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Soil Nitrate Profiles and the Risk of Nitrate Leaching in Sweet Cherry Orchards Subjected to Different Management Schemes

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When nitrogen is applied to sweet cherry orchards, losses can take place. The authors determined the soil nitrate distribution in fertilized sweet cherry orchards in Southern Patagonia (Argentina). The treatments were irrigation (drip vs. furrow), soil cover (bare soil vs. grass sward), and fertilization (N vs. NPK). Soil samples were taken in the row and the alley to a depth of 120 cm and nitrates were determined. Soil cover was significant and the irrigation system and fertilization were less important. The grass sward in the alleys is an important factor for sustainable sweet cherry orchard management, because it reduces the risk of nitrate leaching.

KEYWORDS Prunus avium*, nitrogen fertilization, orchard management, irrigation systems*

INTRODUCTION

Nitrogen (N) has an open biogeochemistry cycle in agroecosystems and is subjected to losses from the soil by ammonia volatilization, nitrate denitrification and leaching, and erosion (Ayoub, 1999; Hagin and Lowengart, 1996; Láng, 1996). Leaching losses, in particular, are important in soils with coarse texture and when the crop roots (either by activity or size) are unable to adequately absorb nitrates, which then tend to either leach downward or run

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off the surface (e.g., Rimski-Korsakov et al., 2004; Snyder and Bruulsema, 2002; Tagliavini et al., 1996). This is a common scenario in fruit orchards because they are usually irrigated and receive high doses of N fertilizers (Southwick et al., 1999). In addition, up to 80% of the N applied as fertilizer is not absorbed by fruit crops, due to their low root density (Rey et al., 2006; Tagliavini et al., 1996; Nario et al., 2003; Sánchez et al., 1995). Thus, a high proportion of the N applied is commonly detected below the root zone at the end of crop growth (Kraimer et al., 2001). According to Dawson et al. (2001), roots of sweet cherry only reach around a 1-m depth.

The efficiency of fertilizer N recovery in fruit crops is affected by several factors, such as the nutrient applied and the soil management and irrigation system used (Baligar et al., 2001; Morgan et al., 2006; Delgado et al., 2007). Also, a balanced nutrition leads to an increase in N use efficiency and a decrease in N losses by improving root growth and soil fertility (Hera, 1996), while unbalanced fertilizations may cause nitrate leaching (Ayoub, 1999; Steen, 1996).

Plants, including weeds, absorb nitrates and decrease the concentration of N in the soil solution when compared to that in bare soils. This fact is used to reduce the nitrate leaching risk (Brinsfield, 1988; Wrona and Sadowski, 2004). According to Ramos (1996) and Aronsson and Torstensson (1998), cover crops and catch crops can reduce nitrate leaching from 20% to 80% as compared with bare soils. Grasses are considered to be the most efficient species in this process (Aronsson and Torstensson, 1998; Delgado et al., 2007; Hudska, 1990; Ramos, 1996; Tagliavini et al., 1996).

Irrigation is usually used to supplement the water requirements of the crop when rainfall is inadequate. Open systems, which are the most common around the world, have a low water and nutrient efficiency. Conversely, pressurized irrigation, especially drip irrigation, shows higher efficiency (Hagin and Lowengart, 1996). Drip irrigation reduces the soil volume explored by the roots (Tagliavini et al., 1996). However, roots concentrate in the wet area, which allows maximizing water and nutrient uptake, thus reducing nitrate leaching (Hagin and Lowengart, 1996; Neilsen et al., 1998).

Nitrates in soils are usually separated into residual and leached nitrates. Residual nitrates are typically found from the topsoil to the depth usually explored by roots. They are not considered lost from the soil/plant system, because they can be taken up by the roots (Peterson and Power, 1991). Nitrates located below this depth are considered already leached, because low quantities—if any—are taken up by the roots (Follett et al., 1994).

