Non-uniformity of environmental conditions in greenhouse lettuce production increases the risk of N pollution and lower product quality

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Abstract – Although it is well known that environmental conditions in greenhouse crops are often not uniform, this is rarely taken into account in research into the factors determining product quality and pollution. Yet non-uniformity of irrigation, radiation and effect of compaction doubtless plays a fundamental part in the problems of quality (uniform size) and N pollution faced in lettuce production under plastic. A monitoring study of four lettuce crops showed a high degree of environmental non-uniformity, structured by the cropping methods used, and partly responsible for the variability in lettuce size. A model of the behaviour of the soil-plant system showed that this non-uniformity leads to serious N pollution: meeting the needs of the most disadvantaged plants leads to over-irrigation and over-fertilisation in nitrogen in some zones of the tunnel. If this non-uniformity is ignored, solutions may be proposed that do not match the objectives set in terms of product quality and environmental protection.

Lactuca sativa / nitrate leaching / model / radiation / soil compaction / irrigation

Résumé – L'hétérogénéité du milieu en production de laitue sous abri accroît le risque de pollution nitrique et affecte la qualité du produit. Bien que l'hétérogénéité des conditions du milieu soit un phénomène bien connu pour les cultures abritées, elle est rarement prise en compte dans les études portant sur les déterminants de la qualité des produits et de la pollution. Or les hétérogénéités d'irrigation, de rayonnement ou dues à l'effet de la compaction ont sans doute un rôle fondamental dans les problèmes de qualité (homogénéité des calibres) et de pollution nitrique auxquels sont confrontés les producteurs de laitues sous abri plastique. Un suivi réalisé sur quatre cultures de laitues montre qu'il existe une forte hétérogénéité du milieu, structurée par les techniques culturales utilisées, et en partie responsable de la variabilité des calibres des laitues. L'utilisation d'un modèle de fonctionnement du système sol-plante montre que cette hétérogénéité induit une forte pollution nitrique : la satisfaction des besoins des laitues les plus défavorisées entraîne une sur-irrigation et une sur-fertilisation azotée sur certaines zones de l'abri. Nier cette hétérogénéité pourrait donc amener à proposer des solutions ne répondant pas aux objectifs fixés, en terme de qualité du produit et de respect de l'environnement.

Lactuca sativa / lessivage / modèle / rayonnement / compactage / irrigation

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1. INTRODUCTION

One challenge in greenhouse production is to design policies for cropping system management that improve product quality and reduce environmental impact. There have been many studies of the factors determining product quality and pollution in greenhouses, but most do not fully take the non-uniformity of the system and its components into consideration because they are difficult to characterise, even though it is known that conditions can vary widely within a greenhouse [2]. This can raise problems when inter-plant variability is taken as a decision making indicator [35] or when it is the non-uniformity of the environment that increases the risk of pollution and affects product quality.

Lettuce crops under plastic are an interesting case study for analysing these relations between environmental non-uniformity, product quality and environmental impact. Growers are finding it increasingly difficult to meet one major quality requirement: uniform size, an essential property of any product sold by the unit [12]. Variable weight at harvest may be linked to non-uniform environmental conditions [36, 46, 57] partly due to the combined effects of several cropping techniques.

(i) Sprinkler irrigation, which may spread water very unevenly [9, 26, 32, 33, 39] depending on the type of sprinkler used, conditions of use (water pressure) and the spatial arrangement of the sprinklers (location and direction of spray).

(ii) Use of plastic tunnels, in which the spatial distribution of incident radiation is uneven, as has been shown by experimental studies [22, 27] and modelling [3, 11, 56]. The incident light mainly varies along a transverse gradient across the greenhouse, depending on the type of greenhouse, its orientation and type of covering material, and weather conditions [3, 56].

