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Management of soil nitrate heterogeneity resulting from crop rows in a lettuce–tomato rotation under a greenhouse

François Lecompte

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Abstract Vegetable crops grown under plastic tunnels in the Mediterranean region are intensively managed. Generally, a spring row crop, such as tomatoes, is followed by one or two lettuce crops in the autumn and winter. Lettuce cropping in these systems can generate significant nitrate losses. Thus, nitrogen must be properly managed in such systems. Drip fertigation of the tomato crops prior to lettuce cropping creates an uneven distribution of nitrate in the soil including its accumulation between the rows. However, the fate of this residual, unevenly distributed nitrate and its impact on the following crop nitrogen (N) budget is unknown. Thus, a 2-year experiment was conducted to study N dynamics in a tomato–lettuce rotation. Two different management systems were tested: one with typical current farm practices (“C”) and a second system with decisions based on continuous monitoring of soil nitrate and water content (“L”) that resulted in the requirement of less water and N inputs. We revealed a recurring annual sequence in the two systems: strong N accumulation occurred during the spring crop and autumn fallow followed by soil nitrate exhaustion during lettuce growth as a consequence of crop uptake and leaching. We showed that leaching during lettuce growth appeared unavoidable even in the “L” management system. Between the former tomato rows (in the inter-rows), the higher initial soil N residues resulted in significantly higher N uptake (an increase of 14–25 kg ha⁻¹) and higher leaching (an increase of 2–32 kg ha⁻¹) compared with uptake and leaching within the tomato rows. Therefore, to limit substantial N losses,

nitrogen fertiliser recommendations should take into account the residual nitrate distribution in the soil by adding different amounts of fertiliser depending on the position relative to the previous row crop.

Keywords *Lactuca sativa* · *Lycopersicon esculentum* · Drip fertigation · Nitrate leaching · Mineralisation

1 Introduction

Plastic tunnels are greenhouse structures dedicated to the production of soil-grown, high-value crops such as vegetables. Soil-grown crops are grown in distinct geometries from typical row crops, such as tomatoes that are grown in single or double rows separated by large inter-rows or alleys accessible to field workers, to crops such as lettuce, which cover almost all the soil surface. In a typical Mediterranean rotation with spring tomatoes followed by winter lettuce, lettuce plants are set in zones previously covered by either tomato rows or uncovered soil inter-rows. Therefore, if the soil remaining at the end of the tomato crop is heterogeneous due to this alternation of rows and inter-rows, the subsequent crop is likely to grow in a heterogeneous environment. Indeed, one of the most noticeable examples of heterogeneity created by a fertigated row crop is the uneven distribution of mobile nutrients in the soil. Nitrate in particular is likely to accumulate at the periphery of the wetted soil volume (Bar-Yosef 1999; Gardenas et al. 2005; Lecompte et al. 2008; Li et al. 2004). During tunnel tomato production, this uneven distribution leads to the accumulation of mineral N in the inter-rows, whereas mineral N under the rows remains low (Lecompte et al. 2008). The accumulation of salts can be considerable, even in correctly fertilised fields, and deliberate leaching of residual minerals after row crop harvesting is

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a widespread practice (Thompson et al. 2007) despite the high pollution risk. If the soil is not intentionally leached before the winter lettuce crop, N management problem may occur: N reserves might be sufficient to allow appropriate lettuce nutrition in the former tomato inter-row zones but can be insufficient in the row zones. To avoid any risk of N stress, growers might apply fertiliser before planting the lettuce crop based on the nitrate level found in the former tomato rows; however, by broadcasting fertiliser over the entire soil surface, the mineral N heterogeneity of the soil might remain intact.

The fate of N during the winter lettuce crop is also in doubt due to three other characteristics of plastic tunnel lettuce production. First, lettuce is known to be a water-sensitive crop (Gallardo et al. 1996; Sammis et al. 1988; Thompson and Doerge 1996), and very low water potentials are maintained throughout crop growth. As a consequence, intense nitrate leaching often occurs in lettuce fields (de Tourdonnet 1998; Jackson et al. 1994). Second, weather conditions under plastic tunnels during the autumn and winter can be favourable to mineralisation, and mineralised N can contribute much of the lettuce crop N requirement (Bertuzzi et al. 2002). Finally, solar radiation is not transmitted equally across the tunnel with the lowest transmission rates being found at the edge and the highest rates at the centre (Wang and Boulard 2000). This uneven radiation transmission results in a regular increase in lettuce weight with distance to the tunnel edge (de Tourdonnet et al. 2001).

The variation in N supply resulting from the rotation of species with different crop geometries under protective structures has, to our knowledge, never been studied previously. Three questions arise from the literature summarised above. Is the heterogeneity of soil mineral N present after harvesting a row crop maintained during the following crop? Does this heterogeneity of N distribution affect crop growth or mineral contents? Should one account for field heterogeneity in fertilisation strategies? To answer these questions, an experiment was undertaken where soil N, crop growth and crop exports were monitored over two successive years using a spatially explicit sampling scheme. Because responses might depend on the amount of water and fertiliser given to the crops, we compared two types of crop management: one based on standard recommendations (current farm practices) and another type based on close monitoring of soil water and nitrate contents.