It is widely known that nitrates draining to the groundwater can cause several human health and environmental problems, which is especially affected when the nitrates concentrated in the groundwater are discharged into bodies of water. Aquatic systems require low N concentrations to sustain the life of algae (0.3 ppm according to Biswas and Biswas (1975)) and the excess of N causes negative effects on fish and other aquatic organisms

(Smith et al., 1999; Snyder and Bruulsema, 2002). Several studies have related the content of nitrates in the soil profile to the concentration of nitrates in the groundwater (Schepers et al., 1991).

Our objective was to determine the nitrate distribution in the soil profile of sweet cherry orchards in Southern Patagonia, Argentina, subjected to different management schemes in order to forecast the risk of nitrate leaching. The treatments were irrigation (drip vs. furrow), soil cover between rows (bare soil vs. grass sward), and fertilization (N vs. NPK fertilization).

MATERIALS AND METHODS

Experimental Site and Crop Characteristics

The study was carried out using four 8-year-old sweet cherry (*Prunus avium* L.) trees grafted onto *Prunus mahaleb* rootstocks located in an orchard representative of the Los Antiguos valley (71° 38′ W; 46° 32′ S), province of Santa Cruz, Argentina. The climate is cold and semiarid with low relative humidity and high global solar irradiation. Almost 60% of total rainfall takes place in winter, with a mean of 219 mm per year (Hochmaier, 2011). To fulfill tree water requirements, sweet cherry orchards need to be irrigated daily between November and March, at an average rate of 50 m^3 ha^{-1} d^{-1}.

All orchards were established on Entic Haploxerolls associations (Irisarri et al., 1990) with adequate soil properties for the crop, according to Lichou et al. (1990), Longstroth and Perry (1996) and San Martino et al. (2006). Two composite samples were taken in each site at the 0–30 and 30–60 cm depth to characterize the soils of each orchard. The soil characteristics were determined following standard procedures (Sparks et al., 1996): pH (soil:water 1:2.5); available P (Bray I method); exchangeable K (ammonium acetate method); organic C (Walkley-Black method); total N (Kjeldhal method); and soil particle distribution by the Bouyoucos method (Klute, 1986). The soils had no depth limitations caused by rocks, soil pH was neutral to moderately acid, and there were no salinity or alkalinity problems. Organic C, total N, and exchangeable K were low to very low according to a local Soil Fertility Standards (San Martino et al., 2006), while available P was high in all cases (Table 1).

After harvest, in January of the previous growing season, leaves were sampled for foliar analysis in each orchard. They were analyzed following standard procedures (Temminghoff, 2000) and nutrient foliar levels were determined. Results indicated that the trees had a good nutritional status for all nutrients except for Mn and Zn (Table 2).

All orchards received fertilizers (N, K, Mn, and Zn) previously to the present study, during which they were subjected to different management schemes:

TABLE 1 Soil Analysis Results at Two Depths (0–30 cm and 30–60 cm) Prior to Nitrate Determinations in Four Sweet Cherry Orchards

	Sampling depth (cm)							
	Orchard 1		Orchard 2		Orchard 3		Orchard 4	
Soil characteristic	0–30	30–60	0–30	30–60	0–30	30–60	0–30	30–60
pH (soil:water 1:2.5)	5.70	6.20	6.70	6.40	7.60	7.60	5.70	5.40
Organic carbon (%)	1.28	0.91	0.80	0.53	1.57	0.71	1.68	1.03
Total nitrogen (%)	0.15	0.10	0.07	0.05	0.15	0.08	0.17	0.11
Phosphorous (mg kg^{-1})[z]	212.00	210.00	132.00	222.00	76.00	125.00	184.00	50.00
Potassium ($cmol_c$ kg^{-1})[y]	0.50	0.30	0.60	0.40	0.50	0.30	0.40	0.20
Clay (%)	8.00	10.00	12.00	9.00	25.00	15.00	23.00	37.00
Silt (%)	26.20	23.90	36.50	26.00	35.50	28.30	24.20	27.50
Sand (%)	65.80	66.10	51.50	65.00	39.50	56.70	52.80	35.50
Soil texture[x]	FrAsAr	FrAr	FrAr	FrAr	Fr	FrAr	FrAsAr	FrAs

[z]Available phosphorus.
[y]Exchangeable potassium.
[x]Fr: loamy; As: clayey; Ar: sandy.