(iii) Compaction by tractor wheels during tillage operations, which lead to uneven soil structure [42]. Compacted zones can cover more than 40% of the total greenhouse area. This deterioration of the structural state of the soil can affect soil physical properties [1, 10, 41], biochemical transformation of nitrogen [23] and the root and shoot growth of the lettuces [25, 34, 48].

The combined effect of these cropping techniques can create a structured non-uniformity of the greenhouse environment which is liable to affect input quantities, physical soil characteristics, bio-transformation of nitrogen, flows of water and nitrates, and shoot and root growth.

As well as this, it has been said that the high levels of water and N fertiliser application generally found in greenhouse crops are partly responsible for the nitrate

pollution of groundwater now affecting several intensive market gardening regions in France [7, 13, 19]. Several studies of field lettuce crops, combining experiment with transfer modelling, have shown that nitrate leaching below the root zone can indeed reach very high proportions [8, 24, 30, 31]. Researchers have proposed various tools to allow growers to adjust environmental water and nitrate supply to the demand of a lettuce crop. Some of these tools are based on analysing response curves [18, 43, 52–54], some use simplified water and N budgets [37], some use more complex models of soil-plant system behaviour [24, 30, 31]. But in all these approaches, the input quantities received and the characteristics of soil and crops stand are always considered to be uniform within the plot. Yet Bruckler et al. [8] have shown that leaching under a field salad crop varies very widely owing to the variability of nitrate content in the soil profile and the spatial variability of the amount of water received by the plants. This environmental non-uniformity, which is doubtless even more marked in greenhouse crops, is likely to increase the risk of nitrate pollution through two processes revealed by studies of the consequences of uneven water application. Ben Asher et al. [5] have shown that, for a given average water application, drainage increases when the unevenness of water distribution increases. This theoretical result was subsequently confirmed by experimental data [6]. Another theoretical study has shown that, for a given degree of irrigation uniformity, there is a trade-off between the amount of water applied and the area that receives some target amount of water [9]. Given how sensitive lettuce is to water stress [4, 18, 43, 53, 55], it may be assumed that the grower seeks to reduce any under-irrigated zones to a minimum, and so applies more water than is needed to cover the crop's necessary requirement, increasing drainage in the process. And as over-irrigation often goes hand in hand with over-fertilisation to avoid the risk of nitrogen deficiency [53, 54], the risk of nitrate leaching is thus greatly increased.

One can therefore posit that the relationship between environmental non-uniformity, product quality and N pollution operates at two levels.

(i) A variable environment increases size variability and the risk of N pollution.

(ii) To compensate for the adverse effects of non-uniformity on product quality, growers are tempted to over-irrigate and over-fertilise, so further increasing the risk of N pollution.

The purpose of this article is (i) to characterise spatial variability in a greenhouse, (ii) to examine the impact on the weight of harvested lettuces by monitoring the crop, and (iii) to estimate the impact of non-uniformity on N pollution, using a model. Given the difficulty of

measuring deep flows of water and nitrate, models seem to be very useful tools for estimating nitrate leaching [8, 24, 30, 31]. We used a simulation model of soil-plant system behaviour, calibrated and validated on lettuce crops under plastic [14, 15].

2. MATERIALS AND METHODS

2.1. Crop monitoring

Surveys were conducted in a standard N-S oriented lettuce tunnel located at the experimental station in Alénia, near Perpignan in southern France. The soil is sandy river alluvium (68% sand, 23% silt, 9% clay). Tunnel dimensions were 8.5×49.5 m. The tunnel cover was 200 μ m Halls stabilised opalescent thermal polyethylene sheet. The sprinkler irrigation system consisted of two lines 4 m apart with Naan TMS 710/2 sprinklers (outflow rate: 144 l/h) set in them at 3 m intervals, 2 m in height off the ground. Irrigation was adjusted to the crop's evapotranspiration, estimated using the method proposed by de Villele [16].