2 Materials and methods

2.1 Description of the crop rotation

Four plastic tunnels, 8 m wide \times 20 m long, were used for the experiment. The tunnels were erected in February, 2006, in a field previously under fallow at the INRA research centre of

Avignon, France. The soil was 60 cm deep and was a stony calcareous soil with a loamy texture (45% sand, 30% loam and 25% clay) and 3.5% organic matter. The tunnels were covered with a 200- μ m thick transparent polyethylene film. Three tomato crops (T1 to T3) and two lettuce crops (L1 and L2) were grown between spring 2006 and autumn 2008. Tomato plantlets (cv. Swanson, indeterminate cultivar, De Ruiter Seeds) at the four-leaf stage were planted on 6 April 2006 (T1), 13 March 2007 (T2) and 12 March 2008 (T3). Tomatoes were harvested once per week between June and August, and the plants were removed on 5 September 2006 (T1), 12 September 2007 (T2) and 3 September 2008 (T3). Each tunnel was planted with one single row (R1) on each side of the tunnel and three central double rows (R2 and R3; Fig. 1). Plant spacing within each row was 50 cm, and the distance between rows in the double rows was 45 cm. The rows were covered with black polyethylene mulch and were separated by 80 cm wide alleys (inter-rows IR1 and IR2). Plants were drip-irrigated with one emitter per plant (outflow rate, 2 l h⁻¹) positioned 15 cm away from the plant on the row line. Lettuce plantlets (cv. Leandra, Rijk Zwaan) were transplanted on 30 November 2006 (L1) and 16 November 2007 (L2) and were harvested on 22 February 2007 (L1) and 22 February 2008 (L2). Plant spacing between and within rows was 30 cm. A central alley of 80 cm width was kept free of plants (Fig. 1). The entire planted soil surface was covered with micro-perforated black polyethylene mulch. Lettuce plants were irrigated either with sprinklers or drippers depending on the treatments (see below). Before planting, the soil was deep-ploughed with a chisel plough and levelled with a harrow. Because the chisel did not invert or laterally displace the soil, ploughing did not affect the soil N distribution between rows and inter-rows. No weeding was necessary because most of the cropped area was mulched.

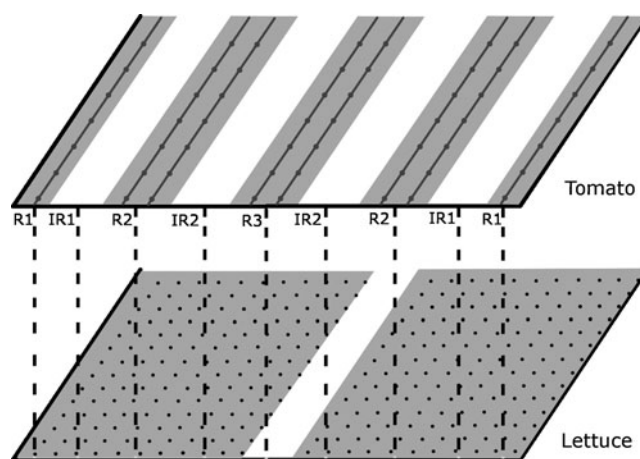


Fig. 1 Field crop geometry showing plant and soil sampling positions. Dots indicate plant positions, and grey surfaces show the polyethylene mulch. R1 to R3 correspond to the position of tomato rows, and IR1 and IR2 indicate the inter-row areas

Plants were treated with fungicides and insecticides as necessary.

2.2 Crop management systems

All four tunnels were managed in the same manner for the first tomato crop T1. Subsequently, two distinct forms of irrigation and fertilisation management were tested: “classical” (“C”, in two tunnels) and “limited” (“L”, in two tunnels). The total amount of irrigation water and NPK (nitrogen, phosphorus, potassium) fertilisers used for each crop and management system are given in Table 1. During T1, plants were irrigated daily according to the daily evapotranspiration reported by the meteorological service and the ground cover coefficient K_c derived from Amayreh and Al-Abed (Amayreh and Al-Abed 2005). Up to six irrigation events per day were programmed according to the total amount of water required. Ten kilogrammes per hectare of triple superphosphate was added at the time of planting. Starting 1 month after transplanting, plants were fertilised weekly with simple fertilisers with NPK ratio of 1/0.4/1.6 according to current practices. Magnesium sulphate was also added regularly. In the “C” system, crop management was similar to that observed in farms of the local region and based on standard recommendations for lettuce and tomato production under plastic tunnels. A few days before each lettuce planting, 20 mm of water was added to the soil. Thereafter, plants were sprinkle-irrigated once a week with increasing amounts of water to match crop evapotranspiration. Before each planting, fertiliser was distributed onto the soil at a rate of 60 N, 10 P and 130 kg ha⁻¹ K (Table 1). Tomato crops in “C” were managed as in T1 except that the NPK ratio of the weekly fertilisation was changed to 1/0.25/1.5 because soil analyses revealed that the soil P was high.