TABLE 2 Nutrient Foliar Levels Determined after Harvest (January) in the Previous Growing Season in Each Orchard

Nutrient	Orchard 1	Orchard 2	Orchard 3	Orchard 4
N (%)	2.81	2.22	2.43	2.78
P (%)	0.42	0.21	0.23	0.36
K (%)	1.88	1.48	1.77	1.75
Ca (%)	2.40	1.17	1.65	1.30
Mg (%)	0.57	0.62	0.67	0.55
Mn (ppm)	29.00	23.00	33.00	40.00
Zn (ppm)	10.00	9.00	13.00	8.00
B (ppm)	31.00	24.00	34.00	24.00

- *Orchard 1*: Furrow irrigation, short grass sward in the alley, and NPK fertilization: 125 kg N ha^{-1} (calcium nitrate in early Feb. 2007); 4 kg P ha^{-1} (triple superphosphate) and 104 kg K ha^{-1} (potassium sulphate) at the end of Aug. 2006.
- *Orchard 2*: Furrow irrigation, bare soil in the alley and NPK fertilization: 125 kg N ha^{-1} (calcium nitrate in early Feb. 2007); 4 kg P ha^{-1} (triple superphosphate) and 104 kg K ha^{-1} (potassium sulphate) at the end of Aug. 2006.
- *Orchard 3*: Drip irrigation, short grass sward in the alley, and NPK fertilization: 78 kg N ha^{-1} (applied every 10 days during the season, starting in Jan. 2007, using soluble calcium nitrate); 3 kg P ha^{-1} (phosphoric acid) and 80 kg K ha^{-1} (potassium sulphate).
- *Orchard 4*: Drip irrigation, short grass sward in the alley and N fertilization: 78 kg N ha^{-1} (applied every 10 days, starting in Jan. 2007, using soluble calcium nitrate).

Micronutrients (Zn, Mn, B) and extra Ca were foliar applied during the season, in the four orchards. Micronutrient applications included: 170 g Zn in 100 L water (as $ZnSO_4$), three occasions (pink bud stage, petal fall, and fruit growth); 500 g Mn in 100 L water (as $MnSO_4$), three occasions (petal fall, fruit growth, and before harvest); 200 g boric acid in 100 L water in one application after harvest; 175 g Ca in 100 L water (as $CaCl_2$), fortnightly during fruit development. In all cases, weeds were controlled using herbicides, complemented with manual control.

The different situations to be compared in the present study were:

- *Situation I*: Alley management: short grasses (orchard 1) versus bare soil (orchard 2);
- *Situation II*: Irrigation management: furrow irrigation (orchard 1) versus drip irrigation (orchard 3);
- *Situation III*: Fertilization management: NPK fertilization (orchard 3) versus N fertilization (orchard 4).

Sampling and Analysis

To determine soil nitrate distribution, we first validated the root depth data of sweet cherry found by Dawson et al. (2001) by digging out the soil in the row 0.5 m from the tree trunk, twice in each orchard. The holes, 1 m wide (0.5 m at each side of the tree trunk), were dug up to the root depth. A grid of 1 m^2, divided in quadrants 0.10 m side, was located in the face of the hole closest to the trunk, and roots of 0–2 mm, 2–5 mm, 5–10 mm, and > 10 mm in each quadrant were mapped. Twenty-four sampling sites were set in each orchard. The samples were taken in two locations around 12 sweet cherry trees: in the row (samples were taken 0.20 m apart from the tree trunk, parallel to the row) and in the alley (1 m away from the tree trunk, perpendicular to the row). Four depths (intervals of 30 cm from 0 to 120 cm depth) were considered in each sampling site. In the furrow-irrigated orchards (orchards 1 and 2), soil samplings were taken 10 days after the first irrigation subsequent to N fertilizer application. For drip-irrigated orchards (orchards 3 and 4), soil samplings were taken after the 3rd daily water application (after completing the period of fertigation).

