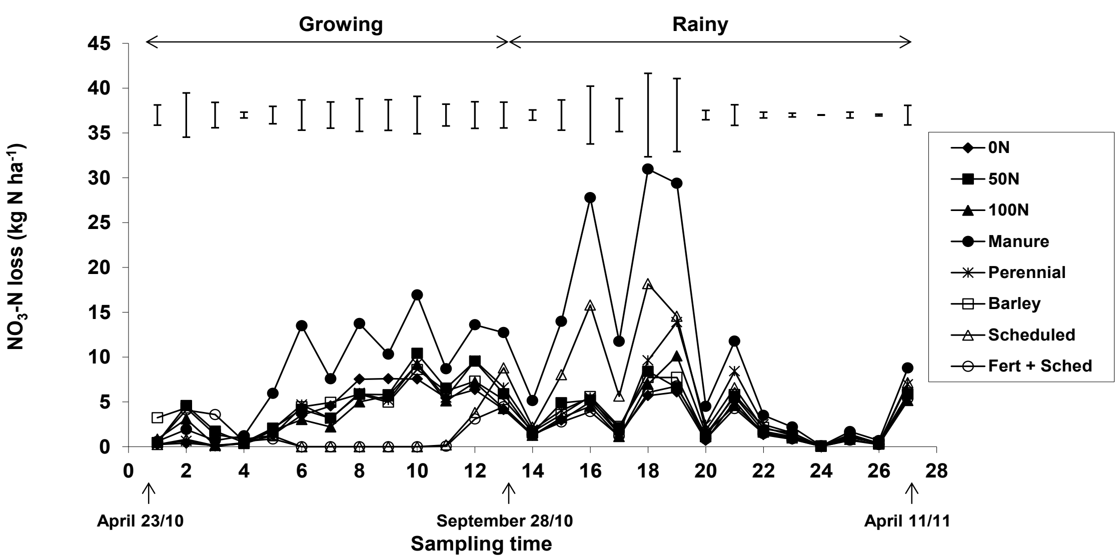

Figure 3.11: Nitrate-N losses in the raspberry row in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.9 and 3.10. Error bars represent +/- 1 SE.

In 2010/2011, the Manure treatment significantly increased drainage volumes compared to the 100N treatment in five individual sampling times (Table 3.9), all of which were during the irrigated portion of the growing season. The Fertigated + Scheduled treatment significantly reduced drainage volumes in the row in seven individual sampling times compared to the 50N treatment, including all but one of the sampling times during the 2010 irrigation season. Drainage losses under the Scheduled treatment were significantly lower in four sampling times compared to the 100N treatment, most of which occurred during the irrigation season. Over the growing season as a whole, scheduled irrigation reduced drainage losses by four times compared to fixed irrigation (Table 3.10). The growing season drainage losses on the row under Manure were increased by two times compared to the 100N conventional management. There were no significant treatment effects on row drainage losses to report over the rainy season or annually.

Table 3.9: Number of times and the individual samplings, that PCAP samplers in the raspberry row measured significant ($p<0.05$) N, irrigation and alley treatment effects on drainage and nitrate-N losses, 2010/2011.

Effect	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	No. times	Sampling(s)	No. times	Sampling(s)
N rate (L)	0		2	7,8
N rate (Q)	0		0	
Manure (M)	5	6-8,10,12	20	5-10,13-24,26,27
Perennial cover (P)	0		1	21
Barley cover (B)	1	4	1	7
Scheduled (S)	4	9-12	11	6-11,13,15-18
Fertigated + Sched (F)	7	6,8,9-12,24	7	6-12

Table 3.10: Drainage and nitrate-N losses in the raspberry row measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2010/2011.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	365	750	1116	49	37	87
50N	412	774	1186	61	46	107
100N	310	723	1033	48	42	90
Manure	548	808	1356	108	152	260
Perennial cover	324	724	1048	53	60	113
Barley cover	443	764	1207	58	46	105
Scheduled	72	689	761	16	85	101
Fertigated + Sched	109	661	771	17	36	53
SE	77	101	160	12	12	18
Significance[b]	M, S, F	ns	ns	M, S, F	M, S	M, F

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

In 2010/2011, PCAP samplers in the row in treatments under scheduled irrigation measured low nitrate-N losses until the beginning of September (near the end of the growing season) while losses generally increased throughout the growing season for those treatments under fixed irrigation (Figure 3.11). Growing season nitrate-N losses in the row ranged from 16 to 108 kg N ha^{-1}. Rainy season losses ranged from 36 to 152 kg N ha^{-1} and annual losses from 53 to 260 kg N ha^{-1}.

In 2010/2011, nitrate-N losses on the row were significantly greater under Manure than the 100N treatment in 20 out of 27 individual sampling times (Table 3.9). Nitrate-N losses under Manure were higher by two, four and three times that of the 100N treatment over the growing and rainy seasons and annually, respectively (Table 3.10). Very high losses over the year in the Manure treatment (260 kg N ha^{-1}) and elevated losses over both the growing and rainy season suggest N applied in excess of plant requirements. The Fertigated + Scheduled management significantly decreased nitrate-N losses relative to the 50N treatment in seven individual sampling times and by factors of four and three over the growing and annual seasons, respectively. There was a significant effect of the Scheduled treatment on nitrate-N losses in 11 individual sampling times compared to the 100N treatment. In six of these sampling times, all occurring during the 2010 growing season, a significant two thirds reduction in nitrate-N losses compared to the 100N treatment was measured. However, in the remaining five (of the 11) individual sampling times, the Scheduled treatment showed significantly higher nitrate-N losses compared to the 100N treatment. These five times occurred in the first half of the rainy season, suggesting excess N available for leaching at the end of the growing season. Over the entire rainy season this translated into two times higher nitrate-N losses under the Scheduled than the 100N treatment. The two opposing effects at different times in the PCAP year led to no significant effect of the Scheduled treatment on nitrate-N loss annually.

In 2010/2011, the effect of the Manure treatment on ammonium-N losses in the row was significant in seven sampling times, leading to significantly higher losses under the Manure treatment during the growing season only (data not shown). Ammonium-N losses were significantly lower in five and seven individual sampling times for Scheduled and Fertigated + Scheduled, respectively, leading to significantly lower losses in these treatments over the growing season alone. All ammonium-N losses were under 0.4 kg NH_4-N ha^{-1} and were therefore minimal relative to the magnitude of the nitrate-N losses.

In 2010/2011, the row PCAPS in treatments under fixed irrigation collected, on average, 29% of their annual drainage losses during the growing season and the remaining 71% during the rainy season (Table 3.11). Nitrate-N losses in the 2010 growing season under these same treatments were 52% of annual losses with the remaining 48% lost during the rainy season. In contrast, PCAPS in treatments under scheduled irrigation collected 12 and 88% of their annual drainage amounts in the growing and rainy seasons, respectively. Nitrate-N losses under scheduled irrigation in the growing and rainy seasons were 25 and 75% of annual losses, respectively.

Table 3.11: Percentage of annual drainage and nitrate-N losses that occurred in the raspberry row in the growing and rainy seasons, 2010/2011, as influenced by N, irrigation and alley management treatments.

Treatment	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	% of annual losses			
	Growing	Rainy	Growing	Rainy
0N	33	67	57	43
50N	35	65	57	43
100N	30	70	53	47
Manure	40	60	41	59
Perennial cover	31	69	47	53
Barley cover	37	63	56	44
Scheduled	9	91	16	84
Fertigated + Sched	14	86	33	67

3.3.3.2 Drainage and nitrate-N losses measured in the alley, 2010/2011

In the 2010/2011 growing season, drainage losses in the alley were generally low (Figure 3.12) and ranged from 93 to 169 mm. In 2010/2011, the planted barley cover crop suffered from early winter kill November 20-27, 2010. This greatly reduced the effectiveness of this cover crop at taking up water and nitrate moving through the root zone. Rainy season alley drainage losses occurred in response to precipitation inputs (Figure 3.2) and ranged from 536 to 778 mm and over the full year from 621 to 947 mm.

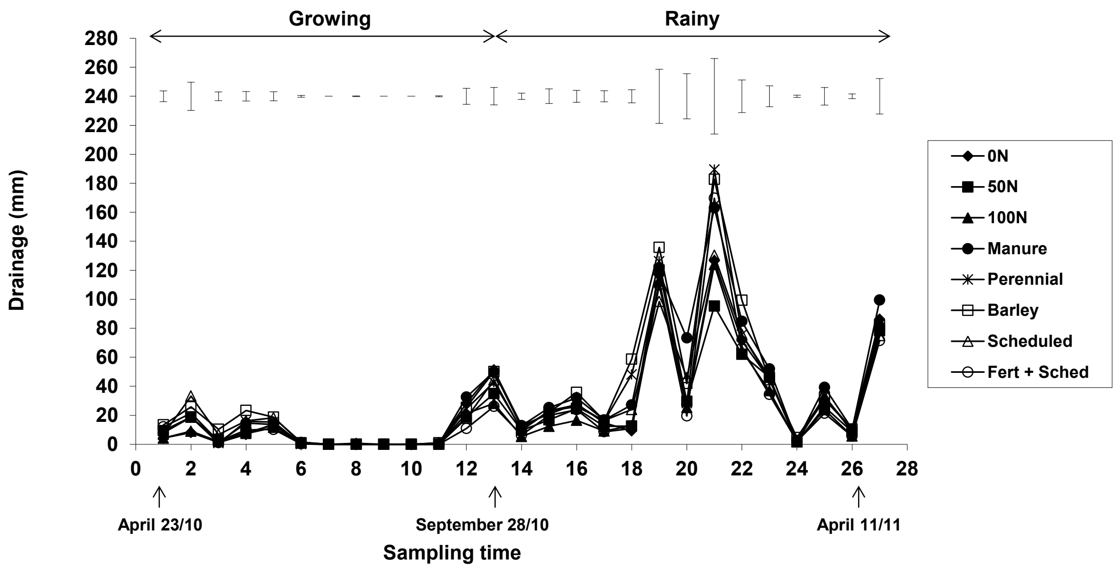

Figure 3.12: Drainage losses in the alley 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.12 and 3.13. Error bars represent +/- 1 SE.

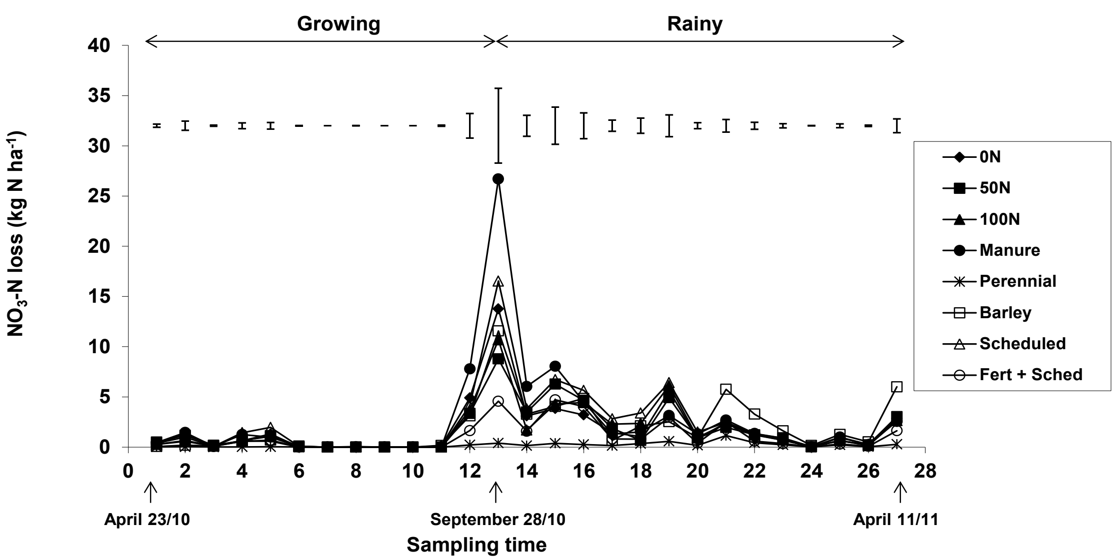

Figure 3.13: Nitrate-N losses in the alley in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Individual sampling periods were two weeks in length. Statistically significant time periods reported in Tables 3.12 and 3.13. Error bars represent +/- 1 SE.

Drainage in the alley in 2010/2011 was significantly higher under the barley cover crop compared to the tilled alleys of the 100N treatment in eight individual sampling times, all but one of which was in the rainy season (Table 3.12). The tilled alleys of the Manure treatment showed significantly higher drainage in six of the 14 individual sampling times comprising the rainy season. However, over the growing and rainy seasons and annually only the Barley treatment had a significant effect with approximately twice the drainage observed as compared to the tilled alleys of the 100N treatment (Table 3.13).

Table 3.12: Number of times and the individual samplings, that PCAP samplers in the alley measured significant (p<0.05) N, irrigation and alley treatment effects on drainage and nitrate-N losses, 2010/2011.

Effect	Drainage losses (mm)		NO_3-N losses (kg N ha^{-1})	
	No. times	Sampling(s)	No. times	Sampling(s)
N rate (L)	3	13,14,26	1	11
N rate (Q)	0		0	
Manure (M)	6	13,14,16,18,20,26	2	13,14
Perennial cover (P)	1	18	16	4,13-27
Barley cover (B)	8	4,13,14,16,18,22,24,26	8	2,17,19,21-24,26
Scheduled (S)	0		0	
Fertigated + Sched (F)	0		4	20,22,23,26

Table 3.13: Drainage and nitrate-N losses in the alley measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2010/2011.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	115	609	724	22	27	49
50N	107	544	651	16	31	47
100N	85	536	621	17	30	47
Manure	140	757	897	39	35	73
Perennial cover	128	715	843	1	4	5
Barley cover	169	778	947	17	37	54
Scheduled	145	615	760	26	39	65
Fertigated + Sched	93	570	663	9	21	30
SE	25	76	97	5	6	10
Significance	B	B	B	P	P	P

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect (p<0.05) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

In 2010/2011, nitrate-N losses in the alleys were low for all treatments during the growing season (Figure 3.13) and ranged from 1 to 39 kg N ha^{-1}. Nitrate-N losses increased in all treatments at the onset of the rainy season, cycled in response to precipitation events and ranged from 4 to 39 kg N ha^{-1}. Over the full year, nitrate-N losses ranged from 5 to 73 kg N ha^{-1}.

In eight sampling times during the 2010/2011 PCAP year, the effect of the barley cover on nitrate-N loss in the alley was significant (Table 3.12). In three samplings (including two in the fall prior to suffering winter kill), barley significantly reduced losses, while N losses increased under barley cover during the five samplings that followed winter-kill. Consequently, over the growing, rainy and annual seasons this treatment had no significant effect on nitrate-N loss (Table 3.13). Conversely, the perennial cover continued to scavenge for N, reducing nitrate-N losses. During the growing season, the perennial cover scavenged almost all the nitrate from the soil water moving through the root zone, significantly reducing nitrate-N loss by 24 times relative to the industry standard tilled alley of the 100N treatment. During the rainy season, the perennial cover reduced nitrate-N losses in all 14 individual sampling times. Over the entire rainy season nitrate-N losses under the perennial cover were a significant seven times less than that under tillage, and over the annual season a significant nine times less than tillage.

The effect of barley cover on ammonium-N loss from the alley root zone was significant over seven individual sampling times and over the growing, rainy and annual seasons during which it significantly increased ammonium-N losses (data not shown). The effect of the Manure treatment on ammonium-N losses in the alley was significant over the growing, rainy and annual seasons. Annual losses in all treatments were less than 0.2 kg NH_4-N ha^{-1}.

In 2010/2011, average growing and rainy season drainage losses in the alleys across all treatments were 16 and 84% of annual losses, respectively. Average nitrate-N losses in the growing and rainy seasons across all treatments were 35 and 65% of annual losses, respectively.