Four monitoring exercises were effected on two successive lettuce crops, two years running (Tab. I). The lettuces (Judy variety) were planted at the four-leaf stage at a density of 14 plants per m^2 . Before planting, N (NO_3^-), P (P_2O_5), K (K_2O), Ca (CaO) and Mg (MgO) were applied, sufficient to meet the needs of the crop according to the soil analysis results [12].

Four sampling plots of 8.5×1 m were selected, 5, 18, 31 and 45 m from the north gable end. Each plot covered the full width of the tunnel (29 rows of 4 lettuces). With this arrangement, it was possible to study the effects of transversal non-uniformity (variation within each plot) and longitudinal non-uniformity (variability between plots). At harvest, each lettuce was identified according to its position, and weighed. Lettuces showing clear signs of disease were not weighed. So for crops 1, 3 and 4 we obtained between 395 and 453 spatialised measurements in fresh weight (Tab. V). With crop 2, heavy rain after planting temporarily flooded the edges of the tunnel, and this affected seedling establishment; we only

weighed the lettuces from a 4-m strip in the middle of the tunnel, which gave us 240 fresh-weight measurements.

To study the unevenness of water distribution by the irrigation system, we set up rain gauges at regular 50-cm intervals in both directions throughout the tunnel, after harvesting crop 1. In this way we were able to study variation in both longitudinal and lateral directions – those that, a priori, structure variability. We used 14.5×11.5 cm rain gauges. They began 25 cm from the tunnel edges, giving 17 lines of 98 rain gauges, or 1666 measurements. The area sampled amounted to 6.7% of the tunnel's ground area. Irrigation of 4 mm was then applied. The quantity of water applied was controlled by a volumetric meter in the tunnel's water supply circuit. The quantity of water received by each rain gauge was then measured by graduated test tube.

Solar radiation distribution was measured using 14 gallium arsenide PAR sensors [40] set up along two sections 5 m from the north and south gable ends during crop 2. During measuring, external PAR was also recorded near the tunnel using the same type of sensor attached to a 3 m high mast. The sensors were linked to a central data acquisition centre (CR10, Campbell). Measurements were taken every 10 seconds then integrated to give 10 min intervals.

There were two tillage operations: one pass with a rotary spade to 30 cm depth, then one pass with a rotary hoe to 10 cm depth. Both operations took 5 trips along the tunnel, giving a total of 13 compacted and uncompacted zones (Fig. 6). To characterise the effects of this compaction on the bulk density of the soil we dug a 50-cm deep profile across the full width of the tunnel just after harvesting crops 3 and 4. Soil cores (diameter: 4 cm, height: 3.8 cm) were taken at 5, 15, 25 and 35 cm depth in each of the 13 areas. They were then placed for 48 h in an oven set at $105^\circ C$. We calculated bulk density by the ratio between dry weight and volume of the soil samples. To study the effects of compaction on the spatial arrangement of roots, we used a method of root mapping that consists of locating the impacts of roots on the vertical section of the profile, using a grid with a $2 \times$

Table I. Planting, harvest dates, mineral fertilisation rates and water inputs for the four crops monitored.

Crop	Planting date	Harvest date	Fertilisation (kg/ha)					Water inputs (mm)
			N	P	K	Ca	Mg	
1	17 October	6 December	80	96	312	46	6	87
2	24 January	23 March	100	0	0	0	0	90
3	17 October	14 Dec.	90	96	364	46	33	110
4	11 January	20 March	100	0	0	0	0	94

2 cm square mesh [49, 50]. With this map, one can establish root density profiles calculated by the number of mesh squares colonised by at least one root.

2.2. Statistical analyses

Analysis of variance was performed using the SAS statistical procedure PROC GLM [44].