In the “L” management system, both lettuce and tomato were fertigated by drippers. However, as in the “C” system, sprinklers were used before lettuce planting to add 20 mm of water to the soil. For lettuce, drip tapes (three drippers per metre; outflow of 2.4 l h⁻¹) were positioned along alternate rows 60 cm apart. Soil water potential sensors (Watermarks CSI 257, Campbell Scientific, France) were used to monitor the soil water status. Sensors were placed at three positions:

R1, R2 and the edge of the plastic mulch near the central alley. Sensors were placed at 10 and 30 cm depths with three replicates for each position and depth. Irrigation was initiated when necessary to maintain the mean soil water potential (SWP) close to -20 kPa at a 10 cm depth. Water quantities varied from one irrigation event to another to maintain SWP between -20 and -30 kPa at a 30 cm depth. This irrigation scheme resulted in water savings (including the initial input of 20 mm in both systems) of 41% in L1 and 31% in L2 in the “L” system relative to the “C” system (Table 1). For tomatoes, drip lines and emitter positions were the same as in the “C” tunnels. Water potential sensors were placed at 10 and 35 cm depths at six positions: R1, IR1, R2, IR2 and on the edge of the plastic mulch between R1 and IR1 and between R2 and IR2. The number of daily irrigation events increased from one to six with crop development. The duration of an irrigation event (and thus the water input) was determined twice a week; the objective was to maintain the mean SWP between -15 and -30 kPa under the row at a 10 cm depth and the mean SWP between -35 and -50 kPa at the edge of the plastic mulch at a 30 cm depth. This irrigation strategy resulted in water savings of 29% in T2 and 47% in T3 in the “L” system relative to the “C” system (Table 1).

Fertilisation in the “L” management system was based on monthly assessments of mineral concentrations in the soil solution. The quantities of fertiliser inputs were determined according to the plant requirements and soil concentration thresholds. For N, plant requirements were based on critical N dilution curves established by Tei et al. (2003) for lettuce and Tei et al. (2002) for tomatoes. The expected N uptake during a given period (N_{exp}) was calculated as $N_{exp} = 10 \times a \times \Delta MS^{(1-b)}$ where ΔMS was the expected crop dry weight increase during the period, and a and b were the parameters of the dilution curve. Given the mean nitrate concentration of the soil solution under the row (C_N), the fertilisation rules for tomatoes were as follows: fertilisation corresponding to the expected crop uptake at C_N below 250 mg l⁻¹; fertilisation corresponding to half of the expected uptake at C_N between 250 and 400 mg l⁻¹; and no fertilisation above a C_N value of 400 mg l⁻¹. Because lettuce cropping can generate nitrate losses by leaching, it was decided that lettuce fertilisation

Table 1 Water and nutrient inputs for each crop of the rotation for two management systems: “C” with current farm practices and “L” with limited water and nitrogen inputs

	C				L			
	Irrigation (mm)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Irrigation (mm)	N (kg/ha)	P (kg/ha)	K (kg/ha)
Tomato 1	518	340	160	550	518	340	160	550
Lettuce 1	113	60	10	130	66	0	9	7
Tomato 2	651	380	95	600	465	346	51	461
Lettuce 2	110	60	10	130	76	0	7	21
Tomato 3	738	505	120	730	394	360	77	766

would be avoided at C_N above 250 mg l^{-1} , and lettuce would be fertilised at the expected crop uptake rate when C_N was below 250 mg l^{-1} . Because the soil nitrate concentrations used for this decision were measured under the row and in well-wetted parts of the soil, variations in soil nitrate concentrations due to changes in soil water content were assumed to be low, and most variations were assumed to be due to nitrate input or output. The use of these rules resulted in the lack of N fertilisation for lettuce crops and a 9% and 29% reduction in N inputs in T2 and T3, respectively, in “L” compared with “C” (Table 1). Similar rules were used for P and K but are not described here because this paper focuses on N balances. Overall, P and K inputs were reduced in the “L” management system by 23% and 19%, respectively.

2.3 Measurements

The soil was sampled every month from November 2006 to September 2008. The tunnels were assumed to have an axial symmetry, and samples were taken on either side of the R3 central line (Fig. 1). At each date, five soil cores were taken at positions R1, IR1, R2, IR2 and R3 along a transect perpendicular to the tunnel with three transect replicates for each management system. The sampling positions along the tunnel were chosen at random. Soil cores of a 50-cm depth were extracted using a percussion drill (SDEC, Tauxigny, France), and 5-cm-long subsamples were collected at 10, 30 and 50-cm depths. Ninety soil samples, corresponding to 5 transverse positions \times 3 depths \times 3 replicates \times 2 management systems, were collected on each date. Fine material was separated from stones using a 2-mm sieve. The gravimetric water content and nitrate concentration of each sample were determined. Nitrate concentrations were measured with a nitrate analyser (FIAstar 5000 analyser, FOSS) after extraction of 5 g soil samples in 20 ml of distilled water.