3.3.4 Row plus alley: drainage and nitrate-N losses measured as management totals

3.3.4.1 Drainage and nitrate-N losses as management totals, 2009/2010

The drainage and nitrate losses under the row and associated alley were combined by multiplying the fraction of the total field hectare area occupied by the row and alley managements to calculate an area-weighted management total for each measured PCAP parameter. In the 2009/2010, drainage losses measured under management totals ranged from 35 to 95 mm over the growing season, 548 to 721 mm over the rainy season and 600 to 801 mm over the year, with no statistical differences to report (Table 3.14). Growing season drainage losses across all treatments averaged 61 mm and amounted to 9% of annual totals. Drainage losses in the rainy season across all treatments averaged 616 mm or 91% of the annual totals.

Growing season nitrate-N losses in 2009/2010 measured under the combination of the row and alley managements ranged from 2 to 11 kg N ha^{-1} and averaged 13% of annual total nitrate-N losses across all treatments, with no significant treatment differences to report (Table 3.14). In the rainy season, nitrate-N losses ranged from 8 to 71 kg N ha^{-1}. Rainy season nitrate-N losses for the Perennial and Barley treatments were 78% of their annual totals. For the remaining treatments, an average of 90% of their annual losses occurred in the rainy season. Annual nitrate-N losses ranged from 12 to 83 kg N ha^{-1}. Over the rainy season and annually, the Perennial and Barley treatments significantly reduced nitrate-N losses relative to the 100N conventional management by an average of four times.

Table 3.14: Combined row and alley drainage and nitrate-N losses measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2009/2010.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	59	548	607	4	27	30
50N	54	562	616	4	31	35
100N	43	557	600	4	41	45
Manure	95	692	787	11	71	83
Perennial cover	77	659	737	4	8	12
Barley cover	80	721	801	3	14	17
Scheduled	35	604	639	2	53	55
Fertigated + Sched	42	584	626	2	23	25
SE	19	106	117	2	11	12
Significance	ns	ns	ns	ns	P, B	P, B

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect (p<0.05) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant.

3.3.4.2 Drainage and nitrate-N losses as management totals, 2010/2011

In the 2010/2011 growing season, drainage losses ranged from 100 to 303 mm. The Manure treatment significantly increased drainage by two times relative to the 100N treatment and the Fertigated + Scheduled treatment significantly decreased drainage by two times compared to the 50N treatment (Table 3.15). Average growing season drainage losses in treatments irrigated on a fixed schedule were 25% of annual losses while those irrigated on a scheduled regime lost only

15% of their annual totals during the growing season. Drainage averaged over all the treatments during the rainy season was 679 mm and no significant treatment effects were measured. Rainy season drainage losses were 75% of annuals totals for treatments under fixed irrigation and 85% for those under scheduled irrigation. No significant treatment effects were measured for annual drainage losses, which averaged 882 mm.

In the 2010/2011 growing season, nitrate-N losses ranged from 12 to 66 kg N ha^{-1}. Treatments irrigated on fixed regime lost, on average, 47% of their annual nitrate-N over the growing season, and those irrigated on a scheduled regime, 29% of their annual totals. Rainy season nitrate-N losses ranged from 27 to 82 kg N ha^{-1}. Manure had a significant effect on management total nitrate-N loss and increased losses by twice that of the 100N treatment over all time periods (Table 3.15). The Fertigated + Scheduled treatment significantly reduced nitrate-N losses by three and two times relative to the 50N treatment during the growing and annual seasons, respectively. During the rainy season, the Scheduled treatment significantly increased nitrate-N loss by twice that of the 100N conventional management, but this effect was not significant over the full year.

Table 3.15: Combined row and alley drainage and nitrate-N losses measured using PCAP samplers, as influenced by N, irrigation and alley management treatments over the growing, rainy and annual seasons, 2010/2011.

Treatment	Drainage losses (mm)			NO_3-N losses[a] (kg N ha^{-1})		
	Growing	Rainy	Annual	Growing	Rainy	Annual
0N	215	666	881	33	31	64
50N	229	636	865	34	37	71
100N	175	611	786	30	35	64
Manure	303	777	1080	66	82	148
Perennial cover	206	719	925	22	27	49
Barley cover	279	772	1051	33	41	74
Scheduled	116	644	760	22	58	79
Fertigated + Sched	100	607	706	12	27	39
SE	40	78	113	5	7	10
Significance	M, F	ns	ns	M, F	M, S	M, F

[a]Non-transformed data and standard errors presented
[b]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

3.3.5 Nitrate-N and water transport through the root zone

3.3.5.1 Transport in the row, 2009/2010

In the 2009/2010 growing season, cumulative nitrate-N losses in all treatments (except Manure) were less than approximately 10 kg N ha^{-1} and cumulative drainage losses less than ~100 mm

(Figure 3.14). Growing season cumulative nitrate-N and drainage losses in the Manure treatment were somewhat elevated relative to all other treatments. In the first few weeks of the rainy season, cumulative drainage (drainage accumulated from the date of the first fertilizer application and the beginning of the PCAP sampling year) for most treatments surpassed the estimated first pore volume (~150 mm). Following the displacement of the first pore volume, the slopes of the cumulative curves for all of the treatments (except Manure) began to level out as the rainy season continued to stimulate drainage, now containing lower amounts of N. The consistent slopes of the curves beyond the first pore volume indicated a consistent rainy season rate of nitrate-N loss, likely due to on-going net mineralization, nitrification and atmospheric deposition during the over-winter period. The time of year at which the rate of cumulative nitrate-N loading under the Manure treatment began to level out was similar to the other treatments but occurred at higher (~300 mm) cumulative drainage since this treatment consistently had higher drainage losses. In 2009, the row PCAPS under the Fertigated + Scheduled, Perennial and Barley treatments had the lowest cumulative nitrate-N losses on the row and the Manure and Scheduled treatments the highest.

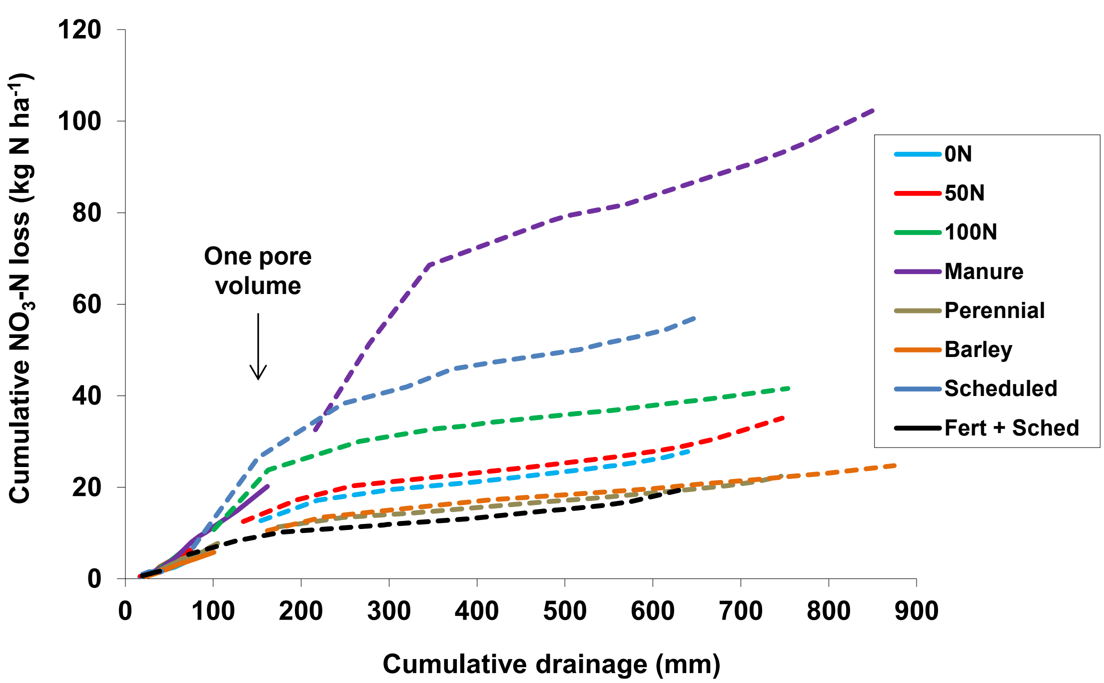

Figure 3.14: Cumulative drainage and nitrate-N losses in the raspberry row in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

In 2009/2010 in the row, the nitrate-N breakthrough curve showed early spring PCAP samplings with high flow-weighted nitrate concentration in the PCAP leachate at low cumulative drainage values, peak nitrate-N concentrations at approximately one soil pore volume (early in the rainy season) and then trailing tails as cumulative drainage continued but flow-weighted nitrate-N concentration in the PCAP leachate decreased (Figure 3.15). Based on this, the nitrate-N breakthrough formed a Gaussian type curve but indicated that the transport of nitrate-N may have been influenced by preferential flow both early in the growing season and over-winter. At approximately 150 mm of cumulative drainage, PCAPS under the Manure, Scheduled and 100N treatments measured greater peak flow-weighted nitrate-N concentration in the PCAP leachate than treatments with lower rates of N applied or the presence of cover crops in the associated alleys. Peak nitrate-N concentration was highest under the Manure treatment.

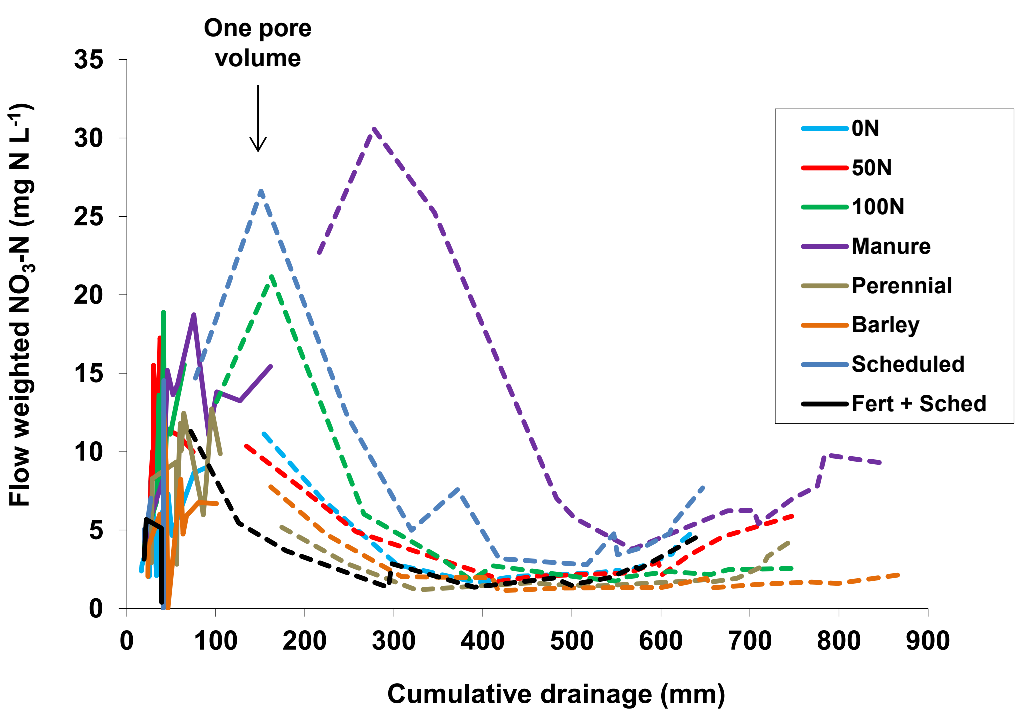

Figure 3.15: Cumulative drainage and flow-weighted nitrate-N concentration in the raspberry row in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

3.3.5.2 Transport in the alley, 2009/2010

Cumulative drainage losses in the 2009/2010 growing season in the alley were less than 70 mm for all treatments. Cumulative drainage volumes in the first few PCAP samplings of the rainy season surpassed the estimated first soil pore volume flushing the residual nitrate-N from the soil profile. Beyond this point, cumulative nitrate-N losses in the tilled alleys of the Manure, Scheduled and 100N treatments were higher than treatments with lower rates of applied N on the row (Figure 3.16). Differences in cumulative nitrate-N losses under the treatments can be attributed primarily to losses in the early part of the rainy season as the slopes of the curves for all treatments (except the cover crops) indicated a similar rate of cumulative nitrate-N loss over the majority of the rainy season. The presence of the perennial and barley cover crops greatly reduced cumulative nitrate-N losses in the alley. While drainage through the soil profile in these alley cover crop treatments continued, the slope of the curves and the magnitude of the cumulative losses indicated substantial uptake of nitrate-N, which lowered the rate of loss and quantity of nitrate-N present in the PCAP leachate.

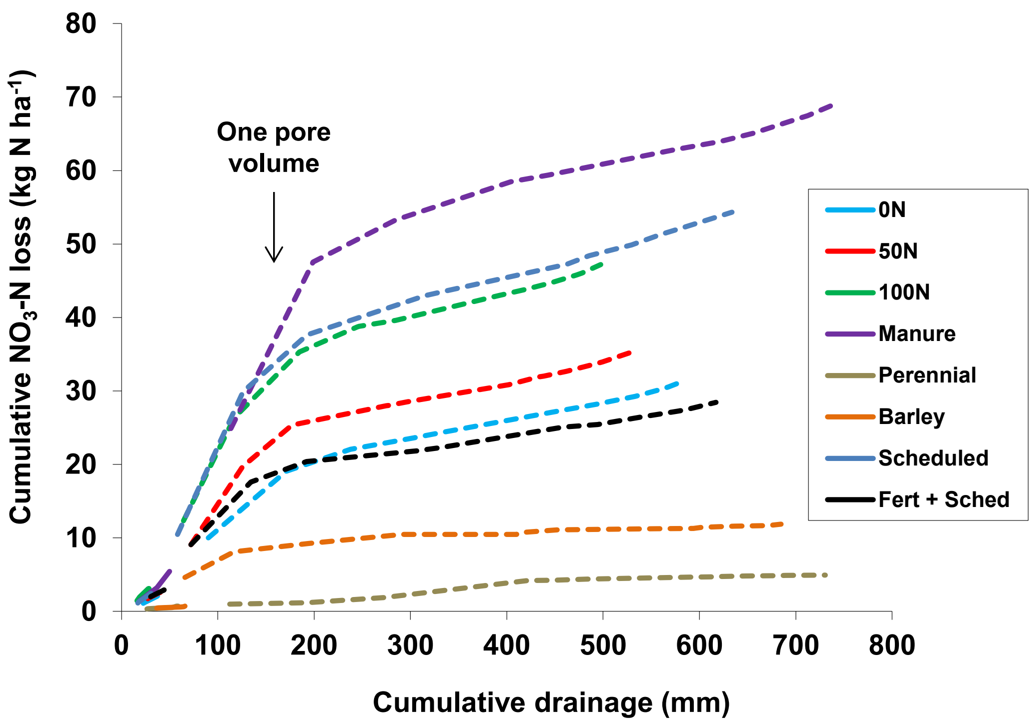

Figure 3.16: Cumulative drainage and nitrate-N losses in the alley in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

In 2009/2010, the nitrate-N breakthrough curves for the alley showed flow-weighted nitrate-N concentrations in the PCAP leachate that peaked at approximately one soil pore volume (Figure 3.17). Flow-weighted nitrate-N concentrations were highest for the Manure, Scheduled and 100N treatments and lowest for the Perennial and Barley treatments which reduced nitrate-N moving through the alley soil profile.