To analyse the spatial non-uniformity of water distribution we used geostatistical methods. With these methods it is possible to analyse the structure of a random regionalised phenomenon, i.e. where the data are spatially correlated and which have both structured and random aspects [20]. The variogram is the key function which quantifies the interdependence of sampling locations. From a directional variogram one can analyse the structure of the phenomenon in a specific direction (in our case, transversal or longitudinal). Warrick and Myers [58] note that a regular grid will tend to ensure a good efficiency of the variogram estimator if the number of samples is large enough. Our sampling strategy for measuring received water met these requirements very adequately. The variograms were calculated using the GEO-EAS package [17].

2.3. Model overview

We obtained the model of lettuce crop functioning by coupling a soil behaviour model [28] already tested and validated for lettuce crops [29], with a model of crop growth and development [14, 15]. The soil behaviour module is based on Darcy's law and simulates water and nitrate flows, heat transfer and biochemical transformation of nitrogen (net mineralisation, denitrification). The crop behaviour module is based on the transformation of light energy into dry matter, which makes it possible to simulate dry matter accumulation as a function of absorbed photosynthetic active radiation. With this module one can also simulate the changes in leaf number, cover rate and water and N demand in a crop stand.

The input variables of the model were technical cropping operations (N fertilisation, irrigation) and climatic data (air temperature, radiation, evapotranspiration). The output variables were the amount of N leached, and the fresh weight and nitrate content of the lettuce plants at harvest. The models' parameters were set on the basis of specific experiments, then validated by independent data [14].

3. RESULTS

3.1. Characterisation of environmental non-uniformity

3.1.1. Quantities of irrigation water received

The water depth collected in the rain gauges with irrigation set at 4 mm proved to be very variable within the tunnel (Fig. 1 and Tab. II): 20% of the rain gauges received less than 2.7 mm while 20% received over 4.2 mm. Mean measured water depth is less than the quantity set for the system, indicating a water loss of 13%. This loss may be due to evaporation during sprinkling and runoff along the underside of the plastic cover to the drainage channels along the tunnel edges.

The directional variograms (Fig. 2) show that this non-uniformity in water distribution is spatially structured and is greater transversally than longitudinally. The transversal variogram shows a non-stationary and highly structured phenomenon. The longitudinal variogram shows a stationary phenomenon, but with a cyclical pattern characterised by a slight drop in the semi-variance every 3 meters. This distance matches the spacing of the sprinklers along the pipelines.

Table II. Basic statistics on water depth measurements for 4 mm of irrigation delivered.

Number of measurements taken	1666
Average	3.46 mm
Minimum	0.56 mm
Maximum	8.87 mm
Standard deviation	0.98 mm
Coefficient of variation	28%
Christiansen Uniformity Coefficient	78%

Figure 1. Histogram of distribution of water depth received from the sprinkler system, for 4 mm irrigation delivered.

Figure 2. Transversal (a) and longitudinal (b) variograms of water depth received from the sprinkler system.

Mean water depth across the transversal axis of the tunnel proved to be symmetrical about the longitudinal axis (Fig. 3). It was higher under the sprinkler lines and decreased towards the sides of the tunnel. However, there was a peak 75 cm from the edge, due to water trickling along the underside of the plastic sheet dripping off where it met the wires upon which the plastic sheet was stretched. Closer to the edge, the slope of the plastic sheet was too acute to allow drips and the water was evacuated into drainage channels along the tunnel edge. Received water depth was more uniform in the centre of the tunnel than along the edges (the standard deviation was less).

3.1.2. Radiation

Incident radiation measurements showed that the transmission coefficient varied considerably across the width of the tunnel. It was as high as 69% in the centre of the tunnel but only 46% at a distance of 50 cm from the sides (Fig. 4). Further, this transversal radiation gradient proved to be symmetrical about the tunnel's longitudinal axis.

There was very little difference in measured radiation between the northern and southern ends of the tunnel.

3.1.3. Effects of compaction

Analysis of variance showed that the bulk density was significantly higher in the compacted zones, and only in the tilled horizon (Tab. III). Compaction had a major impact on bulk density at the surface, but this effect diminished with depth.