At the end of the growing season of each crop, plants were sampled at positions R1, IR1, R2 and IR2 for lettuce and R1 and R3 for tomatoes. Four plants per position and management system were measured. Roots were not recovered. Tomato leaves, stems and green fruits and lettuce leaves were weighed and dried at 70°C for 72 h to determine their water contents. The N contents of dry subsamples were measured using a N analyser (Flash 2000 CHON analyser, Thermo Scientific). At each harvest, tomatoes were weighted, and the final yield was calculated as the total weight of the harvested fruits. The harvest index was also computed as the ratio of the harvested fruit fresh weight to the total plant fresh weight.

2.4 Data analysis

Nitrate reserves within the soil profile were calculated for each sampling date. Percentages of fine soil particles of 70%, 55%

and 30% at 10, 30 and 50 cm, respectively, were used in the calculations in accordance with measurements from soil samples taken before the beginning of the experiment. The soil bulk density was 1.4 g cm^{-3} in the 0–25 cm soil layer and 1.5 g cm^{-3} in the 25–50 cm soil layer, and these values were assumed to be constant throughout the experiment. Two-dimensional profiles of the soil nitrate contents (on a soil dry weight basis) were calculated, and contour plots were created using the G3grid and GContour procedures of the SAS9.2 software package. Nitrogen nutrition indexes (NNI) were calculated as the ratio of the N content of the plants to the critical nitrogen content defined by the critical dilution curves (Tei et al. 2002, 2003).

3 Results and discussion

3.1 Nitrate concentrations in the soil profile

During the 2 years of observation, the pattern in the evolution of nitrate concentrations in the 0–50 cm soil profile was similar in the two management systems but was accentuated in the “C” system (Fig. 2). Soil nitrate concentrations fell

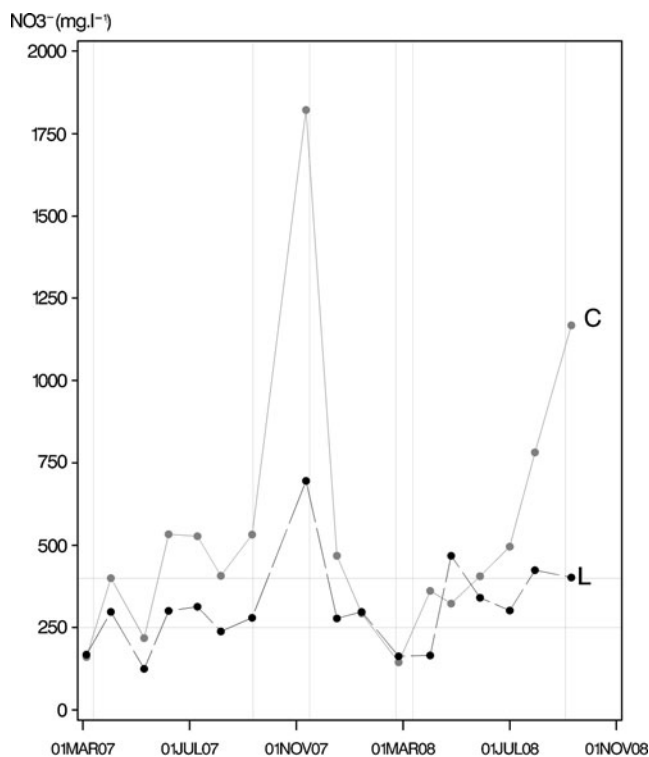
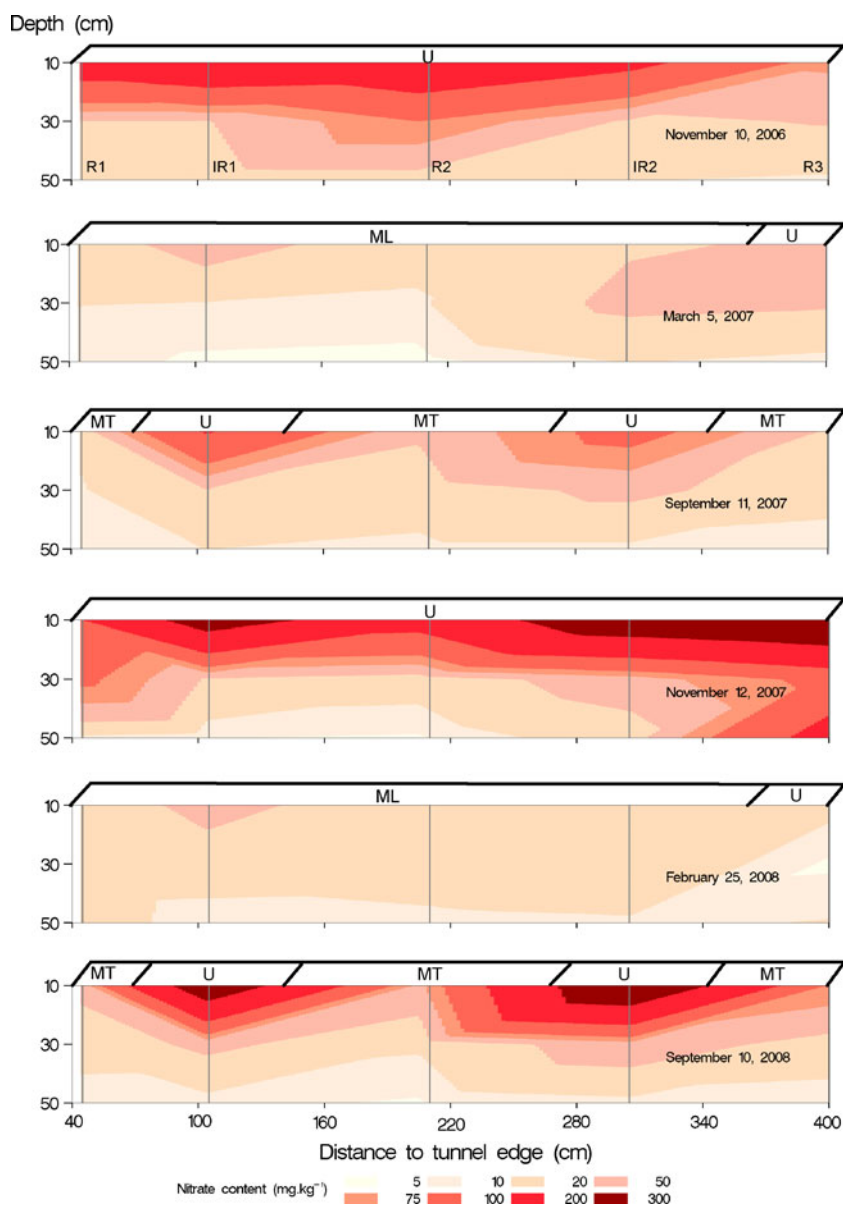