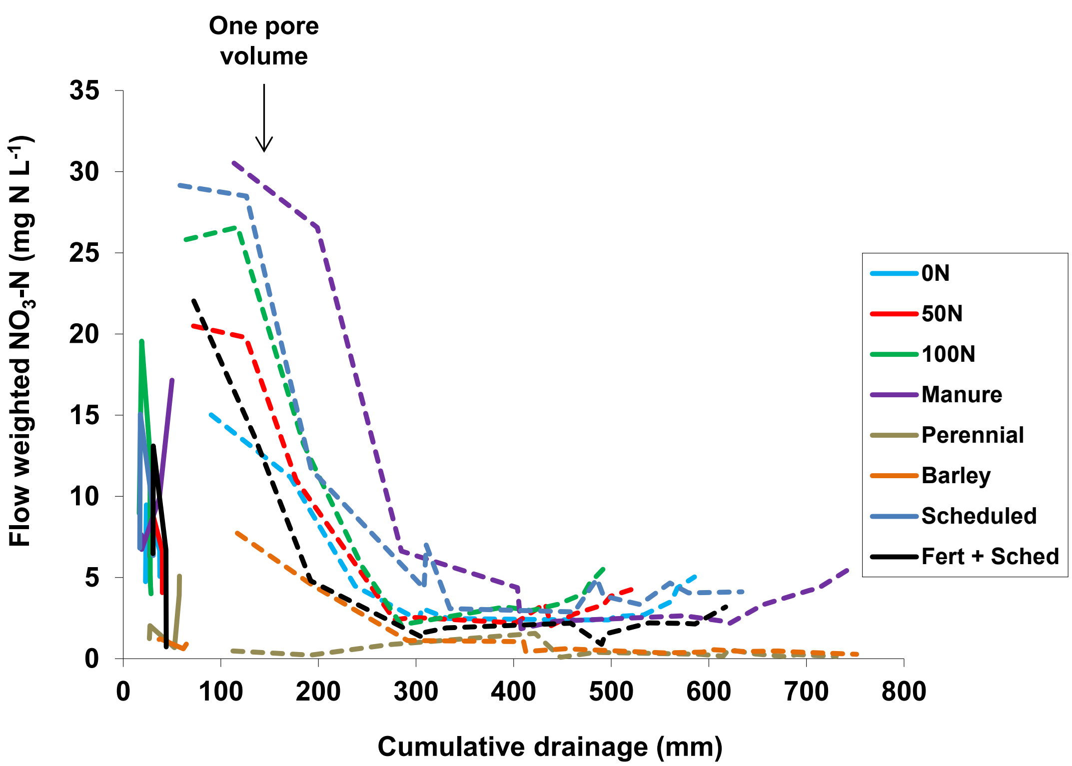

Figure 3.17: Cumulative drainage and flow-weighted nitrate-N concentration in the alley in 2009/2010, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

3.3.5.3 Transport in the row, 2010/2011

In 2010/2011, cumulative drainage losses in the row in all treatments under fixed irrigation were higher due to increased volumes of irrigation water applied which resulted in leaching losses. Unlike 2009/2010, in which growing season drainage losses in the row were limited, consistent drainage losses were recorded in the row under fixed irrigation throughout the 2010/2011 growing season. During the growing season, transport of nitrate-N through the soil profile in all treatments under fixed irrigation occurred at a similar rate as indicated by the similarity in slopes of the cumulative nitrate-N loss curves (Figure 3.18). Growing season cumulative drainage losses under fixed irrigation surpassed one soil pore volume (~150 mm) at approximately the mid-way point of harvest (end of July), an indication of excessive growing season drainage. However, the rate of cumulative nitrate-N loss under fixed irrigation remained nearly constant until the end of the 2010 irrigation season. As irrigation ended and the 2010/2011 rainy season began, the slopes of the cumulative loss curves decreased and then stabilized over the remainder of the rainy season. The exception to this pattern was the Manure treatment which showed a sharp increase in cumulative nitrate-N losses as precipitation in the first few samplings of the rainy season flushed remaining residual nitrate from the root zone of this treatment. Following this flush of nitrate-N from the Manure treatment, the rate of loss decreased and became similar to all the other treatments. For treatments irrigated on a fixed schedule, cumulative nitrate-N losses in the row were highest under the Manure treatment and lowest under the 0N treatment.

Cumulative nitrate-N losses under the treatments irrigated on a scheduled regime were low during the 2010/2011 growing season (Figure 3.18). The leaching of residual nitrate-N retained in the root zone of these treatments began with the arrival of the rainy season and was particularly noticeable in the Scheduled treatment, as evidenced by a sharp rise in the cumulative loss curve for this treatment. By the third PCAP sampling of the rainy season cumulative drainage losses in the treatments under scheduled irrigation had surpassed one soil pore volume and at this point the rate of cumulative nitrate-N losses in these treatments decreased to a similar, consistent rainy season rate of nitrate-N loss as the treatments that had been irrigated on the fixed regime.

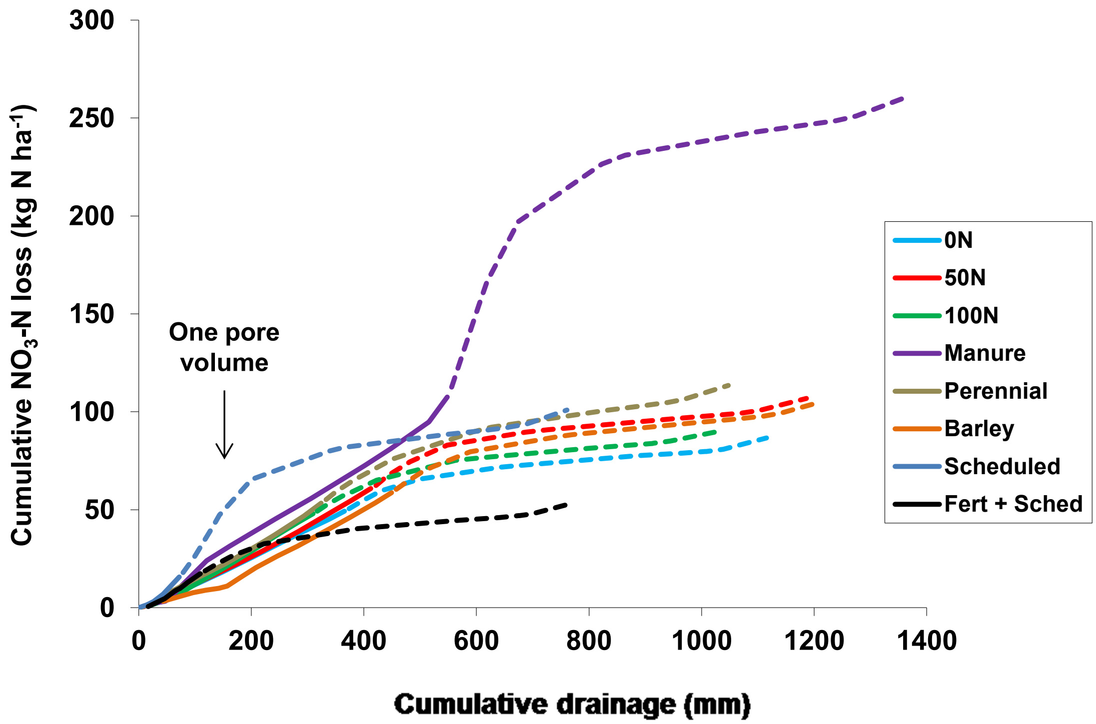

Figure 3.18: Cumulative drainage and nitrate-N losses in the raspberry row in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

In 2010/2011 in the row, the nitrate-N breakthrough curves for treatments under fixed irrigation varied significantly in form from those observed in the row in 2009/2010. The breakthrough curves for the treatments under fixed irrigation lacked clearly defined peaks to indicate drainage of the first soil pore volume and therefore the transport of the center of mass of fertilizer-N out of the root zone (Figure 3.19). Rising limbs were identifiable at low cumulative drainage values (in spring and early summer) when PCAP leachate had elevated flow-weighted nitrate-N. In general, the treatments irrigated on the fixed regime showed small peaks on their breakthrough curves, observed at approximately 100 mm of cumulative drainage. These may identify preferential flow, or, early growing season leaching losses driven by precipitation events and increased irrigation applications. At 100 mm of cumulative drainage, flow-weighted concentration was highest for the Manure treatment, which peaked at ~ 30 mg L^{-1} NO_3-N. Following these early growing season peaks, flow-weighted nitrate-N concentration in treatments under fixed irrigation decreased to around 15 to 20 mg L^{-1} NO_3-N and remained consistent for the majority of the growing season. In the Manure treatment the arrival of the rainy season and the flushing of residual nitrate-N from the soil profile was evidenced by high peak flow-weighted nitrate-N concentrations (~90 mg N L^{-1}) recorded in the PCAP leachate, which decreased to values comparable to all other treatments early in the rainy season. In the remaining treatments that had been irrigated under fixed irrigation, flow-weighted nitrate-N concentrations in the leachate gradually decreased from 15-20 mg L^{-1} NO_3-N to a rainy season background level of 5 mg L^{-1} NO_3-N or less.

As in 2009/2010, the nitrate-N breakthrough curves in the row in 2010/2011 for the Fertigated + Scheduled and Scheduled treatments took on a Gaussian type form (Figure 3.19) with some tailing. May and April losses were low and there were negligible drainage and nitrate-N losses during the majority of the growing season. As cumulative drainage values for these two treatments reached one soil pore volume in the first few samplings in the rainy season, flow-weighted nitrate-N concentrations in the PCAP leachate under these treatments peaked as the center of mass of residual nitrate-N was leached from the root zone. This was particularly evident in the Scheduled treatment with fertilizer N applied at 100 kg N ha^{-1}. Beyond the peaks on the breakthrough curves, flow-weighted nitrate-N concentrations decreased as cumulative drainage continued into the rainy season and then stabilized at a rainy season background level of 5 mg L^{-1} NO_3-N or less, similar to the other treatments in the experiment.

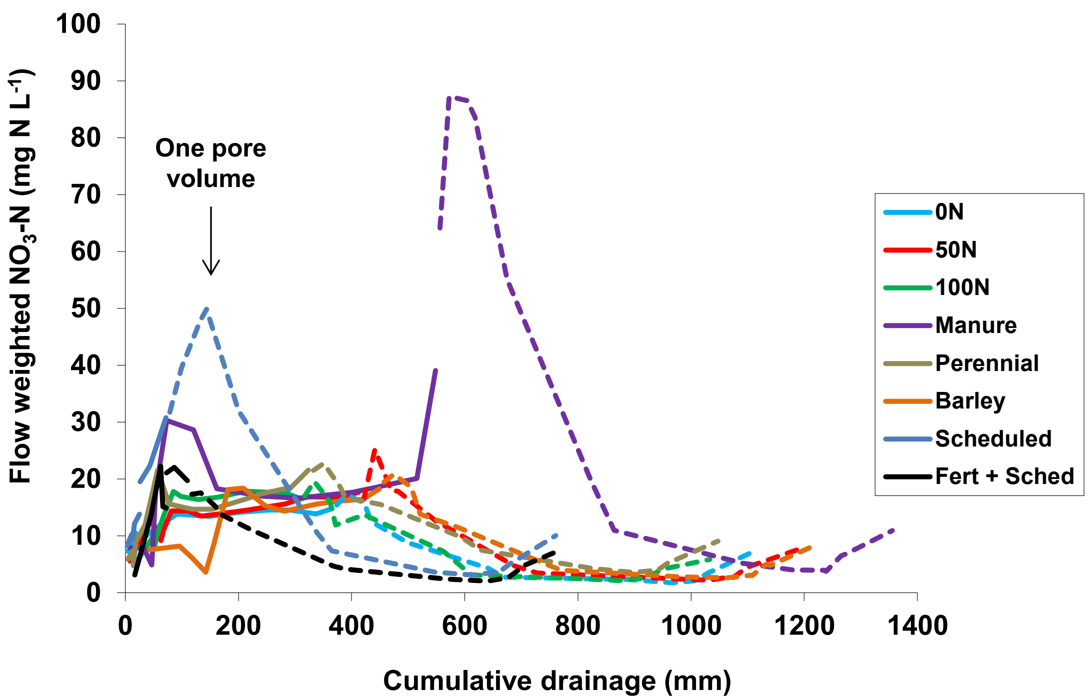

Figure 3.19: Cumulative drainage and flow-weighted nitrate-N concentration in the raspberry row in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

3.3.5.4 Transport in the alley, 2010/2011

Cumulative drainage losses in the 2010/2011 growing season in the alley were low. Cumulative drainage volumes in the first PCAP sampling of the rainy season surpassed the estimated first soil pore volume. Beyond this point, cumulative nitrate-N losses in the tilled alleys of the Manure and Scheduled treatments were highest while the Fertigated + Scheduled and Perennial treatments were lowest (Figure 3.20). The slopes of the curves for all treatments (except the perennial cover) indicated a similar rate of cumulative nitrate-N loss over the rainy season. The perennial cover crop greatly reduced cumulative nitrate-N losses in the alley. In 2010, the barley cover suffered early winter kill (November 20-27) which left little viable barley cover crop to take up nitrogen moving through the soil profile and resulted in cumulative nitrate-N losses similar in magnitude to the alleys under conventional tillage.

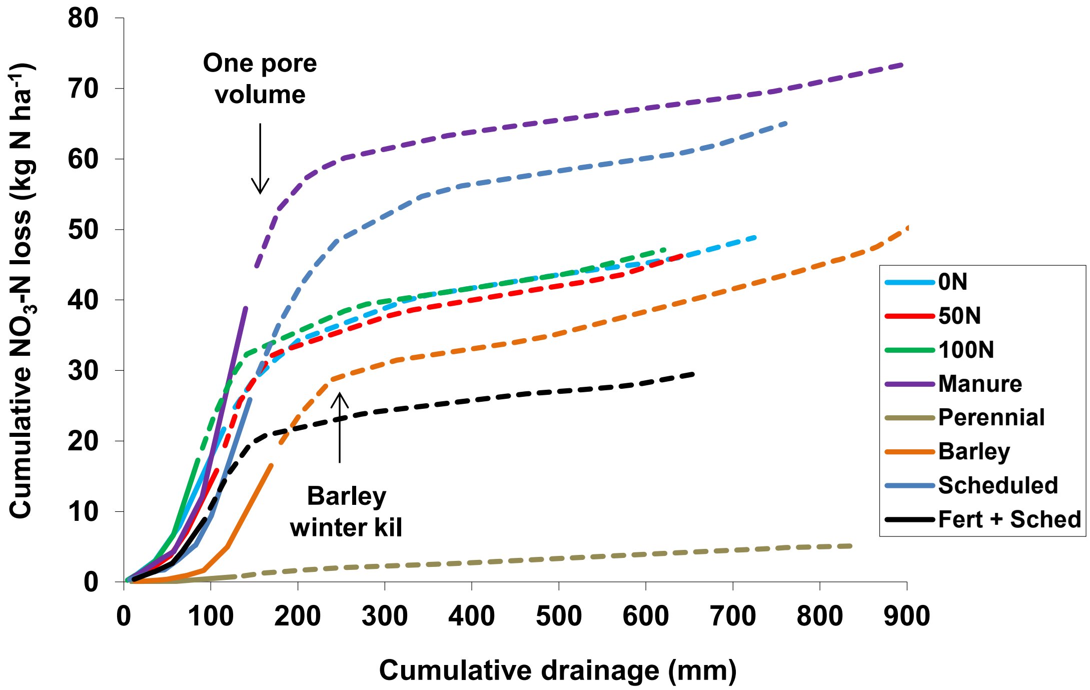

Figure 3.20: Cumulative drainage and nitrate-N losses in the alley in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

As in 2009/2010, the 2010/2011 nitrate-N breakthrough curves for the alley showed flow-weighted nitrate-N concentrations in the PCAP leachate that peaked at approximately one soil pore volume and followed a typical Gaussian form (Figure 3.21). Peak flow-weighted nitrate-N concentration was highest for the Manure treatment at 53 mg L^{-1} NO_3-N. A peak on the breakthrough curve for the Perennial treatment was just detectable at 2 mg L^{-1} NO_3-N.