Soil samples were extracted with KCl 40 nM, in a 1:1 soil:solution ratio and nitrates were determined colorimetrically. Before and after N application, aerial and root biomass samples of the grass sward were taken in the 'cover crop' situation (orchard 1) and total N (Kjeldhal method; Bremmer, 1960) was determined.

Statistical Analysis of Data

A preliminary descriptive analysis showed different standard deviations (SD) according to the management, location, and depth, so that in general, higher SD were found in nitrate values determined in the alleys and in the top soil. There were also significant ($p < 0.05$) positive linear associations among nitrates determined at different depths for orchard 1 in the row and for orchard 2 in the alley (data not shown). The statistical analysis was carried out taking into account those differences in variability and the occurrence of associations. Data were statistically analyzed using a mixed model (Littell et al., 1996; Vittinghoff et al., 2005) in order to detect interactions among managements (depending on the irrigation, soil cover or fertilization), locations and depths and considering the differences in variability according to the management and location as well as the associations among nitrate concentration at different depths of the same sample. Data were analyzed using the SAS/STAT software (proc MIXED), Version 9.2 of the SAS System for Windows (SAS Institute Inc., 2002–2008).

RESULTS

The nutrient foliar levels of the cherry trees in all orchards (Table 2) were similar enough to discard differences in the behavior of nitrates in the soil due to differences in the plant nutritional status. The different orchard managements influenced the distribution of roots within the soils (Fig. 1). Roots were distributed in the soil profile to a maximum depth of 1 m in orchard 1, while roots were found up to a depth of 0.90 m in the other orchards. In orchard 2, the total number of roots in the soil profile and in the top layers was lower than that in the other orchards. Orchards 3 and 4 (drip-irrigated) showed higher root concentration in the first 0.50 m depth than orchards 1 and 2 (furrow-irrigated).

As nitrate distribution showed a triple significant interaction (management * location * depth) ($p = 0.0008$), a mean comparison of the different managements of interest was made within each location and depth (Fig. 2). When evaluating Situation I (short grasses versus bare soil in the alley), the behavior of nitrate values for the two managements in the row was quite the opposite of that in the alley. In the alley, the nitrate concentration in the bare soil was significantly higher than that in the soil covered by short grasses at 0–60 cm depth. In contrast, in the row, the soil covered with short grasses presented significantly higher values than the bare soil at 0–60 cm depth. The highest concentrations of nitrates as well as the highest standard deviations were found in the row in orchard 1 and in the alley in orchard 2, which were the furrow-irrigated orchards, with and without the grass sward in the alley, respectively. The variation coefficients varied from 21% to 172% in