Compaction also affected the root density profile observed at harvest (Fig. 5). In the uncompacted zones,

Figure 3. Mean received water depth ($\pm$ standard deviation) according to distance from side of greenhouse, for 4 mm irrigation delivered by the sprinkler system.

the proportion of grid squares colonised by at least one root varied between 60% and 80% in the top 24 cm of soil. In the compacted zones, root density was slightly lower at the surface but much lower at greater depths, especially with crop 3. Comparing root density in compacted and uncompacted zones for each 2-cm soil layer using a χ^2 test, showed a significantly lower root density in compacted ground at depths between 12 and 26 cm ($p < 0.05$) for the two crops monitored. On the other hand, compaction did not affect maximum root depth, which was between 30 and 34 cm in these crops.

Figure 4. Solar radiation transmission coefficients measured at seven locations across the tunnel: north end (white dots) and south end (black dots).

3.1.4. Environmental zoning

These results show that soil characteristics, incident radiation and received water depth are all very unevenly distributed in the greenhouse. In our experimental conditions, this non-uniformity proved to be structured transversally across the tunnel, and symmetrically in relation to the tunnel's longitudinal axis (Fig. 3, Fig. 4, Fig. 6). To study the consequences of this non-uniformity on lettuce weight and N pollution, we defined seven zones within the tunnel, marked out by borders between compacted and uncompacted areas, and symmetrical about the longitudinal axis (Fig. 6). Each zone was charac-

Table III. Bulk density ($\text{g}\cdot\text{cm}^{-3}$) measured in non-compacted and compacted zones.

Soil depth	Non-compacted zones	Compacted zones	<i>p</i>	
5 cm	1.25	1.43	0.005	§ Ploughed soil layer
15 cm	1.53	1.62	0.008	§
25 cm	1.48	1.55	0.003	§
35 cm	1.58	1.60	0.740	Sub-soil

p: probability linked to test of density equality between zones.

§: significant difference (threshold 5%).

terised by soil condition (compacted or uncompacted), the incident radiation transmission coefficient and the relative water depth received during irrigation (Tab. IV).

3.2. Consequences of environmental non-uniformity on lettuce weight variability

The mean fresh weight of the lettuces at harvest varied from trial to trial (Tab. V); this could be due to differences in incident radiation between the spring and autumn crops. Cumulative incident radiation throughout the cropping period was 356, 647, 420 et 596 MJ/m^2 for trials 1, 2, 3 and 4 respectively. Fresh weight results fell into the same order of classification. Fresh weight varied

Figure 5. Root density profiles obtained at harvest of crops 3 (a) and 4 (b) for compacted zones (black dots) and non-compacted (white dots). Root density is calculated by the proportion of mesh squares colonised by at least one root. HL indicates the soil layer which was both ploughed and hoed (0–10 cm); PL the soil layer which was only ploughed (10–30 cm).

Figure 6. Spatial subdivision of greenhouse.

Table V. Basic statistics on fresh weight of harvested lettuces, for the four crops monitored.

Crop	1	2*	3	4
Number of measurements	453	240	395	437
Average (g)	415	561	416	440
Least squares means (g)	409	522	411	435
Minimum (g)	125	207	80	23
Maximum (g)	597	775	611	668
Standard deviation (g)	70	95	84	126
Coefficient of variation	17%	17%	20%	29%
Proportion of lettuces below 300 g	4.6%	0.8%	7.3%	11.6%

* In zones D, E, F, and G only, because of flooding in zones A, B and C at the start of crop 2.

widely within each trial, with variation coefficients of 17% to 29% depending on the trial. Thus despite a high mean fresh weight, the proportion of unmarketable let-

tuces (fresh weight below 300 g) was quite high for this type of intensive cropping system.