Fig. 2 Dynamics of mean soil nitrate concentrations in the 0–50 cm layer (45 samples per date) for the “C” (current farm practices) and “L” (limited water and nutrient inputs) management systems. Vertical lines represent the beginning and end of each crop (IC: fallow). Horizontal lines represent the thresholds of 250 and 400 mg l^{-1} for triggering N fertilisation

sharply each year between November and March. The concentration was highest just before lettuce planting and lowest at the time of tomato planting. During tomato growth, the soil nitrate concentration increased more abruptly in the “C” system. The rise in nitrate concentrations during the fallow in autumn 2007 in the “L” system might have been a consequence of soil drying and/or organic matter mineralisation. In system “C”, the increase in N concentrations was also due to the addition of N fertiliser before lettuce planting. Figures 3 and 4 shows the spatial distribution of nitrate in the profile, on a soil dry weight basis, at the beginning and end of each crop. Spatial patterns were comparable in the two systems, although the range of soil nitrate content was higher in “C” due to higher N inputs. Tomato crops created a pronounced nitrate gradient between the rows and the inter-

rows, which was apparent from the September 2007 and September 2008 samplings. This variability remained large at the time of lettuce planting in November, although N mineralisation (in both the “L” and “C” systems) and N fertilisation (in “C”) tended to reduce the spatial differences between the rows and the inter-rows. Nitrate concentrations in the inter-row areas reached values up to ten times higher than those measured in the rows in the “C” system (Fig. 3), and inter-row nitrate levels were up to five times higher in the “L” system (Fig. 4). In a similar crop design, but in a different soil, comparable horizontal gradients were observed (Lecompte et al. 2008). Although horizontal nitrate flow might depend on the soil hydraulic properties and the timing of fertiliser addition during an irrigation event (Gardenas et al. 2005), salt accumulation at the periphery of the wetted

Fig. 3 Two-dimensional contour plots of soil nitrate contents at different sampling dates for the “C” (current farm practices) management system, showing the periodical accumulation of nitrate under the inter-rows. Vertical lines on the plot indicate soil sampling positions (R1, R2 and R3: position of tomato lines, IR1 and IR2: center of the inter-row). U: uncovered soil; MT: mulched soil planted with tomatoes; ML: mulched soil planted with lettuce



soil volume in surface drip-irrigated tomatoes is a very common occurrence. At the time of the lettuce harvest, in March 2007 and March 2008, the soil was much more uniform and was almost exhausted of nitrate. Therefore, nitrate was either captured by the crop or lost by leaching or volatilisation.

3.2 Crop growth and nitrogen nutrition

Lettuce fresh weights at harvest were not significantly different in 2007 and 2008 ($p=0.23$ for “C” and $p=0.10$ for “L”; data not shown). Mean lettuce NNI values for both years were 1.12 in the “C” system and 0.62 in the “L” system with no significant inter-annual difference. Thus, lettuces in “L” suffered from nitrogen stress in both years.