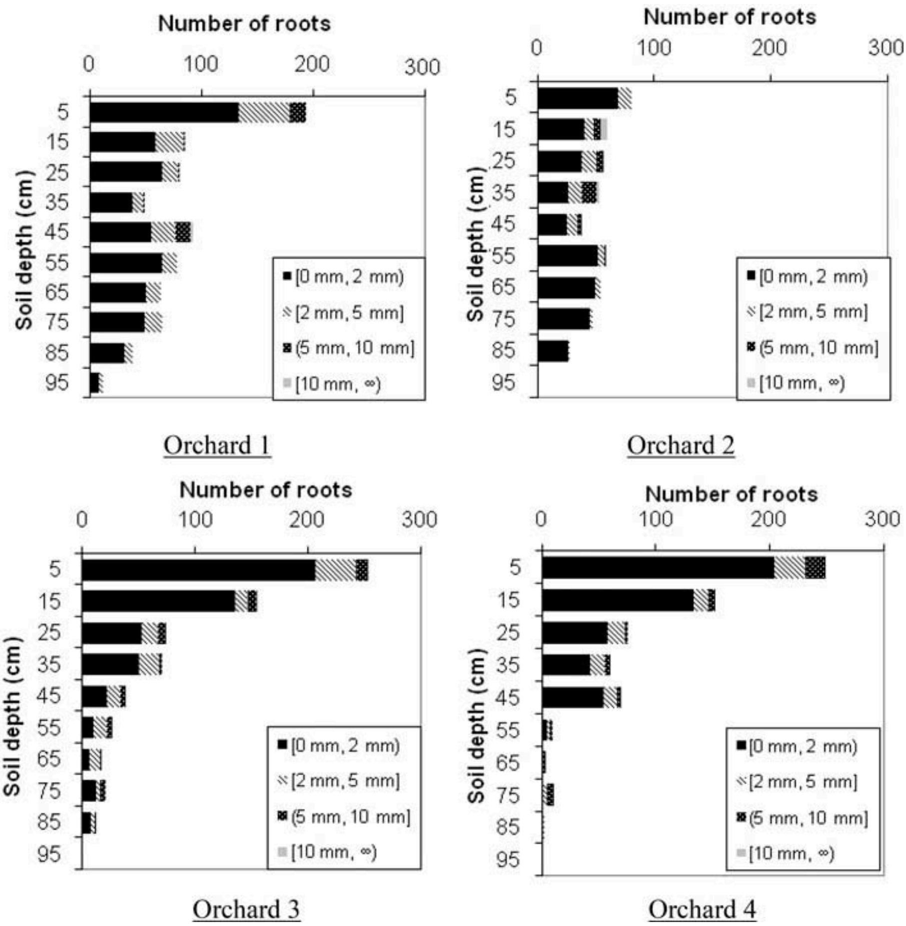

FIGURE 1 Number of roots in the soil profile (mean of two holes in each of four sweet cherry (*Prunus avium* cv. 'Bing' grafted onto *P. mahaleb*) orchards, classified according to their diameter (legend in the bottom of each figure). Orchards are identified by number (1 to 4).

the furrow-irrigated orchards as compared to 8% to 33% in the drip-irrigated ones. Situation II (furrow irrigation versus drip irrigation) showed that the lowest nitrate concentrations up to 60 cm depth were found when drip irrigation was applied, both in the row and in the alley, averaging less than 7 mg kg^{-1}. With furrow irrigation, nitrate concentration varied from 5 to more than 120 mg kg^{-1}. The highest nitrate concentration was found at 0, a 30-cm depth when furrow irrigation was applied. According to our results, Situation III (NPK versus N fertilization) showed that in a context of very low nitrate content when N was applied as the only macronutrient, there was a significant nitrate accumulation in the 30–60 cm depth layer in the alley.