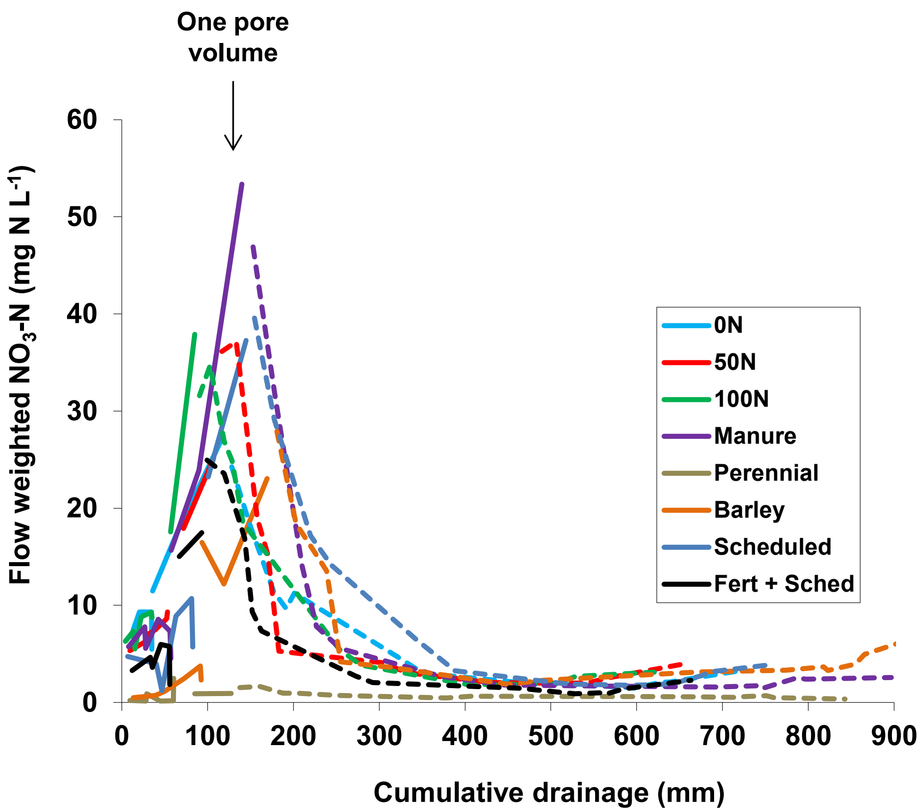

Figure 3.21: Cumulative drainage and flow-weighted nitrate-N concentration in the alley in 2010/2011, measured using PCAP samplers, as influenced by N, irrigation and alley management treatments. Solid lines represent losses during the growing season and dashed lines the rainy season.

3.3.5.5 Annual flow-weighted nitrate-N concentrations in drainage water over management totals

In 2009/2010, the annual flow-weighted nitrate-N concentrations leaving the root zone at a depth of 55 cm were lowest in the Perennial and Barley treatments (2 mg L^{-1}) which had effectively scavenged for the majority of excess nitrate-N, and was highest in the Manure treatment (10 mg L^{-1}). The nitrate-N concentration in the Manure treatment was already at the Canadian drinking water guideline for nitrate-N following the first year of treatment applications (Table 3.16). The treatments with 100 kg N ha^{-1} applied on the row and no alley cover crops had the next highest nitrate-N concentrations (just below the drinking water guideline) with the reduced N rate treatments at concentrations about half of the drinking water guideline. In 2010/2011, flow-weighted nitrate-N concentrations increased in almost all treatments. Cover crops again had the lowest flow-weighted nitrate-N concentrations, followed by the reduced N rate treatments, the

100 kg N ha^{-1} treatments without cover crops and finally the Manure treatment, at 14 mg L^{-1} nitrate-N.

Table 3.16: Annual flow-weighted nitrate-N concentrations for combined row and alley managements measured using PCAP samplers, as influenced by N, irrigation and alley management treatments.

Treatment	Annual flow-weighted NO_3-N (mg L^{-1})	
	2009/2010	2010/2011
0N	5	7
50N	6	8
100N	8	8
Manure	10	14
Perennial cover	2	5
Barley cover	2	7
Scheduled	9	10
Fertigated + Sched	4	6

3.3.6 PCAP sampler collection efficiency

Sampler collection efficiencies of the alley and row PCAPS for each sampling year were calculated using a simple water balance to compare expected drainage (precipitation + irrigation – ET_o) to PCAP measured drainage (Table 3.17). PCAPS under the fixed and scheduled irrigation regimes were handled separately due to differing water input amounts. Measured drainage and expected drainage matched well with collection efficiencies ranging between 70 to 105%, with a mean of 87% over the reporting period.

Table 3.17: Expected drainage from a simple water balance (Precipitation (P) + Irrigation (I) – ET_o) to calculate row and alley PCAP sampler collection efficiencies (Measured drainage/Expected drainage *100) over individual sampling years.

Year, Location/Irrigation	P + I (mm)	ET_o (mm)	Expected drainage (mm)	Measured drainage (mm)	Collection efficiency (%)
2009/2010, Alley	1400	795	605	636	105
2009/2010, Row/Fixed	1685	795	890	769	86
2009/2010, Row/Scheduled	1552	795	757	643	85
2010/2011, Alley	1674	734	940	763	82
2010/2011, Row/Fixed	1994	734	1260	1159	92
2010/2011, Row/Scheduled	1832	734	1098	766	70

3.4 Soil nitrate-N and ammonium-N content

3.4.1 Soil nitrate-N and ammonium-N content, 0 to 30 cm, 2009

In 2009, soil NO_3-N content in the row on April 3 (following the over-winter rainy season and before treatment application) was low for all treatments (Table 3.18) following complete over-winter leaching of the soil profile. On this sampling date, the barley cover crop significantly reduced soil nitrate in the row by about 50% compared to the 100N treatment. At first berry ripening (June 29/09), soil nitrate increased (Figure 3.22) and ranged from 8 to 105 kg N ha^{-1}. Soil nitrate increased linearly with increasing N rate and this effect was significant on the June 29/09 sampling. On this date, the Scheduled treatment significantly reduced soil nitrate content by two times, relative to the 100N treatment. Post-harvest (August 19/09) soil NO_3-N was generally low in all treatments likely due to plant uptake and the movement of nitrate downward in the soil profile and ranged from 5 to 31 kg N ha^{-1}. On this date, both the 0N and the Barley treatments had significantly lower soil nitrate-N (about three times) than the 100N treatment. Based on post-harvest soil nitrate, all treatments had low to very low residual soil nitrate-N (Table 1.1). On the September 28/09 sampling, soil nitrate-N in the row averaged 30 kg N ha^{-1} over all the treatments, with no significant effects to report.

Table 3.18: Soil NO_3-N and NH_4-N content to 30 cm depth in the raspberry row on four sampling dates, as influenced by N, irrigation and alley management treatments, 2009.

Treatment	April 3/09		June 29/09		August 19/09		September 28/09	
	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N
	kg N ha^{-1}							
0N	13	21	8	15	5	12	23	12
50N	13	22	38	36	9	10	21	9
100N	17	21	78	63	28	15	35	9
Manure	11	20	105	22	31	13	47	12
Perennial cover	14	21	63	41	17	14	26	14
Barley cover	9	18	69	47	7	11	24	10
Scheduled	14	25	35	66	31	15	40	10
Fertigated + Sched	13	24	35	15	8	8	21	16
SE	2	2	10	13	4	3	6	2
Significance[a]	B	ns	L, S	L, M	L, B	ns	ns	F

[a]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

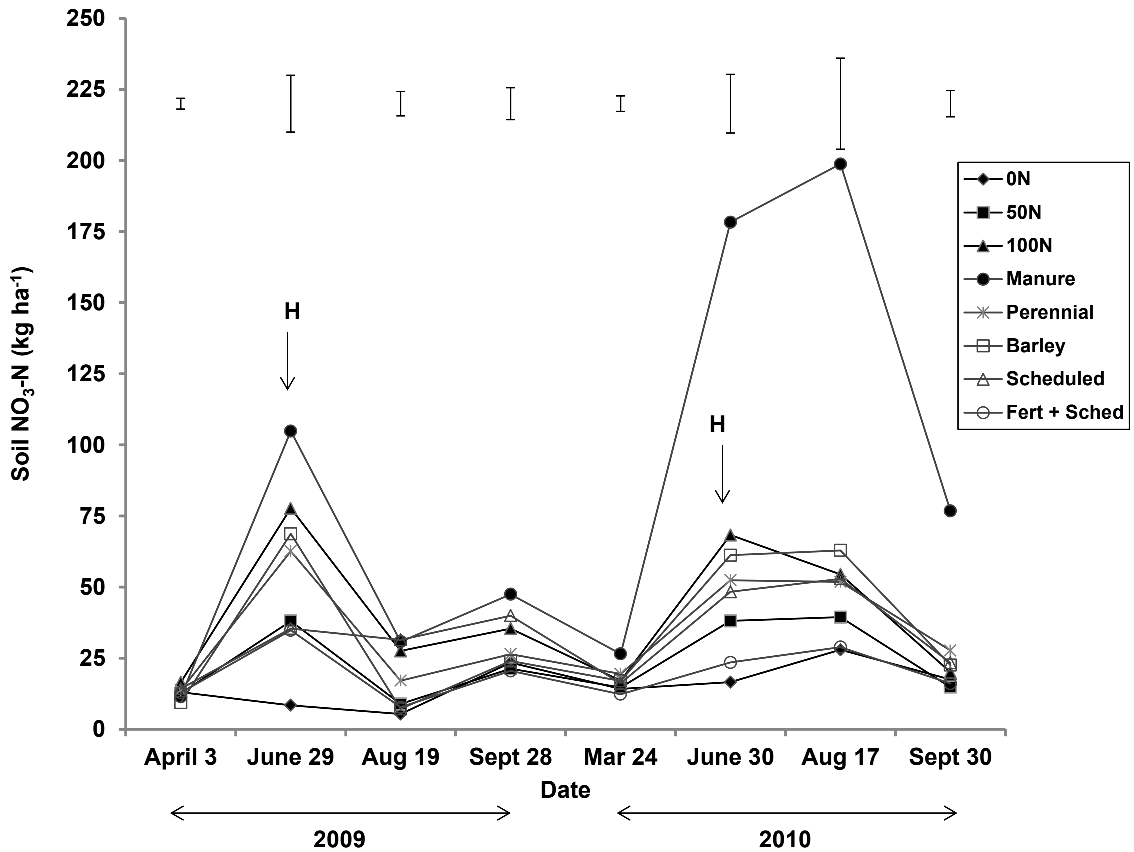

Figure 3.22: Soil extractable nitrate-N in the raspberry row, 0 to 30 cm, in 2009 and 2010, as influenced by N, irrigation and alley management treatments. Statistically significant sampling dates reported in Tables 3.18 and 3.20. The arrow "H" represents times of first berry ripening. Error bars represent +/- 1 SE.

Soil NH_4-N in the row on April 3rd averaged 22 kg N ha^{-1} and did not vary among treatments (Table 3.18). The soil NH_4-N pattern over the growing season (Figure 3.23) was similar to that of nitrate, peaking at harvest. On the June 29/09 sampling, soil NH_4-N ranged from 15 to 66 kg N ha^{-1}. Soil NH_4-N was significantly reduced in the 0N and Manure treatments relative to the 100N treatment. The August 19/09 sampling time showed no treatment differences in soil NH_4-N and an average of 12 kg N ha^{-1} over all treatments. On the September 28/09 sampling, the effect of the Fertigated + Scheduled treatment was significant, increasing soil NH_4-N relative to the 50N treatment.

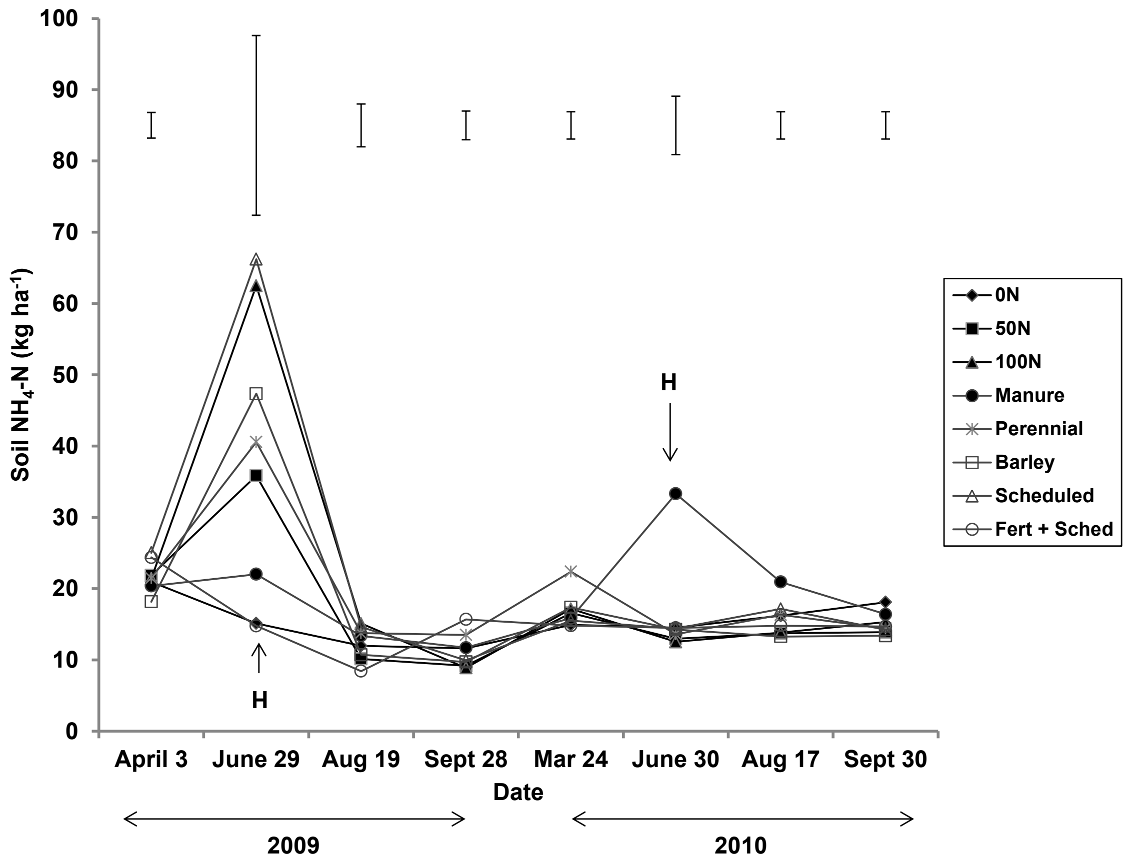

Figure 3.23: Soil extractable ammonium-N in the raspberry row, 0 to 30 cm, in 2009 and 2010, as influenced by N, irrigation and alley management treatments. Statistically significant time periods reported in Tables 3.18 and 3.20. The arrow "H" represents times of first berry ripening. Error bars represent +/- 1 SE.

In the alleys in 2009, the perennial and barley covers reduced soil nitrate relative to the tilled alleys of the 100N treatment by an average of 20 and two times, respectively (Table 3.19 and Figure 3.24). The effect of the perennial cover was significant at all four sampling dates and that of barley at three sampling dates. Soil NH_4-N contents in the alleys were generally low over all samplings and treatment effects limited. Cover crops, depending on the sampling time, both increased and decreased soil NH_4-N relative to tillage (Table 3.19 and Figure 3.25).

Table 3.19: Soil NO_3-N and NH_4-N content to 30 cm depth in the alley on four sampling dates, as influenced by N, irrigation and alley management treatments, 2009.