The threshold of 250 mg l^{-1} for triggering N fertilisation was apparently too low. Furthermore, the soil nitrate concentration quickly fell below this limit during the second half of growth (Fig. 2) when N demand was high. At the time of the third soil nitrate measurement, just before harvest in 2007 and just after in 2008, it was too late to rectify the soil N content. A fertilisation decision rule similar to that used for tomatoes, i.e., a half-dose fertilisation at C_N between 250 and 400 mg l^{-1} , could have led to better results. In this soil, C_N values of 250 and 400 mg l^{-1} corresponded to N reserves of 50 and 80 kg ha^{-1} , respectively, at 0.2 w/w soil water content, which is generally sufficient to ensure adequate lettuce nutrition during the second half of the cropping period (de Tourdonnet 1998). Drip-irrigation and soil water potential monitoring allowed for significant water savings and is

Fig. 4 Two-dimensional contour plots of soil nitrate contents at different sampling dates for the “L” (limited water and nutrient inputs) management system, showing the periodical accumulation of nitrate under the inter-rows. Vertical lines on the plot indicate soil sampling positions (R1, R2 and R3: position of tomato lines, IR1 and IR2: center of the inter-row). U: uncovered soil; MT: mulched soil planted with tomatoes; ML: mulched soil planted with lettuce

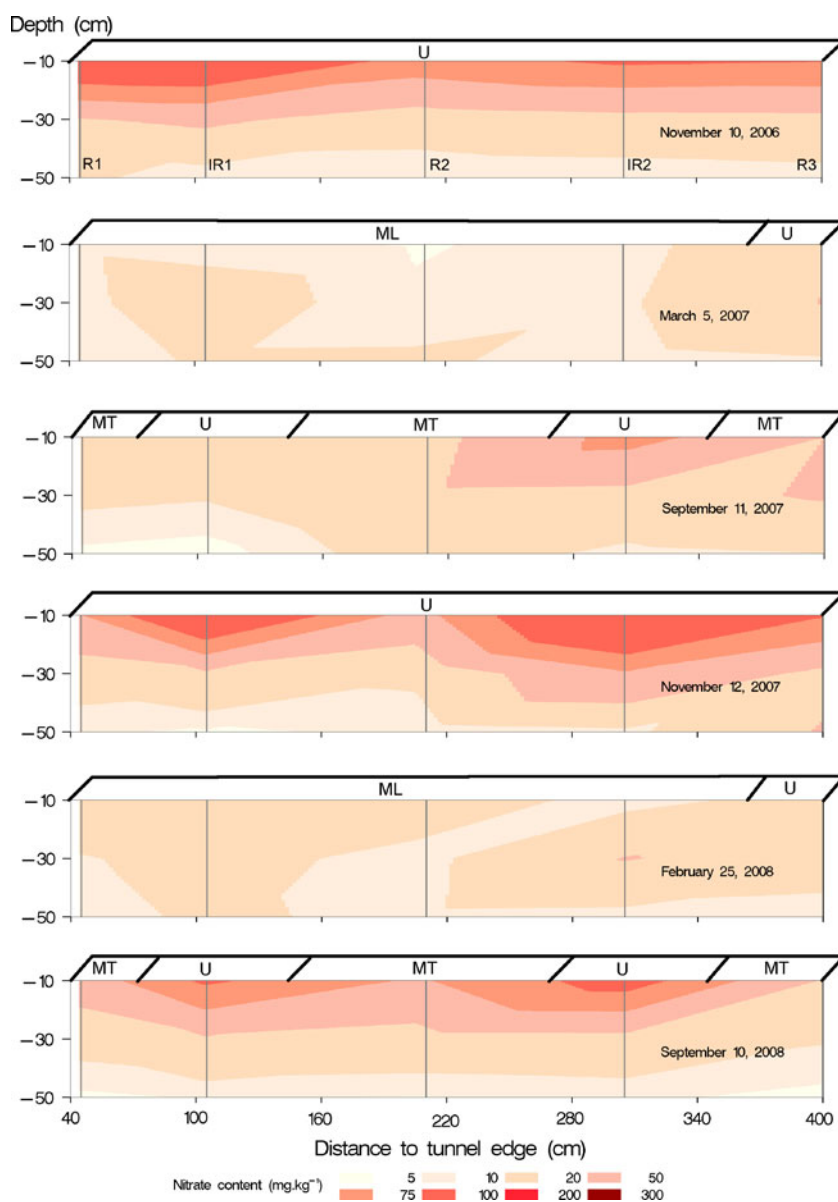


Table 2 Mean and standard error of fresh weight, harvest index, and Nitrogen Nutrition Index (NNI) values for tomato plants for two management systems “C” (current farm practices) and “L” (limited water and nitrogen inputs) and two plant positions R1 and R3

	C	L	Significance	R1	R3	Significance
Fresh weight (g)	11,481±667	10,863±394	n.s.	12,309±464	10,036±476	*
Harvest index	0.74±0.01	0.77±0.02	n.s.	0.75±0.02	0.76±0.02	n.s.
NNI	1.33±0.05	1.19±0.07	n.s.	1.22±0.06	1.30±0.05	n.s.