Analysis of variance showed that trial number and zone had a significant effect on the fresh weight of lettuces at harvest ($F_{3,1524} = 98$, $p < 0.0001$ and $F_{6,1524} = 74$, $p < 0.0001$ respectively). However, there was no significant difference between the repetitions ($F_{3,1524} = 1.9$, $p = 0.12$), which suggests that weight varies mainly according to a transversal gradient. The zone effect is reflected in the fact that weight declined sharply from the centre of the tunnel towards the edges. Weight was slightly lower in the compacted areas, especially in zone F (Fig. 7). The general linear model, which includes the zoning effect, explains 40% of the weight variability observed at harvest.

3.3. Consequences of non-uniformity on N pollution

We simulated the two successive lettuce crops 3 and 4, with a one-month interval between the two. We ran a simulation for each zone of the tunnel, taking as our input variables the measurements taken, during the two trials, of temperature, radiation multiplied by the transmission coefficient, and mean relative water depth received as % of irrigation water applied (Tab. IV). An input of N fertiliser was simulated before each planting, based on the quantity actually applied in each trial (Tab. I). The initial state of the environment before the first crop was assumed to be uniform with a residual N amount in the soil from the previous crop of 10 kg/ha.

The non-uniform distribution of the water led to simulated drainage that varied within the tunnel, between 28 l/m² in zone A (the least watered) and 54 l/m² in zone E (the most heavily watered) for crop 3 and between 19 and 37 l/m² for crop 4 (Tab. VI). Over the whole tunnel area, the quantity of water drained was 41 l/m² and

Table IV. Characteristics of the seven zones identified in the greenhouse.

Zone	A	B	C	D	E	F	G
Area of zone as % of greenhouse area	6.25%	8.75%	20%	17.5%	20%	17.5%	10%
Compacting	uncompacted	compacted	uncompacted	compacted	uncompacted	compacted	uncompacted
Mean relative water depth received (as % of irrigation water applied)	54%	87%	77%	92%	107%	91%	87%
Transmission coefficient for incident radiation	46%	54%	61%	63%	67%	69%	69%

Figure 7. Mean fresh weight of lettuces at harvest ($\pm$ confidence interval) for the four crops monitored, according to greenhouse zone.

25 l/m² for irrigation of 110 l/m² and 94 l/m², on crops 3 and 4 respectively. Application efficiency (defined as the useful amount of water divided by the amount applied)

was quite low: 63% and 72% on average, indicating that 37% and 28% of water received drained away, with crops 3 and 4 respectively. No drainage was simulated in the interval between crops as there was no irrigation during this time.

Simulated mineralisation did not vary between zones or between the two crops: around 38 kg N/ha over roughly a two-month period (Tab. VI). During the interval between crops, simulated mineralisation was lower owing to the low temperature at this time of year (between 7 and 13 °C) and because the soils dried out slightly due to the lack of irrigation.

Simulated quantities of denitrified nitrogen were low and were mainly due to the compaction effect (Tab. VI). Denitrification occurs when soil is anaerobic (pore space filled with water to over 80%). In our simulations, this occurred only in the hours following each irrigation. This period of denitrification lasted longer on compacted ground than on uncompacted ground, owing to the lesser porosity of the soil.

Table VI. Simulated water and nitrogen flows in the seven zones of the greenhouse, for two successive crops.