Treatment	April 3/09		June 29/09		August 19/09		September 28/09	
	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N
	kg N ha^{-1}							
100N	3	12	49	14	18	9	33	8
Perennial cover	0	8	0	7	1	9	4	12
Barley cover	0	6	13	21	14	13	17	13
SE	1	2	4	3	3	2	3	2
Significance[a]	P, B	B	P, B	ns	P	ns	P, B	ns

[a]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

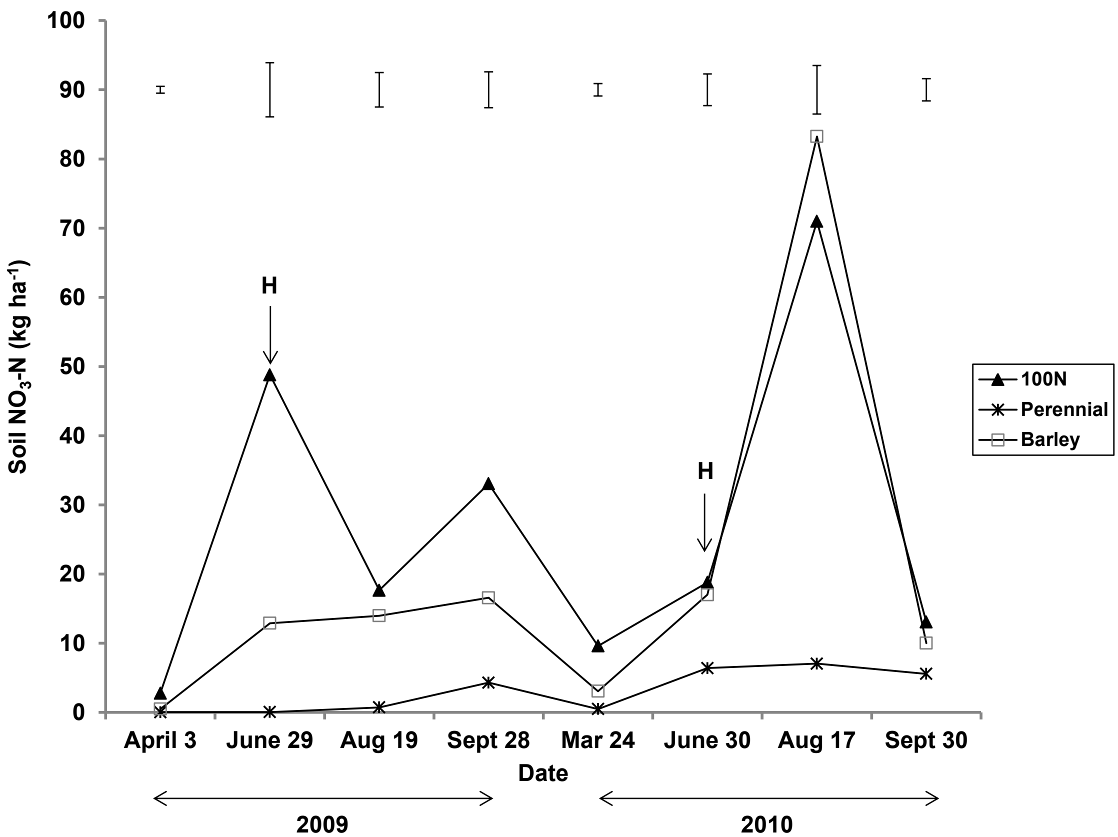

Figure 3.24: Soil extractable nitrate-N in the alley, 0 to 30 cm, in 2009 and 2010, as influenced by N, irrigation and alley management treatments. Statistically significant time periods reported in Tables 3.19 and 3.21. The arrow "H" represents times of first berry ripening. Error bars represent +/- 1 SE.

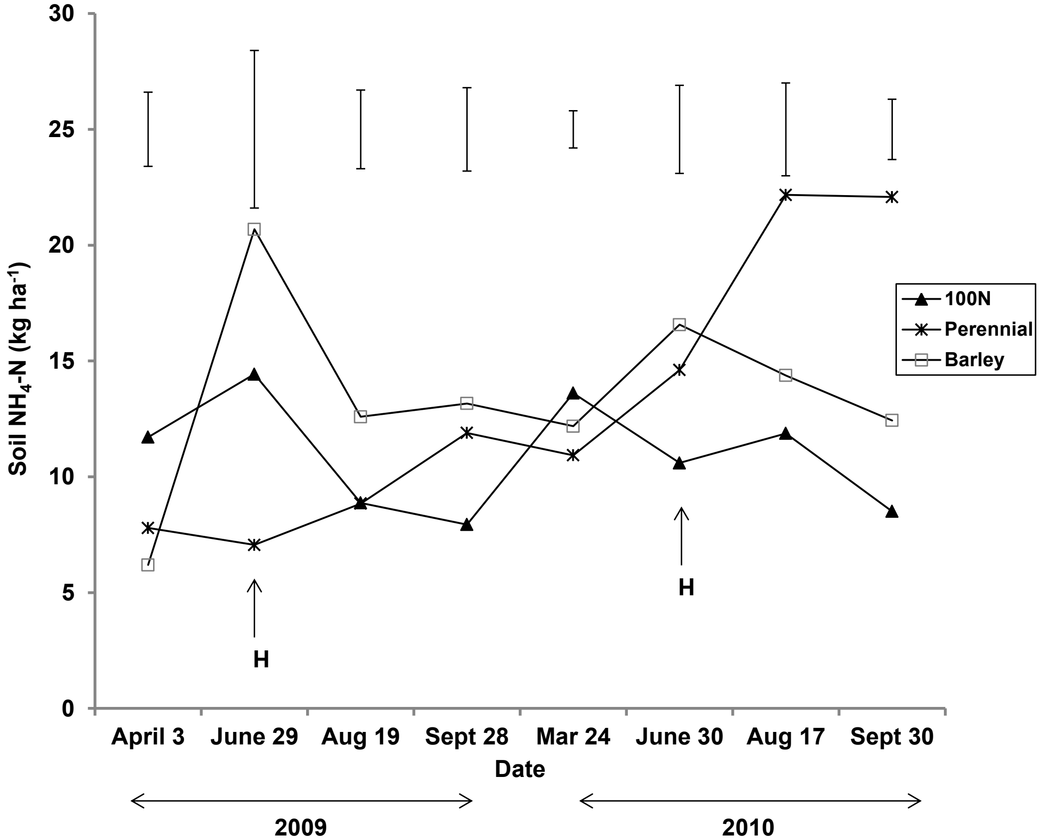

Figure 3.25: Soil extractable ammonium-N in the alley, 0 to 30 cm, in 2009 and 2010, as influenced by N, irrigation and alley management treatments. Statistically significant time periods reported in Tables 3.19 and 3.21. The arrow "H" represents times of first berry ripening. Error bars represent +/- 1 SE.

3.4.2 Soil nitrate-N and ammonium-N content, 0 to 30 cm, 2010

On March 24/10, soil NO_3-N content to 30 cm depth in the row for non-manured treatments had decreased following the rainy season to an average of 16 kg N ha^{-1}, which was similar to spring levels in 2009. The 100N treatment measured 17 kg N ha^{-1} which was significantly less than the 27 kg N ha^{-1} for the Manure treatment (Table 3.20). Soil nitrate increased in most treatments at harvest time (June 30/10 sampling) and ranged from 17 to 178 kg N ha^{-1} (Figure 3.22). At harvest, there was a linear response to N rate with the 0N treatment having four times less soil NO_3-N than the 100N treatment. Soil NO_3-N measured in the Manure treatment was significantly higher and almost three times that in the 100N treatment. The effect of the Manure treatment remained significant at the post-harvest (August 17/10) and September 30/10 sampling times and increased soil nitrate by four times and three times that of the 100N treatment at those sampling times, respectively. Soil NH_4-N to 30 cm on the row showed treatments effects limited to a significant effect of the Manure treatment at the harvest and post-harvest sampling times (Table 3.20 and Figure 3.23).

Table 3.20: Soil NO_3-N and NH_4-N content to 30 cm depth in the raspberry row on four sampling dates, as influenced by N, irrigation and alley management treatments, 2010.

Treatment	March 24/10		June 30/10		August 17/10		September 30/10	
	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N
	kg N ha^{-1}							
0N	14	15	17	15	28	16	17	18
50N	15	17	38	13	39	14	15	14
100N	17	17	68	13	54	14	20	15
Manure	27	16	178	33	199	21	77	16
Perennial cover	19	22	52	14	52	16	28	14
Barley cover	17	17	61	14	63	13	23	13
Scheduled	16	16	48	14	53	17	23	14
Fertigated + Sched	12	15	24	14	29	15	16	15
SE	3	2	10	4	16	2	5	2
Significance[a]	M	ns	L, M	M	M	M	M	ns

[a]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

In the alleys in 2010, soil NO_3-N was significantly lower at all four sampling times for perennial cover which decreased soil nitrate by an average of six fold relative to tillage (Table 3.21 and Figure 3.24). The barley cover performance was inconsistent and offered reductions in soil nitrate at certain sampling times and increases or no difference at others. Soil NH_4-N content to 30 cm in the alley was significantly greater in the perennial cover plots than under tillage at the post-harvest and fall samplings (Table 3.21 and Figure 3.25).

Table 3.21: Soil NO_3-N and NH_4-N content to 30 cm depth in the alley on four sampling dates, as influenced by N, irrigation and alley management treatments, 2010.

Treatment	March 24/10		June 30/10		August 17/10		September 30/10	
	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N
	kg N ha^{-1}							
100N	10	14	19	11	71	12	13	9
Perennial cover	0	11	6	15	7	22	6	22
Barley cover	3	12	17	17	83	14	10	12
SE	1	1	2	2	3	2	2	1
Significance[a]	P, B	P	P	ns	P, B	P	P	P

[a]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

3.5 Plant Response

3.5.1 Plant vigour and nitrogen status

In 2009, plant response to the N, water and alley management strategies was limited (Table 3.22). Primocane leaf N concentration in 2009 increased linearly with N rate and was also significantly higher in the Manure treatment relative to the 100N treatment. There was a significant quadratic response in cane N concentrations such that the 50N treatment had lower cane N concentration relative to the 0N and 100N treatments. The perennial treatment also significantly reduced cane N concentration relative to the 100N treatment. In 2009, cane diameter and length increased linearly with increasing N rate.

Table 3.22: Primocane leaf N, N status and vigour measures, as influenced by N, irrigation and alley management treatments, 2009.

Treatment	Leaf N[a] (%)	Cane N[b] (%)	Diameter[b] (mm)	Length[b] (m)
0N	2.2	0.95	8.6	2.03
50N	2.4	0.85	9.8	2.41
100N	2.5	0.93	10.4	2.65
Manure	2.7	0.96	10.1	2.67
Perennial	2.3	0.84	9.7	2.60
Barley	2.4	0.90	10.0	2.58
Scheduled	2.5	0.95	9.8	2.46
Fertigated + Sched	2.3	0.87	9.4	2.28
SE	0.1	0.02	0.3	0.08
Significance[c]	L, M	Q, P	L	L

[a]September 29, 2009 primocane sampling
[b]December 15, 2009 primocane sampling
[c]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

There were no significant treatment effects on primocane leaf N, cane N, cane diameter or length measurements in 2010 (Table 3.23). There was significant quadratic response to N rate in the final count of viable primocanes following removal of canes for sampling and by pruning, such that there were more primocanes in the 50N treatment compared to the 0N and 100N treatments.

Table 3.23: Primocane N status and vigour measures, as influenced by N, irrigation and alley management treatments, 2010.

Treatment	Leaf N[a] (%)	Cane N[b] (%)	Diameter[b] (mm)	Length[b] (m)	Viable canes[bc] (#)
0N	3.2	0.90	10.7	2.54	63
50N	3.1	0.91	11.3	2.64	83
100N	3.2	0.92	11.5	2.60	64
Manure	3.3	0.96	11.4	2.71	81
Perennial	3.1	0.90	10.7	2.64	68
Barley	3.2	0.93	11.6	2.72	74
Scheduled	3.2	0.96	11.6	2.65	63
Fertigated + Sched	3.0	0.84	11.7	2.64	66
SE	0.1	0.03	0.5	0.08	7
Significance[d]	ns	ns	ns	ns	Q

[a]September 21, 2010 primocane leaf sampling
[b]January 11, 2011 primocane sampling
[c]Viable canes is the number of primocanes left after sampling and the removal of weak primocanes
[d]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

Similarly, the N, irrigation and alley treatment effects on the floricane measurements at first berry ripening (week of June 25-30) in 2010 were limited, with no differences in leaf concentration, cane N concentration or the number of fruiting structures (berries and/or flowers) to report (Table 3.24). The 0N treatment showed significantly lower N content in the laterals but significantly higher numbers of laterals and smaller cane diameters than the 100N treatment. Compared to the 100N treatment, the Manure treatment had significantly higher lateral N content and the floricanes next to alleys planted with the barley cover crop significantly lower cane diameters.

Table 3.24: Floricane N status and vigour measures at first berry ripening, as influenced by N, irrigation and alley management treatments, 2010.

Treatment	Leaf N (%)	Cane N (%)	Lateral N (%)	Diameter (mm)	Fruit Structures (#)	Laterals (#)
0N	2.1	0.44	1.63	10.4	202	22
50N	2.1	0.48	1.99	12.1	244	18
100N	2.2	0.48	2.20	13.1	243	18
Manure	2.5	0.50	2.37	13.2	257	18
Perennial	2.2	0.47	2.20	12.4	251	18
Barley	2.3	0.49	2.29	11.7	219	18
Scheduled	2.3	0.50	2.20	12.5	264	19
Fertigated + Sched	2.1	0.50	2.15	11.9	262	19
SE	0.1	0.02	0.05	0.5	26	1
Significance[a]	ns	ns	L, M	L, B	ns	L

[a]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

3.5.2 Yield

The 2010 growing season produced the first crop of 'Saanich' raspberries and demonstrated limited treatment effects on berry yield and no effects on mean berry weight (Table 3.25). There was a linear response to N rate with the 0N treatment showing a 25% reduction in yield compared to the 100N treatment. It is noteworthy that the raspberry plots neighbouring the alleys planted with perennial cover had the highest yield in 2010 (although this effect was not statistically significant).

Table 3.25: Yield and mean berry weight of 'Saanich' raspberry as influenced by N, irrigation and alley management treatments, 2010.

Treatment	Yield[a] (kg ha^{-1})	Berry wt. (g)
0N	8507	3.6
50N	10307	4.0
100N	11412	3.9
Manure	9688	4.2
Perennial	12225	4.1
Barley	10178	4.1
Scheduled	9397	3.9
Fertigated + Sched	10447	3.7
SE	821	0.1
Significance[b]	L	ns

[a]Total yield measured on 12 canes per plot (all plots standardized to 48 canes)
[b]Contrast showed significant effect ($p<0.05$) of; L=N rate linear, Q=N rate quadratic, M=Manure (N source), P=Perennial cover, B=Barley cover, S=Scheduled, F=Fertigated + Scheduled, ns=Not significant

Chapter 4: Discussion

4.1 PCAP sampler performance

In comparing drainage and nitrate-N losses measured by PCAP samplers the validity of statistical comparisons among treatments is reliant upon the leachate volume being accurate, or for collection to have a consistent systematic error. Soil water potential was monitored at the edge of the PCAP installations and in undisturbed soil at the same depth and in the same plot to check for disturbance effects due to the presence of the PCAP instrumentation and any sampling biases related to treatments imposed. Overall collection efficiency of the PCAPS was also assessed.

Under both the fixed and scheduled irrigation regimes, time periods were identified during which soil water potential in undisturbed soil was different than that measured at the edge of the PCAP instrumentation (Figure 3.5); however, overall, the differences in time-averaged soil water potential between the two monitoring locations on each plot were ~2 kPa or less (Table 3.3), indicating a small disturbance of the native water potential due to the presence of the PCAPS. This result is consistent with the findings of other researchers who chose PCAPS for their ability to continuously monitor soil water in the unsaturated zone and who, through tracer breakthrough studies, concluded that wick samplers caused only minimal disturbance to the native flow regimes in the experimental soils (Boll et al., 1992; Brandi-Dohrn et al., 1996b).