Data represent the overall mean for the 2007 and 2008 cropping seasons. Column “Significance” indicates the result of a *t* test for mean differences

n.s. not significant

*Indicates a significant difference at 5%

recommended for lettuce production under plastic tunnels in Mediterranean regions where rain is scarce. Surface drip-irrigation can also limit the incidence of fungal diseases, such as lettuce drop caused by *Scerotinia sclerotium* (Wu and Subbarao 2006). In both “C” and “L” systems, lettuce NNIs were significantly higher ($p < 0.0001$) at the position of the former tomato inter-rows IR1 and IR2 (Fig. 5). In system “C”, lettuce N nutrition at IR1 and IR2 positions was excessive. Plant fresh weights at harvest closely followed the NNI in treatment “L” (Fig. 5, Pearson correlation coefficient of 0.76 between fresh weights and NNI) confirming that lettuce growth was limited by nitrogen. Conversely, in system “C”, a regular increase in fresh weights with distance from the edge of the tunnel was observed. The range of weight increase with distance to the edge of the tunnel was comparable to that reported by De Tourdonnet et al. (2001) and was probably linked to the light gradient induced by differential light transmission depending on the radial position under the tunnel. Lettuce dry weights are known to increase significantly with limited supplementary light at moderate radiation levels (McCall and Willumsen 1999), which was the case during winter plastic tunnel production.

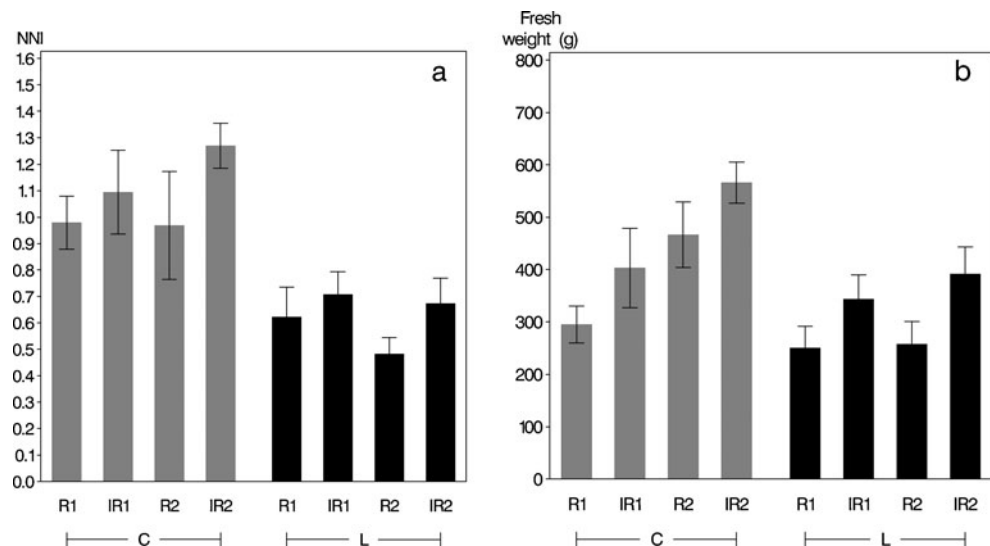
Tomato crop yields were also significantly higher in 2007 than 2008, although no differences were observed between the management systems for the fresh weight, the harvest index or the NNI (Table 2). Spatial differences were recorded, and plants were significantly heavier in R1 than in R3 (Table 2). This spatial difference might have been a result of the plant spacing with slightly faster plant growth in single than double rows. However, the harvest index, NNIs and total crop N exports were similar in R1 and R3 (data not shown). The yields obtained in this experiment, which approached 17 kg m⁻², were typical of this type of spring tomato production under plastic tunnels. Therefore, important savings of water and nutrients were made in this experiment without affecting tomato yields.

3.3 N balances for lettuce cropping

A nitrogen balance for lettuce cropping can be written as follows:

$$S_f - S_i = (M + F + C) - (U + D + L + V)$$

Fig. 5 Nitrogen nutrition index (NNI) (a) and fresh weight (b) of lettuce plants at harvest at different sampling positions for the “C” (current farm practices) and “L” (limited water and nutrient inputs) management systems. Each bar is the mean ±SE of eight plants



where S_f and S_i are the N reserve at the end and the beginning of the cropping period, respectively, M is the net N mineralisation, F is the amount of fertiliser added to the soil, C is the N input due to capillary rise, U is the crop uptake, D is denitrification, L is the loss due to leaching and V is the loss due to volatilisation (all terms are in kilogrammes N per hectare). Variables C , D and V can be considered to be low relative to the other terms and can be neglected as a first approximation. Denitrification when the soil is unsaturated is usually less than 10 kg ha^{-1} (de Tourdonnet et al. 2001; Leenhardt et al. 1998). Water content at a 50 cm depth in this experiment was always less than in the upper soil; therefore, water flow at the bottom of the root zone was downwards, and capillary rise should not have occurred (data not shown). S_f , S_i , F and U were measured during the experiment. A rough estimate of M could be obtained by considering the variations in the N reserve during periods with uncovered soil and no irrigation. There was a positive difference in the N reserve of 24 kgN ha^{-1} in the soil profile between 11 September 2007 and 12 November 2007 after the tomato removal and before lettuce planting. This positive difference would correspond to a daily mineralisation rate of $0.4 \text{ kgN ha}^{-1} \text{ d}^{-1}$. Eight nitrogen balances were calculated corresponding to each year, management system and position relative to the previous tomato crop (i.e. row (R) or inter-row (IR); Table 3). The balances between 27 November 2006 and 3 March 2007 for L1 and 12 November 2007 and 25 February 2008 for L2 were calculated. The ratio of S_f in R to S_f in IR ranged between