Zone		A	B	C	D	E	F	G	All
Irrigation (l/m ²)	Crop 3	69	109	96	114	133	113	108	110
	Intercrop	0	0	0	0	0	0	0	0
	Crop 4	59	93	82	98	113	97	92	94
Drainage (l/m ²)	Crop 3	28	35	40	36	54	36	44	41
	Intercrop	0	0	0	0	0	0	0	0
	Crop 4	19	22	25	22	37	22	28	26
Mineralisation (kg N/ha)	Crop 3	36	37	37	37	38	37	38	37
	Intercrop	5	5	5	5	5	5	5	5
	Crop 4	35	39	38	39	41	39	40	39
Denitrification (kg N/ha)	Crop 3	2.1	6.8	2.5	6.7	2.7	6.7	2.5	4.4
	Intercrop	0	0	0	0	0	0	0	0
	Crop 4	2.1	14.8	2.6	14.5	2.1	14.3	2.8	7.7
Absorption (kg N/ha)	Crop 3	53	61	70	72	77	78	78	72
	Intercrop	0	0	0	0	0	0	0	0
	Crop 4	64	74	84	86	92	93	93	86
Leaching (kg N/ha)	Crop 3	12	28	24	27	43	26	23	28
	Intercrop	0	0	0	0	0	0	0	0
	Crop 4	16	38	32	34	54	33	36	37
N residue at harvest (kg N/ha)	Crop 3	69	41	41	31	15	26	35	33
	Crop 4	127	58	65	41	13	30	48	46
N content of percolated water (mg/l)	Crop 3	190	354	266	332	353	320	231	304
	Crop 4	373	765	567	684	646	664	569	626

The simulated quantities of N absorbed by the crop were fairly variable within the tunnel: 53 to 78 kg N/ha for crop 3 and 64 to 93 kg N/ha for crop 4 (Tab. VI). This variability is due to the variability of production potential, which depends on incident radiation.

Simulated leaching varied from zone to zone (Tab. VI) according to the amount of water received, and was slightly greater during the second crop (when drainage was less) because of the accumulation of N in the profile. For the tunnel as a whole, simulated leaching was 28 and 37 kg N/ha for crops 3 and 4 respectively. The mean nitrate content of the drained water was very high and varied between zones and between trials: 190 to 354 mg/l for crop 3 and 373 to 765 mg/l for crop 4. The mean value for the tunnel was twice as high for crop 4 because leaching was slightly greater and drainage less.

The mineral N residue in the soil was assumed to be uniform at the time crop 3 was planted. The simulation results show that at the end of this crop, this residue was already very uneven, with values ranging from 15 to 69 kg N/ha (Tab. VI). During crop 4, this non-uniformity increased further, with values ranging from 13 to 127 kg N/ha at harvest. The simulation results also showed that N residue at harvest was low in zone E: 15 and 13 kg N/ha for trials 3 and 4 respectively. Decreasing the input of N fertiliser would doubtless have led to a deficiency in this zone. So the situation is not one of over-fertilisation over the greenhouse as a whole, despite local over-fertilisation in some zones.

4. DISCUSSION

4.1 Characterisation of environmental non-uniformity

That sprinkler irrigation systems distribute the water unevenly is well known [8, 9, 26, 32, 39, 47, 57]. However, this non-uniformity seems to be greater with greenhouse crops than in other cropping systems. The value we obtained for the Christiansen uniformity coefficient ($CuC=78\%$: Tab. II) is low compared to values reported in the literature. Li and Kawano [33] measured $CuCs$ varying between 82 and 90% when sprinklers were arranged in a 18×18 m pattern. Penadille [39] records a value of 92% with a 12×12 m pattern. Warrick [57] considers the variation coefficient of a sprinkler system to be between 10 and 20% (compared to 28% in our trials: Tab. II) and in a study of field lettuce crops, Bruckler et al. [8] found a variation coefficient for the quantities of water received from a sprinkler system to vary between 12 and 19%, depending on the trial.

The poor performance of sprinkler irrigation systems in greenhouses may be due to the sprinkler pattern overlap and interaction with the plastic cover. It has been shown that increasing sprinkler overlap by spacing sprinklers closer together does distribute the water more uniformly [9, 33, 39]. But in greenhouses, overlap is necessarily less good for zones outside the sprinkler lines. While with field crops these bordering areas can be ignored, in a greenhouse they account for half the ground area. Moreover, water that trickles along the covering plastic and drips from it (Fig. 3) further increases the non-uniformity along the tunnel edges. CuC calculated only for the zone between the sprinkler lines is 85%, which is an adequate value, but because of these specific effects it is only 72% for the 2-m band along the tunnel edge.