The efficacy of the PCAP samplers was also evidenced by comparing measured drainage with expected drainage, collected over a range of fluxes in the current research, calculated using a simple water balance. Average collection efficiency was 87% over the two year reporting period (Table 3.17). This result agrees closely with collection efficiencies of other PCAP designs reported in the literature of 66 to 80% measured by Brandi-Dohrn et al. (1996a), 70 to 100% measured by Gee et al. (2004), 125% measured by Louie et al. (2000) and 101% measured by Zhu et al. (2002). These efficiencies were calculated by comparing measured drainage to expected drainage using similar water balance calculations to those used in the current study.

A time-averaged value of the soil water potential gradients towards or away from the PCAP samplers was valuable to identify disturbance effects and consistent (systematic) biases only but does not confirm whether the water potential in the wick and the soil were matched over the range of soil water potentials and soil water fluxes experienced in the current study. To overcome the uncertainty remaining in a time-averaged approach to identify convergent or divergent flow, a modelling exercise of PCAP function could be undertaken. In the model, changes in soil hydraulic properties and sampler performance (water potential generated by the wick) would be incorporated to estimate flow-averaged biases to confirm the ability of the current PCAP design to accurately measure drainage over the range of fluxes typical of the Abbotsford area. If modelling identified biases, conclusions about the magnitude and timing of convergent or divergent flows around the sampler could lead to improvements to sampler design or provide sound basis for scaling data to more accurately represent the system being sampled. In future designs, changes could be made to the wick properties (material, length, diameter) (Boll et al., 1992; Knutson et al., 1994) or flow barriers could be used to control for some of these effects (Gee et al., 2004; Gee et al., 2009) and improve overall sampler performance.

4.2 Irrigation and soil monitoring

Scheduled irrigation reduced water inputs to the raspberry crop by approximately 50% compared to fixed irrigation in both growing seasons, representing a significant savings in water use (Table 3.2), with no adverse effects on crop performance. This finding agrees closely with water savings of 39 to 73% realized through a scheduled irrigation strategy in Chilean raspberry production on sandy and volcanic ash soils with good drainage (Gurovich, 2008) and water savings of approximately 50% using scheduled irrigation in high-density apple production on a loamy sand soil (Neilsen and Neilsen, 2002). The results of the current study, and those reported in the literature in other cropping systems and growing conditions, demonstrate that matching water inputs to plant water demand through scheduling is an efficient approach to irrigation management. The water savings achieved by irrigation scheduling in the current study were substantial and could significantly reduce overall water use by the raspberry industry in south coastal BC.

Though the amount of water delivered by irrigation can be reduced, a consistent supply of plant available water is needed to maximize raspberry plant growth and yield (Dale, 1989). Together, the soil volumetric water content and soil water potential data (Table 3.3, Figure 3.4) indicated that both the fixed and scheduled irrigation regimes maintained soil moisture at levels above 18% VWC and at average soil water potentials of -24 kPa or higher, which provided readily available water (Annandale et al., 2011; Brady and Weil, 2008; Van der Gulik, 1999) to the raspberry crop at all times during the irrigated growing seasons. The slight decrease (of ~ 3-6%) in soil moisture observed in the scheduled irrigation treatments of the current study did not have a negative impact on the raspberry crop. Considerable lowering of soil water content does not adversely affect many other crops, and may, in fact, benefit yield, quality and growth when various forms of regulated deficit irrigation maintain soil below field capacity (Annandale et al., 2011; Greenwood et al., 2010; Jones, 2004). Results of this study suggest that raspberries can tolerate irrigation inputs that are significantly reduced from recommended rates of application. This is useful information in irrigation planning and is an area that warrants future research in raspberry production in south coastal BC.

4.3 Water and nitrate-N losses from the raspberry root zone

4.3.1 Linking drainage and nitrate losses

The PCAP drainage and nitrate-N data in the current study showed that nitrate-N leaching increased with increasing drainage. Drainage and nitrate-N losses generally moved in tandem (Sections 3.3.2 to 3.3.3), identifying that whether it was through precipitation or irrigation inputs, the addition of water beyond that which the raspberry plants could use or the soil could hold resulted in drainage and nitrate-N losses from the root zone. While nitrate losses within a two-week sampling interval always coincided with drainage losses, the magnitude of the nitrate losses from the root zone relative to the drainage losses varied depending on the time of the year and the extent of leaching that had occurred prior. For example, drainage losses, and therefore nitrate-N losses, in the 2009 growing season were generally low both in the rows and the alleys (Figures 3.6 to 3.9). The root zone drainage that resulted from the arrival of fall rains flushed large amounts of residual nitrate from the profile (Figures 3.6 to 3.9, sampling times 12 to 18). However, once the residual nitrate had been leached from the profile, subsequent heavy mid-winter rainfalls which caused significant root zone drainage (Figures 3.6 and 3.8, sampling times 18 to 22) resulted in lower nitrate-N leaching losses than had been recorded under similar drainage losses at the end of the growing season. In the current study, the link between drainage and nitrate-N loss in raspberry production was clearly demonstrated with the N, water and alley management strategies imposed impacting, in part, the timing and magnitude of the root zone losses.

4.3.2 Effects of irrigation on root zone losses

Growing season drainage losses under fixed irrigation in 2010 were four times higher than under scheduled irrigation. This can be explained by examining the water inputs under fixed irrigation, the resulting soil moisture status and the duration of irrigation application. Water supplied by fixed irrigation in the 2009 and 2010 irrigation seasons was 89 and 114% of expected crop water use over the same period, respectively. Including precipitation in this calculation indicated that total water inputs (precipitation plus irrigation) were 148 and 122 mm in excess of expected plant water use, respectively. Soil moisture content in the top 30 cm of the raspberry root zone under fixed irrigation was consistently higher (by 3-6% VWC) than under scheduled irrigation during the irrigated portion of the growing seasons. Similarly, soil water potential data at a depth of 55 cm under fixed irrigation was on average 8 kPa higher (ie. wetter, Table 3.3) than under scheduled irrigation. Basic principles of unsaturated flow indicate that as soil moisture increases the unsaturated hydraulic conductivity of the soil increases and water movement is facilitated. Excess water inputs resulted in higher soil moisture status in the fixed irrigation plots, which increased the risk of leaching losses.

The water surpluses (148 vs 122 mm) under fixed irrigation in 2009 and 2010 were similar in magnitude but resulted in different effects on drainage and nitrate-N losses from the root zone when compared to scheduled irrigation. This indicated that under fixed irrigation, growing season drainage losses on the row were highly sensitive to irrigation management. In 2010, the first production year, fixed irrigation was increased by 11% from 2009 levels (Table 3.2) to replicate current grower practice and recommended irrigation rates. In the field, this meant increasing the irrigation duration under the fixed regime from 4 hours (in 2009) to 6 hours (at peak demand in 2010) every second day. The small increase in irrigation amounts between the two years, but particularly the increased duration of watering in 2010, together with the elevated moisture status of the soil profile under fixed irrigation, significantly increased measured drainage and N losses on the row in 2010, compared to the negligible growing season losses under scheduled irrigation (Figures 3.10, 3.11 and Table 3.10).

The climate data over the study period identified that water deficits during the growing season required irrigation inputs (Figures 3.1 and 3.2) and the root zone losses measured on the row in the 2010 growing season under fixed irrigation identified that how that irrigation water was applied to make-up the deficit was a critical management decision. The fixed irrigation regime in this study applied water every second day, a typical grower practice (Mark Sweeney personal communication, 2009), and at recommended application volumes (Van der Gulik, 1999). However, if the fixed irrigation regime in this experiment had, instead, applied water every day but for half the duration, root zone losses may have been different. In the experimental soil, the frequency and duration of watering in the fixed irrigation regime in 2010 may have routinely exceeded the soil's field capacity and therefore the ability of the soil to hold the water volume applied, thereby increasing leaching losses.

The sensitivity of drainage losses in the raspberry system to over-application of water using drip irrigation is consistent with the observations of Neilsen and Neilsen (2002) and Neilsen et al. (2008) in drip-irrigated apple production. This research in apples, grown in a loamy sand soil (similar to the soil in the current study), measured increased root zone losses from trees irrigated on a fixed regime compared to a scheduled regime. This was observed particularly in the cooler months (May, June and September) when plant water demand was low. However, in the current study, differences in root zone losses between fixed and scheduled irrigation were measured over much of the 2010 growing season (Figures 3.10 and 3.11). Excessive drainage through the root zone in the coarse soils of the Abbotsford aquifer system can result in increased nitrate transport (Chesnaux and Allen, 2008).

The root zone losses measured by the PCAPS in the current study indicated that over-application of water under fixed irrigation increased drainage from the root zone in the row (in 2010) which removed plant-available N, in contrast to scheduled irrigation which retained nitrate in the raspberry root zone in both years. While there are no previous reports of raspberry root zone nitrate-N losses measured using PCAPS, these findings support those of others who quantified retention of N in the root zone in raspberry under scheduled irrigation, measured by comparing plant productivity to water and N inputs (Gurovich, 2008) and in apple through greater retention time of N in the root zone and lower leaching losses measured using suction lysimeters and PCAPS (Neilsen and Neilsen, 2002; Neilsen et al., 1998; Neilsen et al., 2001). The sensitivity of root zone losses to irrigation inputs and management in the raspberry system under study should be viewed in a positive light, in that, incremental but well-informed decisions regarding water management, such as a move to daily, climate-based, precision water management through scheduled irrigation, have the potential to significantly improve efficiency and environmental sustainability in raspberry production in south coastal BC.

Irrigation water was a significant source of N additions over the reporting period and had an average concentration of 17 mg N L^{-1}. Irrigation water contributed 49 and 55 kg N ha^{-1} to the raspberry row in 2009 and 2010, respectively, in the fixed irrigation treatments. These additions were very close to the general fertilizer-N application rate of 55 kg N ha^{-1} recommended for raspberry in the 1994 berry production guide (British Columbia Ministry of Agriculture Fisheries and Food, 1994). The calculated N applied through the irrigation water in this experiment was almost twice the N contribution of 30 kg N ha^{-1} from irrigation water suggested by Dean (1996), likely due to lower estimated irrigation inputs or irrigation water with lower levels of nitrate contamination. Nonetheless, it is clear that nitrogen applied through irrigation water must be accounted for when determining N-fertilizer application rates in raspberry production. In research on irrigated corn production, differences in the amount of N applied to the crop were also mostly due to differing amounts of water applied by the irrigation treatments (Spalding et al., 2001). Irrigation water in the corn trial was found to contain nitrate-N averaging 30 mg N L^{-1}. This justified recommendations to reduce N-fertilizer application rates allowing the corn crop to extract N from the irrigation water applied. Similarly, adjusting fertilizer-N recommendations in raspberry to encourage increased N uptake from other ecosystem inputs, such as nitrate-N in irrigation water, is an important step to maximizing efficiency, minimizing costs and reducing environmental impacts.

The PCAP data (Figures 3.7 and 3.11) and the transport curves (Figures 3.14 and 3.18) for the Scheduled treatment identified minimal root zone losses during the growing seasons in both years, indicating that nitrogen applied at 100 kg N ha^{-1} and followed by scheduled irrigation was retained in the root zone during the growing season as plant-available. Growing season N losses under the Scheduled treatment were low at only 3 and 16% of annual totals in 2009 and 2010, respectively, while under the 100N treatment N losses were 14 and 53% of annual losses over 2009 and 2010, respectively (Tables 3.6 and 3.11). However, annually, total nitrate-N losses on the row from the root zone in the 100N treatment and the Scheduled treatment in 2009/2010 and 2010/2011 were similar in magnitude and not statistically different (Tables 3.5 and 3.10). Therefore, in the current study, retaining N in the root zone through proper irrigation management did not appear to increase plant N uptake as the subsequent high N-leaching losses from the Scheduled treatment in the rainy seasons suggested that N supplied at 100 kg N ha^{-1} was in excess of plant requirements. The 100 kg N ha^{-1} rate used in the current study represents typical grower application rates of fertilizer-N (British Columbia Ministry of Agriculture and Lands, 2009; Jeffries et al., 2008) and is even less than the average application rate of 130 kg N ha^{-1} calculated across Fraser Valley raspberry production from 1981 Census data (Kowalenko, 2000). The excess N captured by the PCAPS following the growing season confirms the findings of Zebarth et al. (1998; 2007) that many raspberry fields have excess soil inorganic nitrogen due, in part, to fertilizer-N supplied beyond plant demand, even at recommended rates of application. Both the current study and the findings of Rempel et al. (2004), who suggested that a N application rate of

40 kg N ha^{-1} would likely be sufficient to maintain production, can be used as basis for considering significant application rate reductions from current conventional practice. This experiment demonstrated the over-arching principle that in crop production it is a combination of both well-managed irrigation and appropriate N-fertilizer rates that are key to maximizing the efficiency of plant N use while minimizing losses (Delgado et al., 2001; Neilsen and Neilsen, 2002).

With nitrate-N retained in the root zone over the growing season by scheduled irrigation it might be expected that the post-harvest soil nitrate-N content (August soil sampling each year) in the Scheduled treatment would be higher than in the 100N treatment, which had experienced significant growing season leaching losses prior to the post-harvest soil sampling time (Figure 3.22). The 0 to 30 cm post-harvest soil sampling strategy did not detect this effect, likely due to the significant contribution of N to the soil profile through the irrigation water. In the 100N treatment (under fixed irrigation), the N delivered by irrigation water amounted to approximately twice that delivered to the Scheduled treatment, masking the effect of growing season leaching under fixed irrigation when a post-harvest soil sampling strategy was used to monitor soil nitrate concentration. The continuous monitoring of the root zone leachate using PCAPS over the growing seasons, however, measured both the minimal root zone losses under scheduled irrigation and the growing season leaching losses under fixed irrigation, highlighting the ability of this monitoring tool to measure root zone losses over time periods of interest.

The over-winter rainy season, during which time the soil profile is leached of all residual nitrate-N by high amounts of precipitation, has typically been synonymous with the "leaching season". However, this research demonstrated that growing season nitrate-N leaching losses in the row under conventional raspberry management were significant; up to 53% of annual losses in 2010/2011 (Table 3.11). Other researchers have observed movement of nitrate downwards through the soil profile during the growing season but did so through soil sampling strategies. Zebarth et al. (1997) measured up to one third to one half of total soil nitrate-N in the root zone in the lower 30 to 60 cm depth increment by August, suggesting irrigation application in excess of plant demand, resulting in growing season leaching. However, this was measured in only some fields and some years and was data collected in fields irrigated mostly by overhead gun (opposed to drip irrigation). The PCAP results from treatments under fixed irrigation in the current study, and findings of Rempel et al. (2004) and Zebarth et al. (1997; 2007) who concluded that there was some evidence of growing season leaching, contradict earlier findings that indicated very little risk of growing season leaching and suggested that even lower risk could be anticipated in the presence of transpiring plants (Kowalenko, 1987). However, the Kowalenko study (1987) study monitored soil nitrate content in the profile on bare, non-irrigated soil and did in fact see leaching in summer during a year where precipitation was higher than normal. Kowalenko (2000) later qualified his earlier conclusions identifying that the risk of nitrate leaching during the growing season was low if irrigation had not been excessive or precipitation extreme. The climate during the current study was, on average, a little dryer and warmer than typical, which would have increased plant water use and evaporative losses, likely reducing root zone losses. Under more typical precipitation amounts and cooler temperatures, root zone losses might have been even greater than those measured in the current study. The PCAP data in this study has confirmed and directly quantified that growing season leaching losses in raspberry production under conventional management in south coastal BC do occur and can be significant.