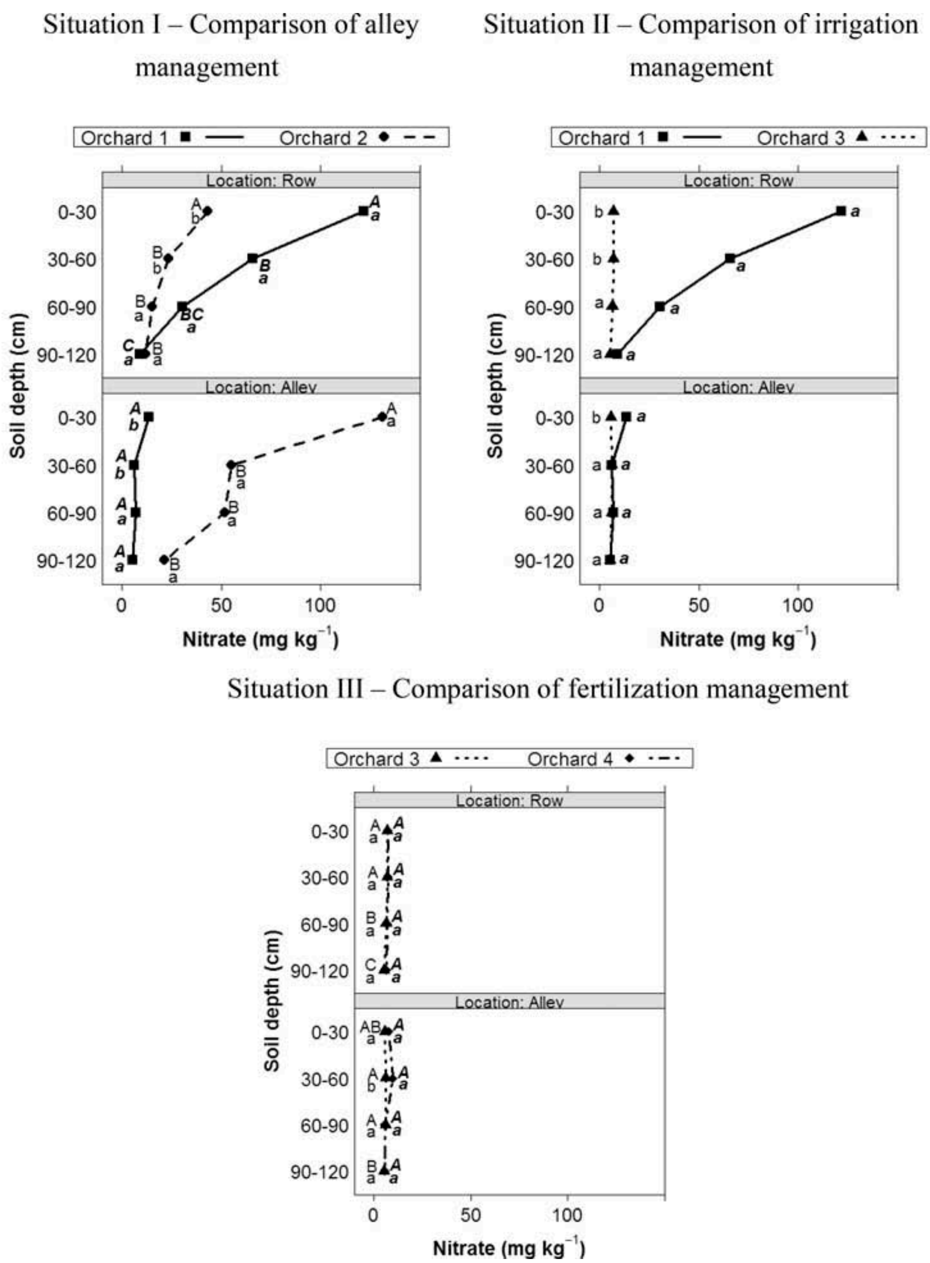

FIGURE 2 Nitrate means (mg kg^{-1}) comparison between situations (alley, irrigation, and fertilization managements) and depths (0 to 120 cm), within each location (alley or row) of the sweet cherry (*Prunus avium* cv. 'Bing' grafted onto *P. mahaleb*) orchards. In each location and depth, equal lower-case letters indicate no significant differences ($p > 0.05$) in nitrate means between orchards. In each orchard and location, equal capital letters indicate no significant differences ($p > 0.05$) in nitrate means between depths. *Note*: Italic bold letters were used for Orchard 1 or 4 while plain letters were used for Orchard 2 or 3.

TABLE 3 Total N (%) mean and standard deviation (between brackets) in aerial and root biomass of the grass sward in the alley of orchard 1, before and after N-fertilizer application

Aerial biomass	Before	1.29 (0.19)a[z]
	After	1.86 (0.24)b
Roots biomass	Before	0.55 (0.13)a
	After	0.64 (0.14)a

[z]Means followed by the same letter indicate no significant differences ($p > 0.05$) in total N, within each biomass class.

Complementarily to the previous analysis, a mean comparison of depths within each orchard and location was made (Fig. 2) and a mean comparison of location within each orchard and depth was made as well (data not shown). In orchard 1, nitrates significantly decreased with depth in the row, and nitrate concentration at 0–30 cm depth was higher (121.8 mg kg^{-1}) than that in the alley (13.3 mg kg^{-1}). In this last location, nitrate values remained always low, showing no differences between depths. In orchard 2, nitrate concentration was higher in the top soil layer than in the 30–120 cm depth, both in the row and in the alley. In contrast with the results observed in orchard 1, nitrates were higher in the top soil layer in the alley (131.3 mg kg^{-1}) than in the row (43.3 mg kg^{-1}). So, in the alley of orchard 2, some lateral movement of nitrates may have taken place, as shown by the higher concentration found in the top soil and also in depth. In orchard 3, there were also differences in nitrate concentration at the different depths, both in the row and in the alley. In this orchard, the nitrate concentrations at 0–60 cm depth were lower than those in orchards 1 and 2, and the nitrate concentrations in the alley were similar to or lower than those in the row. In orchard 4, no differences in nitrate concentrations were found either in depth or in location.