0.44 and 0.78 depending on the crop management system and year. At mid-crop, these ratios were similar to those measured at planting (data not shown). These ratios indicate that N losses and uptake were approximately proportional to the available soil N. Conversely, at harvest, as already stated, differences in soil N between R and IR were small. Mean N leaching was 33 kg ha^{-1} in the “L” system and 66 kg ha^{-1} in the “C” system and accounted for 27% to 45% of the available N. Leaching at position IR was 2 to 32 kg ha^{-1} more than that at position R, indicating that a significant, although variable (8–66%), part of the initial supplemental N in the IR was lost to the environment.

The calculated losses by leaching were intrinsically dependent on the estimation of N mineralisation, and higher mineralisation rates would have resulted in higher losses. The estimated mineralisation rate of $0.4 \text{ kgN ha}^{-1} \text{ day}^{-1}$ was within the range (0.27–0.65) of measured mineralisation rates in autumn and winter under plastic tunnels in south-eastern France (Bertuzzi et al. 2002). Other mineralisation rates in lettuce fields were obtained using simulations and were higher than those observed here— 0.56 and $0.64 \text{ kg ha}^{-1} \text{ d}^{-1}$ in autumn and winter, respectively, under plastic tunnels (de Tourdonnet et al. 2001) and $1 \text{ kg ha}^{-1} \text{ d}^{-1}$ in autumn in the open (Leenhardt et al. 1998). The amount of leached N calculated here was almost proportional to the available soil nitrate, i.e. the leached N was equal to the sum of the residual soil nitrate after tomato harvesting, N fertilisation and N mineralisation. This extent of leaching has been reported previously (Bruckler et al. 1997) and confirms that heavy nitrate pollution can result from lettuce cropping. Two factors explain why lettuce soils are very sensitive to leaching: Lettuce is shallow-rooted, and a small downward movement of nitrate past the roots limits N recovery by the plants. Also, lettuce is very sensitive to water stress and is grown at a high soil water content to avoid any water shortage, especially in the Mediterranean region where evapotranspiration rates are high. Thus, any attempt to avoid N leaching must be based on the limitation of nitrate concentration in the soil solution, especially at the beginning of growth. This N limitation was illustrated in the “L” management system where leaching was limited when initial reserves were low (Table 3). In the “C” system, 60 kg ha^{-1} of N fertiliser was added to the soil before transplanting. In the former tomato rows (R position), part of this N was leached, although the crop NNI was optimal. Conversely, in the IR positions, a larger amount of residual N was available, and this resulted in an above optimal NNI and greater losses due to leaching or denitrification. Therefore, part, if not all, of the fertiliser added in the IR position in the “C” system was unnecessary. Also, because a significant part of the N was leached at the beginning of the cropping period, fertilisation could have been delayed and performed at a time when nitrate uptake by the crop was maximal.

Table 3 N balance components for lettuce at two positions (row R and inter-row IR) and for two management systems “C” (current farm practices) and “L” (limited water and nutrient inputs)

		C		L	
		IR	R	IR	R
2006–2007 (L1)	kgN/ha				
	Initial stock (S_i) ^a	160	106	59	34
	Final stock (S_f)	30	16	13	10
	$S_f - S_i$	–130	–90	–46	–24
	Crop uptake (U)	99	76	58	38
	Mineralisation (M) ^b	39	39	39	39
	Leaching (L) ^c	70	53	27	25
2007–2008 (L2)	Initial stock (S_i) ^a	156	96	78	34
	Final stock (S_f)	25	21	19	18
	$S_f - S_i$	–131	–75	–59	–16
	Crop uptake (U)	87	63	47	33
	Mineralisation (M) ^b	42	42	42	42
	Leaching (L) ^c	86	54	54	75

^a Includes N fertilisation before lettuce transplanting in system C

^b Estimated from stock variations between September and November 2008

^c $L = M - U - (S_f - S_i)$; part of this term may include unaccounted denitrification or volatilisation

4 Conclusions

Tomato crops generate N accumulations in the uncovered inter-rows. Part of the accumulated N is retrieved in the succeeding crop, but, as in the case of lettuce, a significant amount of N is also leached such that the soil profile is depleted with N at the end of the season. If the field is uniformly fertilised before lettuce planting, then the heterogeneity of N distribution in the soil will be maintained, and N losses can be maximised. One solution would be to take this heterogeneity into account within the fertilisation programme by applying different amounts of N to the former rows and inter-rows. In the inter-row areas, lettuce would mainly recover residual N from the previous crop, whereas fertiliser N would allow adequate N nutrition in the former rows. In addition, the fertiliser should be added as late as possible during the growing season to maintain low mineral N reserves in early growth where large N losses due to leaching can occur.

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