Post-harvest soil nitrate-N on the row (in August) in all fertilizer-N treatments was low (Tables 3.18, 3.20 and Figure 3.22) and would be classified according to the testing criteria as having minimal risk for nitrate leaching (British Columbia Ministry of Agriculture and Lands, 2009; Hughes-Games and Zebarth, 1999; Jeffries et al., 2008) (Table 1.1). In the current study, the 0N treatment had the lowest post-harvest soil nitrate-N, as found by Rempel et al. (2004), suggesting that the raspberry plants utilized soil N supply and irrigation water N. Post-harvest soil nitrate-N tended to be lower where lower rates of N had been applied which Jeffries et al. (2008) also observed in a survey of raspberry fields over four years and Zebarth et al. (1997) observed in some years. Jeffries et al. (2008) found that for fields where only inorganic fertilizers had been applied, only 24% showed post-harvest soil nitrate levels (0 to 30 cm) over 55 ppm (120 kg N ha^{-1}), classified as high risk for nitrate leaching. The findings of the current study and the Jeffries et al. (2008) survey appear to contradict Zebarth et al. (1997; 2007) who instead, measured very high post-harvest residual N, at times, even where no additional fertilizer-N or where recommended N rates had been applied. The differences can likely be explained by the depths to which soil was sampled, with Zebarth et al. (1997; 2007) sampling to 60 cm and Jeffries et al. (2008) to 30 cm, and likely also the management history of the fields, particularly history of manure use. Some of the nitrate leached to lower depths earlier in the growing season was likely measured by Zebarth et al. (1997; 2007) in the additional 30 to 60 cm depth profile they sampled, thus providing a more complete accounting of the amount and location of nitrate in the soil system.

A key assumption of the recommended 0 to 30 cm post-harvest soil nitrate test is that there are minimal leaching losses under raspberry production during the growing season (Bernie Zebarth personal communication, 2012). If growing season leaching is occurring, interpretation of the post-harvest soil nitrate test results become more difficult. The findings of the current study have established that growing season leaching under conventional management (100N treatment) is occurring. Therefore, the recommended 0 to 30 cm post-harvest soil test designed to measure residual soil nitrate and guide future nutrient management decisions was not a complete accounting of N surpluses, did not measure nitrate leached to lower depths or at times earlier in the growing season and would have instead exacerbated the problem of leaching losses by under-estimating N surpluses and recommending excessive N application rates for the following year. Given the more recent industry-wide change in irrigation system design from overhead gun to drip micro-irrigation, and the accumulation of evidence that growing season leaching losses are likely significant, it is clear that some of the assumptions of the post-harvest soil nitrate test, and therefore interpretation of the results, should be modified and updated to reflect this new information and current industry practice.

4.3.3 Matching nitrogen delivery to raspberry plant nitrogen demand

Six weeks of daily fertigation followed by scheduled irrigation reduced growing season drainage and N losses on the row in 2010 and may be a useful strategy in raspberry production to better match N delivery to plant N requirements. This application strategy utilized the irrigation system already in service in the raspberry block to facilitate nutrient application from a centralized location and reduced the need for field access during the spring when soil was wet and traffic on the soil undesirable. In contrast to broadcast split applications of granular fertilizer, the small, daily doses of fertigated-N over a six week period meant less fertilizer-N was delivered to the soil system at each application, which reduced growing season root zone losses. In 2009, the trend in the PCAP data indicated a reduction in growing season nitrate-N losses of approximately 50% using this management strategy compared to a broadcast split application and fixed irrigation (Table 3.5). In 2010, this same comparison resulted in a significant 72% reduction in growing season nitrate-N losses (Table 3.10) by the fertigation strategy. It is important to recognize that the Fertigated + Scheduled treatment combined two alternative management strategies to conventional practice in one treatment: fertigation to deliver the annual nitrogen fertilizer requirement as well as scheduled irrigation. The experimental design in the current study made it difficult to isolate the effects of fertigation from those of scheduling on root zone losses in this single treatment. However, during the fertigation time periods in both years, no differences in drainage and N losses from the root zone under this management strategy compared to the 50N treatment were detected by PCAPS or soil sampling, while differences during the sampling times that fell within the irrigated portions of the growing seasons were more pronounced (Tables 3.4 and 3.9). This, and the effect of irrigation scheduling observed in other treatments, suggests that scheduled irrigation likely played the most significant role in reducing root zone losses from the Fertigated + Scheduled treatment.

In the current study, fertigation required the application of small amounts of irrigation water at a time when irrigation was not required, in order to meet the high N requirement for raspberries in early spring. However, this application of water for the purpose of N delivery did not increase drainage or nitrate losses compared to the 50N treatment in the sampling times early in the growing season of either year (Tables 3.4 and 3.9) when there would be increased risk of leaching caused by (unneeded) water inputs to a soil profile with an already high moisture content from spring rainfall. There is some evidence in previous research on fertigation in raspberries in south coastal BC that N leaching was accelerated by fertigation compared to conventional broadcast applications and offered no improvement in plant performance (Kowalenko et al., 2000). However, fertigation as ammonium nitrate was applied once weekly in an unreported amount of water and began early May, possibly accounting for the differences in leaching and plant response compared to the present study. Early research in apple found additional care was required to avoid N leaching stimulated by fertigation strategies (Neilsen et al., 1995). Though the current trial observed reductions in drainage and N losses from the root zone through a combination of fertigation and scheduled irrigation, this N application strategy has the potential to accelerate leaching losses if not done correctly and monitored closely (Haynes, 1985), particularly in coarse-textured soils (Gärdenäs et al., 2005).

4.3.4 Effect of nitrogen source on root zone losses

The greatest leaching losses were measured where manure was applied as the N source. Nitrate-N loss from the root zone of the Manure treatment measured by PCAPS in 2009/2010 was double that from a fertilizer-N source (Table 3.5) despite the fact that the post-harvest soil test in 2009 measured low residual nitrate-N in the Manure treatment (31 kg N ha^{-1}) and no significant difference in residual soil nitrate compared to a fertilizer-N source (Table 3.18). In 2010/2011, nitrate-N loss from the root zone was triple that of a fertilizer source (Table 3.10), indicating that the effect of repeated manure application on root zone losses may be compounding with time, likely due to increased long-term N supply. The carryover of N from previous manure application was further evidenced by significantly higher soil nitrate measured under manure compared to a fertilizer-N source at all sampling times in 2010 (Table 3.20), with post-harvest soil nitrate reaching 199 kg N ha^{-1} in 2010, indicating N inputs in excess of plant requirements and significant risk of nitrate leaching (British Columbia Ministry of Agriculture and Lands, 2009; Hughes-Games and Zebarth, 1999; Jeffries et al., 2008). In 2009/2010, the leachate water captured by the PCAPS beneath the root zone under manure had a flow-weighted nitrate-N concentration for the combined row and alley managements of 10 mg N L^{-1}, which was already at the drinking water guideline (Table 3.16). In 2010/2011, the flow-weighted nitrate-N concentration in the leachate increased from the 2009/2010 concentration and exceeded the drinking water guideline, reaching 14 mg N L^{-1}.

There is leaching risk associated with all raspberry fields but especially those with a history of high manure application rates (Dean et al., 2000). Findings in the current study, such as the elevated post-harvest nitrate-N measured by soil sampling in the Manure treatment in 2010 (199 kg N ha^{-1}), fall within the range of values of 100 to 670 kg N ha^{-1} residual soil N found in other studies on manured fields in the Abbotsford region (Dean et al., 2000; Jeffries et al., 2008; Zebarth et al., 1997; Zebarth et al., 1998). In addition to elevated post-harvest soil nitrate, this study measured high leaching losses by PCAPS and elevated flow-weighted nitrate concentration leaving the raspberry root zone where manure was used as a source of nitrogen. Previous research indicated that post-harvest soil nitrate levels greater than 100 kg N ha^{-1} in the soil root zone (0 to 60 cm), regardless of N source, may result in greater than 10 mg N L^{-1} as nitrate-N in the groundwater (Zebarth et al., 1995). It is noteworthy that after only two years of manure application in the current study, where there has been minimal previous manure application (Table 2.2), residual soil nitrate levels in the top 30 cm of soil in the root zone were twice this allowable level and flow-weighted nitrate concentration leaving the root zone 1.4 times the Canadian drinking water guideline. The Manure treatment also showed higher drainage losses than the 100N treatment in certain sampling times over the growing seasons, an effect which was significant over the 2010 growing season as a whole, suggesting a possible effect on soil structure contributing to increased water movement through the soil, compounding the risk of leaching losses under manure application.

In this study, an assumed 33% total N availability in the year of application was used to calculate the amount of manure required to supply 100 kg of plant-available nitrogen per hectare in the year of application, to the raspberry crop. The significantly larger nitrate-N losses observed under manure suggests a need to refine the estimate of the N-mineralization rate for surface applied broiler manure as more N is being supplied annually than expected. The availability of N from poultry manure applied in the field is influenced by a number of processes and is often based only on lab incubation studies (Dean et al., 2000). Dean et al. (2000) recovered approximately 50% of total manure N, however, this was applied as layer manure in the alleys of a raspberry planting and incorporated by tillage. Losses in the current study may also be increasing over time because no attempt was made in this study to account for the increase in longer-term N supply (mineralization potential carried over from the previous years' application) from annual re-applications of manure. There was no explicit accounting for mineralization of previous years' manure use and, based on the post-harvest soil nitrate test recommended for use by producers, residual soil nitrate in August of 2009 in the Manure treatment (even in the absence of significant growing season leaching in 2009) did not indicate N supply in excess of plant demand and would not have recommended adjustment to nitrogen application rates in the subsequent year. Therefore, N management in the Manure treatment in the current study was in accordance with berry production standards at the inception of the current study. A new recommendation in the subsequent production guide (British Columbia Ministry of Agriculture and Lands, 2009) explicitly estimates a N credit of 22% of the previous year's potentially available N, applied through broiler manure, to account for N carryover when determining N requirements for a new growing season. Accurately predicting the carryover in N supply from past manure applications is difficult. Assumptions about mineralization rates, differences between manure sources, effects of application timings and methods as well as conditions during and following application contribute to the uncertainty. From the apparent compounding effect of manure re-application observed in the current study, explicitly accounting for this carryover in subsequent nutrient management plans when manure re-application is a component of production or field renovation is an important step toward responsible manure use in raspberry production.

4.3.5 Effect of alley management on root zone losses

In raspberry production, approximately 60% of the land base is accounted for by the alleys between the raspberry rows. In 2009/2010, nitrate-N losses measured by PCAPS from the tilled alleys accounted for an average of 61% of management total annual losses (combined losses over the row plus the alley, Table 3.14) while nitrate-N losses from alleys planted with perennial grass or barley covers in the same year decreased losses to 33% of management total annual losses. In 2010/2011, the percentage of management total annual nitrate-N losses that occurred in tilled alleys and those planted with cover crops averaged 42 and 25%, respectively. The magnitude of annual nitrate-N losses that occurred in the tilled alleys in both years, and the reduced losses in alleys planted in cover crops, highlight the significant contribution of nitrate-N losses from the alleys in the raspberry system, and therefore, the importance of proper alley management in raspberry production in south coastal BC.

Perennial grass and fall seeded barley cover crops grown in the alley foraged effectively for nitrate in the alley, reduced leaching losses from the alley by up to 68 kg N ha^{-1} or 82% compared to tillage (Table 3.8) and reduced flow-weighted nitrate-N concentration in PCAP leachate to concentrations as low as 2 mg N L^{-1}, well below the drinking water guideline (Table 3.16, Figures 3.17 and 3.21). These findings are consistent with others who indicated that cover crops have the potential to reduce nitrate leaching (Brandi-Dohrn et al., 1997; Power and Schepers, 1989; Rasse et al., 2000; Stevenson and Neilsen, 1990) by up to 67% (Martinez and Guirard, 1990) with some taking up greater than 60 kg N ha^{-1} (Dean et al., 2000; Hughes-Games and Zebarth, 1999; Jeffries et al., 2008). Zebarth et al. (1993) identified that both permanent and seasonal cover crops enhance nitrogen cycling and reduce leaching risks.

The ability of alley cover crops to reduce nitrate-N losses from the alley root zone was related more to their ability to scavenge for nitrate rather than reduce drainage losses (Figures 3.8 and 3.12). The cover crop treatments did not reduce drainage and, in some sampling times, stimulated higher drainage losses from the alley root zone (Tables 3.7 and 3.12), likely due to improvements to soil structure compared to the degradation of structure typically observed under clean cultivation. These findings are similar to reports in the literature on the effect of vegetative covers on infiltration and drainage. Some studies indicate that vegetative covers and crop residues can increase infiltration (Follett and Delgado, 2002), while Brandi-Dohrn et al. (1997) found no significant difference in the volume of leachate collected under rye cover or winter fallow. The presence of a cover crop which may aid in field drainage but, most importantly, actively take up nitrate moving through the soil zone in the alleys of raspberry production is a valuable management tool.

It is well documented that tillage stimulates organic matter decomposition and thus soil N mineralization. This mineralized N, if not taken up (by plants), is therefore available to be leached, as confirmed by the magnitude of the annual nitrate-N losses measured in the tilled alleys of the current study. The reduction in nitrate-N losses from the alleys planted in cover crops compared to the tilled alleys of the 100N treatment is thus due to both the reduced tillage in the alleys managed with cover crops and the ability of the cover crops to take-up nitrogen moving through the soil profile. In the current study, the perennial grass cover performed particularly well and, overall, reduced nitrate-N losses compared to tillage in more individual sampling times than did the barley cover (Tables 3.7 and 3.12). The fall seeded barley was susceptible to cold damage, suffering early winter-kill in 2010, which greatly reduced its ability to take up nitrate (Figure 3.20). The barley also required annual re-seeding in the fall, a spring herbicide application and was followed by tillage throughout the growing season which stimulated organic matter decomposition and left no plant material in place to intercept nutrients, enhance drainage, provide habitat for beneficial insects or compete with weeds. Alternatively, the perennial grass cover required no tillage (except at establishment) and only mowing to maintain the herbicide strip and avoid encroachment on the raspberry row. The perennial cover crop, once established, offered all the potential benefits of a cover crop over the entire study period by providing a permanent cover in the alleys.

4.4 Transport through the root zone

There was evidence from the nitrate-N breakthrough curves in the current study indicating that PCAPS sampled both matrix flow and preferential flow and that preferential flow may have influenced the transport of nitrate-N through the soil zone. Other research confirms the ability of wick samplers to accurately measure water and solute movement through the soil zone by capturing both matrix and preferential flow (Boll et al., 1992; Brandi-Dohrn et al., 1996b; Brandi-Dohrn et al., 1997; Chen et al., 2002). Brandi-Dohrn et al. (1996b) suggested preferential flow was being collected by their PCAPS in a cover crop/crop rotation study after observing more than three quarters of their samplers with elevated bromide tracer concentrations within 0.14 pore volumes of drainage, but that matrix flow was also collected, as evidenced by peak flow-weighted solute concentrations at approximately one pore volume. In the current study, peaks on the nitrate-N breakthrough curves at one estimated pore volume identified that the PCAPS captured matrix flow (Figures 3.15, 3.17 and 3.21) and in the early parts of the growing seasons the occurrence of preferential flow was suggested by drainage losses with elevated flow-weighted nitrate-N concentrations at approximately 0.3 pore volumes (Figures 3.15, 3.17 and 3.19). The N inputs to the system, coupled with spring precipitation events all at a time when the soil profile was still wet (Figure 3.4), increased the potential for leaching losses. During the rainy season, preferential flow was evidenced by dispersion and trailing (spreading out of) tails on the breakthrough curves for both the row and alley PCAPS as the intense precipitation, typical of south coastal BC, travelled down preferential flow pathways but also stimulated transport of remaining nitrate out of the bulk of the root zone soil matrix (Figures 3.15, 3.17, 3.19, 3.21). Fingered-flow due to soil texture differences, the presence of macropores, such as root and earthworm channels, may also have been involved in facilitating preferential flow. Using a soil sampling strategy, movement of nitrate through the soil profile during a wet spring was also observed by Dean et al. (2000) while a modelling exercise by Chesnaux et al. (2007) predicted the possibility of root zone leaching losses in the Abbotsford system in the springtime. Results from both of these studies suggest that preferential flow may be moving nitrate through the soil profile.