Total N determined in the grass sward biomass of the alley in orchard 1 (Table 3) showed that total N in the aerial biomass was significantly higher ($p = 0.0328$) after N application, while total N in root biomass showed no significant differences ($p = 0.4563$).

DISCUSSION

Roots were observed up to 0.90–1.00 m depth regardless of the management of the orchards, whereas the irrigation system influenced the number of roots in the top layers with more than 60% of the roots being found in the first 10 cm of soil in the drip-irrigated orchards versus 30% to 37% in the furrow-irrigated orchards. The relationship between root proliferation and management has been thoroughly studied. For instance, Dawson et al. (2001) found an increase in the number of cherry roots due to the use of herbicides around the tree, because of the reduction of competition with grass roots.

These authors also found that when grass roots were eliminated by herbicide application, tree roots tended to grow more superficially, especially roots of trees that had received higher N fertilizer doses. The same was found in our study in the orchards with grass sward in the alley (orchards 1, 3, and 4). This information supports the idea to consider a depth of 120 cm as the depth of residual nitrates in this crop. This depth could also be considered for other fruit trees, even apple trees, as furrow-irrigated trees have even shallower root systems (Aruani et al., 2007).

Nitrate vertical movement was affected by the alley management, and this is in agreement with the findings of Wrona and Sadowski (2004) in apple trees. These authors showed that mineral N increased in the soil zones where weeds were controlled with herbicides, but that with grasses this effect was less important. In the soil covered by a grass sward, water use efficiency and N absorption seem to be higher (Aronsson and Torstensson, 1998; Dawson et al., 2001; Sánchez et al., 1995). The increase in grass N concentration (Table 3) agreed with the data obtained for nitrates in the soil profile and the occurrence of more roots in the topsoil when grass occupied the alley, showing that grasses accumulated N when sweet cherry was fertilized.

When furrow irrigation is used, the wet area is usually wider than the irrigation furrow itself, and some horizontal movement of nitrates should be expected, following the water saturated flux towards the plant and the alley. We found lateral nitrate movement in bare soils (Fig. 2), but no lateral movement of nitrates towards the alley with the grass sward: in fact, nitrate concentrations were always lower than in the row. The irrigation system is key to localizing and keeping nutrients in the root zone. It is well known that frequent and low doses of N added by fertigation are more efficient than the application of granulated fertilizers and the use of gravitational irrigation (e.g., Hagin and Lowengart, 1996; Neilsen et al., 1998; Ramos, 1996; Sánchez et al., 1995). In accordance, when the fertilizer was applied by fertigation, the nitrate concentrations at different soil depths, both in the rows and in the alley, were lower and less variable.

In studies where mineral fertilizers or manure were applied at normal rates (90–110 kg N ha^{-1}), undersown grasses used as catch crops reduced nitrate leaching by 50% or more (Aronsson and Torstensson, 1998). In our study, the higher N concentration determined in the grass aerial biomass after N-fertilization may indicate that part of the N that was not absorbed by the sweet cherry roots was taken up by the grasses in the alley. This fact may have contributed to the lower occurrence of potentially leached nitrates observed below the roots depth. An unbalanced (only N) drip fertigation showed nitrate accumulation between rows in the 30–60 cm soil depth layer, although this nitrate accumulation was lower than that observed in furrow irrigation. This could be caused by the large number of roots found below 45 cm depth in this orchard (orchard 3).

CONCLUSIONS

The accumulation of residual nitrates at a depth of 120 cm that are prone to being leached in the future were found to be higher in sweet cherry orchards with bare soil in the alley. The effects of the irrigation system and fertilization were less important in this matter. The modern production technologies recommend orchards with short grass sward in the alley, mainly because of the negative effects of tillage between the rows to maintain the soil free of weeds. According to our results, the short grass sward in the alleys must also be considered as an important environmental factor for sustainable sweet cherry orchards, because it reduces the risk of nitrate leaching.

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