Monitoring nitrate-N movement through the soil zone in the current study using PCAPS was not a proper tracer test. The complexity of the N cycling in the raspberry system under study and the many inputs of N, such as from soil mineralization, atmospheric deposition, irrigation water, spring fertilizer and manure applications, as well as losses through plant N uptake and leaching, complicate the interpretation of the transport data presented. Nonetheless, findings in the literature and those of the current study, suggest preferential flow in the system under study may be occurring and highlight the need for well-timed nutrient applications in raspberry production in order to avoid early season N losses.

Following the early growing season N losses in 2009, losses in the row remained low until the start of the rainy season (Figures 3.7, 3.15, Table 3.4). The breakthrough curves peaked, at approximately one estimated pore volume, as the bulk of residual nitrate-N was flushed out of the root zone relatively quickly with the arrival of fall rains (Figure 3.15). Flow-weighted nitrate concentrations in the PCAP leachate were highest in both the rows and the alleys for treatments with the highest rates of N applied and peaked for a short time at ~ 30 mg N L^{-1}; three times the drinking water guideline. In the 2010 growing season on the row, the PCAP data over time and the transport graphs both indicated that the increase in irrigation water applied to treatments under the fixed regime increased growing season leaching losses compared to scheduled irrigation (Figures 3.11 and 3.19, Table 3.10), once again highlighting the sensitivity of the system to small changes in water management and the potential for significant growing season leaching (Table 3.11). The flow-weighted nitrate-N concentration in the leachate during the 2010 growing season for all treatments under fixed irrigation remained around 17 mg N L^{-1} (Figure 3.19), the concentration of nitrate-N in the irrigation well-water. This suggested that in these treatments, irrigation water had a relatively short residence time in the root zone when applied in excess of plant requirements and exceeded the plant's ability to utilize the water or the N contained within, therefore making a significant contribution to root zone losses. This finding is similar to that of Stevenson and Neilsen (1990) who concluded that when the depth of drainage water becomes large enough all other factors involved in N retention in the root zone are overwhelmed.

The nitrate-N breakthrough curves for the Manure treatment indicated a rapidly available supply of N following manure application (Figures 3.15 and 3.19), similar to a fertilizer-N source, with additional N supplied throughout and beyond the growing season likely by on-going mineralization. Flow-weighted nitrate-N concentration on the row under manure management, despite significant growing season leaching, increased to nine times that of the Canadian drinking water guideline (Figure 3.19). Excess N supplied by manure was also confirmed by the high soil nitrate-N measured both post-harvest and in autumn just prior to fall rains (Figure 3.22, Table 3.20). The decomposition rate of organic matter is largely controlled by soil temperature and literature identifies that the microbes that are involved in soil organic matter decomposition can be very active in the conditions of warm summer soil when soil moisture conditions are adequate (Addiscott, 2000). In addition, re-wetting soil (as when fall rains arrive) stimulates a flush of N-mineralization; however, Addiscott (2000) indicates that the nitrate produced may be untimely. This seems to have been the case in this study where gradual, but continual, mineralization of N from manure appeared to be released through the fall, a time in the year when plant N demand was low. The result in the current trial was much higher nitrate-N leaching losses where manure had been applied.

Following the loss of residual N from the root zone, all row and alley PCAPS showed similar rainy season rates of N loss and flow-weighted nitrate-N concentrations of ~ 5 mg N L^{-1} or less. This suggests that there is a consistent amount of nitrate-N moving through the soil over-winter, likely as a combination of N inputs from atmospheric sources (precipitation and deposition) and over-winter soil N mineralization, and that PCAPS could be a useful tool to quantify over-winter mineralization. Microbial activity has been observed throughout the mild winters of south coastal BC, as evidenced by over-winter nitrification (Kowalenko and Hall, 1987) and denitrification (Paul and Zebarth, 1997). In the current study, healthy cover crops scavenged for nitrate-N, decreased the rate of N loss and reduced the flow-weighted nitrate-N concentration in root zone leachate throughout the rainy season (Figures 3.16, 3.17, 3.20, 3.21). The rate of N loss and the flow-weighted nitrate-N concentrations in leachate were lower for the cover crop treatments than for the tilled alleys of the 100N treatment (Table 3.16).

The reported flow-weighted nitrate-N concentrations summarize data collected by PCAP samplers at 55 cm below the soil surface. Treatment effects on flow-weighted nitrate-N concentrations in leachate have been compared to the Canadian drinking water guideline to provide a basis for interpreting the relevance of the root zone losses; however, PCAP flow-weighted nitrate-N concentrations do not necessarily represent the concentration of nitrate-N reaching the groundwater as there may be additional N transformations that take place between the PCAP and the water table.

4.5 Plant response to management strategies

Overall, measurements of plant N status, vigour and yield indicated that the N, irrigation and alley crop management treatments had few effects on plant performance in the short term. Zebarth et al. (2007) reported that increasing N fertilizer rates increased crop N status of raspberry in about 40% of trials but that this did not usually translate into increased crop yield indices or vigour. Likewise, N-fertility treatments across multiple sites had little impact on indices of yield (Zebarth et al., 1997). Dean et al. (2000) measured increased floricane N concentration with increased fertilization while Kowalenko et al. (2000) measured significant but inconsistent effects of N rate on plant vigour and berry size over 3 years. Similarly, primocane leaf N in the current trial did increase in response to N application in 2009 (Table 3.22) which carried over to affect floricane lateral N content in 2010 (Table 3.24). Primocane vigour also increased linearly with N rate (Tables 3.22) likely due to the lower inherent fertility of the soil in the current trial (related to limited history of manure use) relative to the commercial fields monitored in other trials. The 0N treatment did show reduced yield in the first harvest year (Table 3.25) confirming the findings of Rempel et al. (2004) who measured a tendency for unfertilized raspberry to have lower yields and other researchers who found that increasing N fertilizer rates stimulated small but significant yield increases (Kowalenko, 1981). In the current study, the Fertigation + Scheduled treatment maintained yields that were equal to conventional management practice (100N) whereas Gurovich (2008) stated that fertigation strategies in raspberry production in five different locations in Chile have, over five production years, trended towards improved yield and fruit quality. The Gurovich (2008) study, however, was not a scientific experiment (no statistical comparisons between treatments made) and fertigation was applied to the whole planted area. In other crops such as apple, fertigation has been shown to reduce fertilizer-N inputs without effect on plant N status (Neilsen et al., 1999). Comparable yields measured between conventional practice and the fertigation strategy of the current study are in contrast to Kowalenko et al. (2000) who measured increased yields from broadcast fertilizer application when compared to fertigation, however, timing, delivery and form of fertilizer used for fertigation differed from that employed in this experiment.

The limited effect of fertilizer-N applications on plant performance in the current study and in the literature suggests that the ecosystem N in south coastal BC (N from soil mineralization, in irrigation water and from atmospheric deposition) supplies a large proportion of the plant N requirements. Previous research that used soil sampling strategies to determine soil inorganic N concentration in raspberry fields, suggests that the amount of N supplied to a raspberry crop by mineralization of soil organic matter, particularly in fields with a history of manure use, may even be larger than that supplied by fertilizer (Zebarth et al., 1997) and that net soil mineralization in raspberry fields is high (>150 kg N ha^{-1}), especially in fields with a history of manure application (Dean et al., 2000; Zebarth et al., 1998). Atmospheric deposition may provide up to 40 kg N ha^{-1} (Belzer et al., 1997) while irrigation water contributions on the row were found to approach 50 kg N ha^{-1} in the current study. This amount of N supply, before fertilization, and in a crop with low N uptake due to large inter-row spacing (Kowalenko, 1994), explains why ecosystem N supply may already be in excess of plant demand (Zebarth et al., 2007) and response to treatments limited and inconsistent. For this reason, the ecosystem contributions must be accounted for in determining fertilizer-N rates to avoid applications in excess of plant requirements.

Perennial grass and fall seeded barley cover crops grown in the alley reduced nitrate leaching and soil nitrate concentration with few effects on raspberry growth and yield, identifying that competition for water and nutrients between the raspberry crop and alley covers was limited (Tables 3.22, 3.23, 3.24 and 3.25). These findings are in contrast to the reductions in cane diameter and length as well as berry yield and raspberry plant photosynthesis measured with perennial ryegrass (*Lolium perenne* L.) planted as an alley cover (Bowen and Freyman, 1995). However, these affects were attributed to the allelopathic properties of ryegrass (due to chemicals released by ryegrass which have harmful effects on other plants), whereas the barley cover crop planted in the current study is not known to be allelopathic. In another study, cane diameters were reduced next to perennial ryegrass cover but with limited yield effects (Zebarth et al., 1993) while a 25% yield reduction and reduced plant vigour was measured in a study comparing grass sod to tillage and oats in the inter-row (Sanderson and Cutcliffe, 1988). These kinds of impacts were minimal in the current experiment. Clearly, both the choice and management of alley crops can influence plant performance and should be well-informed when alley crops are included as components in raspberry production.

Chapter 5: Conclusions and future research

This study examined the impacts of conventional and alternative N, water and alley management strategies in red raspberry production on nitrate and water losses from the root zone using PCAPS to capture leachate and soil instrumentation and sampling strategies to measure root zone soil moisture, soil N content and plant performance.

Together, soil water potential measures and calculated sampler collection efficiencies indicated that the PCAPS successfully measured total root zone drainage and nitrate leaching without causing significant disturbance to native soil water potential or sampling biases caused by continuous divergent or convergent flow towards the samplers. Both matrix and preferential flow were captured by the samplers, with some indications of preferential flow of nitrate out of the root zone in early spring and small but consistent N loss from over-winter mineralization and deposition. This highlights the utility of this sampler type to provide a continuous monitoring of root zone losses and quantify losses over time and as a function of water movement (transport). Modelling the function of any current PCAP design over a range of field conditions may serve to improve sampler design in the future.

Daily ET measures combined with raspberry crop and irrigation system parameters can be used to calculate raspberry crop water needs and schedule irrigation, resulting in substantial water savings, without impacting plant performance in the short-term. Based on the difference between the 2010 fixed and scheduled irrigation applications in the current study, the volume of water per year that could be saved across the reported 1600 ha of Fraser Valley raspberry production (Mark Sweeney personal communication, 2012; Statistics Canada, 2011) by the scheduling technique reported amounts to an estimated 2.6×10^9 L of water. Soil moisture sensors provided valuable feedback on the moisture status of the soil confirming that water was readily available to the raspberry plants at all times and that atmometer scheduled irrigation is an effective and efficient irrigation model for use in raspberry production. In the coarse soils over the Abbotsford Aquifer, future research should include examining the benefits of higher frequency, pulsed irrigation to maximize and retain plant available water in the upper portion of the root zone. Furthermore, in order to establish safety margins for irrigation management, the tolerance of raspberries to irrigation deficits is an area warranting further study.

Scheduling irrigation utilizes the irrigation systems already in place in the raspberry industry. There is a need to educate and enable producers on the "how" of incorporating daily measures of ET with site, soil and crop specific factors, into irrigation planning that matches water inputs to plant water use. Available sources of ET information should be identified (e.g. Farmwest.com), but more importantly, a convenient method which automates ET based irrigation calculations and adjusts irrigation times accordingly (as demonstrated herein) is important for industry wide adoption.

Delivery of N using a fertigation strategy followed by scheduled irrigation reduced growing season and annual N losses, indicating that supplying N through the irrigation system may be a useful strategy in raspberry production. This treatment combined lower N inputs, daily nutrient injections from a centralized location (as opposed to field access for tractor application), and scheduled irrigation, all of which offer potential for increased production efficiency. As part of on-going research in this experiment, quantifying the ability of this management strategy to better match delivery of N to plant N requirements, measured as efficiency of plant N uptake, is being undertaken. Fertigation through existing irrigation systems may be an alternative management strategy that could be easily adopted by the industry.

In this study, nitrate leaching increased with increasing drainage and was impacted by the various N, water and alley management strategies imposed. Water inputs (irrigation plus precipitation) under fixed irrigation were in excess of expected crop water use, which resulted in higher soil moisture status on the row than under scheduled irrigation and resulted in root zones losses on the row in the coarse textured soil in Abbotsford that were highly sensitive to changes in fixed irrigation duration. Excessive water inputs resulted in drainage which carried away plant-available N while irrigation inputs scheduled to meet plant water requirements retained N in the root zone over the growing season. Data from the continuous capture of leachate by PCAPS was used to calculate that, under conventional raspberry management over a two year period in the current study, up to 53% of annual nitrate-N losses on the raspberry row occurred as growing season leaching. This was measured over a time period in which the climate, overall, was a little drier and warmer, but close to the 30 year average for precipitation and temperature. While changing the time periods which define the growing and rainy seasons will influence to the calculated proportion of leaching occurring in each, this is new evidence to support research that inferred growing season leaching using soil sampling strategies and challenges the long-held belief that the vast majority of leaching from the raspberry row occurs in the over-winter rainy season. Relating measured root zone losses during the experiment back to duration and intensity of precipitation events may be a useful exercise in the future to link climate and nitrate leaching risk.

Post-harvest soil nitrate levels were low to very low for all fertilizer-N treatments, classifying the soils as having a minimal risk of nitrate leaching. However, with new evidence of the magnitude of growing season leaching losses collected at 55 cm below the soil surface, a basic assumption of the post-harvest test was violated. Therefore, results of the post-harvest soil test (0 to 30 cm) could not adequately reflect whether or not N application rates had matched plant N requirements. To better report on the success of a current year's nutrient management plan, a test for post-harvest residual soil N should be extended beyond the 30 cm depth or, better still, coupled with additional root zone measurements that quantify or estimate leaching losses throughout the growing season.

Elevated root zone nitrate-N losses measured by PCAPS, high flow-weighted nitrate-N concentrations and high residual soil N demonstrated that manure application can impose significant risk to the environment even in a site with limited history of manure use. Over two years, nitrate-N loss under a broiler manure source was two to three times greater than under a urea fertilizer-N source. A portion of the nitrogen in manure was released quickly, similar to fertilizer N, but mineralization continued into the rainy season, an indication that nitrogen availability from a broiler manure source was not synchronized with plant demand. Drainage amounts were also significantly higher under manure, exacerbating the environmental impacts. The effects of repeated manure applications on root zone losses compounded quickly over time. This highlights the need for refined estimates of the amount of plant-available nitrogen supplied from manure sources in the year of application and a nitrogen credit system that accounts for the effects of manure application in previous years. In addition, investigation of the effects of manure application on soil structure, and their implications on water infiltration and drainage in raspberry production, should be investigated further. Research on the production and use of composted or stabilized manure products in raspberry production may assist in retaining the benefits of regular organic matter additions while mitigating the environmental risks.

Despite the successful retention of N in the root zone by scheduled irrigation during the growing season, significantly higher rainy season N losses indicated that N application at 100 kg N ha^{-1}

was likely in excess of plant requirements. Therefore, efficient irrigation management must be combined with a well-informed nitrogen management plan to mitigate root zone losses.

Decisions on appropriate N management within the raspberry system in the Lower Fraser Valley require incorporation of all potential sources of N and should look to maximize the ecosystem's inherent fertility, such as N supplied by soil N mineralization, irrigation water and atmospheric deposition. This will increase N use efficiency, reduce grower input costs and minimize environmental impacts. Nitrogen application rates from all sources, matched to raspberry plant N demand, will encourage increased uptake from soil and irrigation water which may play a role in the remediation of groundwater contamination. Plant response to N fertility treatments was limited identifying that N from the ecosystem was able to supply the majority of plant requirements. Therefore, N inputs over the short term can likely be reduced without affecting plant performance. The current study, among others reported in the literature, identifies that further research on matching N application rates and total N supply to plant demand in raspberry production is required.

This study demonstrated that cover crops grown in the alleys reduce nitrate-N losses, scavenge for nutrients, reduce the nitrate concentration in water leaving the root zone and can be effective management tools in mitigating nitrate contamination to groundwater from raspberry production without sacrificing crop performance. Future research on alternative plant species, particularly perennial covers, for cover cropping in raspberry production is needed.

Chapter 6: Bibliography

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