Our results show a high degree of non-uniformity in incident radiation in a greenhouse oriented N-S. This non-uniformity is mainly structured on a transversal gradient, symmetrical about the longitudinal axis of the tunnel (Fig. 4). Wang and Boulard [56] recently proposed a model for predicting solar radiation distribution in full-scale greenhouse tunnels. It is based on sun movement, greenhouse geometry, transmittance of the cover and weather conditions. The transmission coefficients simulated by this model for a 8 m wide N-S oriented tunnel varied from side to side of the tunnel, between 48% at a distance of 50 cm from the edge and 69% in the centre (Wang and Boulard [56]: Fig. 8b). We obtained the same range of variation in our trials. The symmetry we observed is also simulated by Wang and Boulard's model in the case of a north-south oriented tunnel.

This non-uniformity of incident radiation results in an uneven production potential within the greenhouse, given the relationship between maximum dry matter output and intercepted radiation [3, 21].

Compaction by tractor wheels during soil preparation had a marked impact on the bulk density (Tab. III) and spatial arrangement of roots (Fig. 5). Compaction reduced root density throughout the profile, but this effect was more marked in the soil layer which was only ploughed (10–30 cm). Montagu et al. [34] obtained comparable results with field lettuces. They showed that root growth is restricted by a compact subsoil at 0.17–0.35 m, with root length densities 60–75% lower than in the loosened subsoil. The reduced root length in the subsoil was not compensated for by increased root growth in the topsoil.

Soil compaction did not only affect mean root density, but also its spatial distribution (result not shown here: see de Tourdonnet cited by Jones and Tardieu [25], Fig. 3). This tends to cause considerable spatial variation in the capacity of the lettuces to take in water and

minerals. Where root distribution is irregular, the distance that water and nutrients have to cross to reach the nearest root can be longer by one order of magnitude than that which would be observed where roots have the same mean density but a regular spatial arrangement [50]. This phenomenon is likely to be especially marked with greenhouse lettuces, since the compacted areas account for nearly half the ground area (Tab. IV).

4.2. Consequences of non-uniformity for variability of crop weight

The degree of irregularity in the fresh weight of harvested lettuces seems to vary considerably, along a transversal gradient across the greenhouse. The zoning we carried out, enabling us to take account of part of the structured non-uniformity of the environment, explains 40% of the observed variability. Mean fresh weight, measured for each zone of the greenhouse (Fig. 7), showed that it is the effect of the transversal gradient of incident radiation that predominated here. The lesser fresh weight in uncompacted zones compared to zone G correlates with the decline in measured radiation: 32%, 13% and 1% for fresh weight, 33%, 12% and 3% for radiation in zones A, C and E respectively. These results confirm the hypothesis that production potential in the greenhouse varies as a result of the radiation gradient [56].

Compaction seems to have less effect on the fresh weight of the harvested lettuces than incident radiation; this effect is most visible in zone F, where fresh weight is reduced by 8% (Fig. 7). In fact the main effect of compaction is to reduce the plants' ability to take in water and minerals, because of its effect on the spatial arrangement of roots. But since the supply of water and N was amply sufficient in our trials, the simulation results show that there were no resource intake problems, even in compacted areas. The literature on the effects of compaction when water and nutrients are available in sufficient quantities reports contradictory findings. Montagu et al. [34] conclude that compaction has no effect on the growth of a field lettuce, whereas Stirzaker et al. [48] show that lettuce yield declines by 12% on compacted ground. To explain this result, Stirzaker et al. put forward the hypothesis that this is due to an inhibitory root signal which has been shown under controlled conditions to reduce shoot growth in hard soil even when the plant is well supplied with water and nutrients [25, 38, 51]. Our results are further evidence that compaction does have this direct effect on lettuce growth.

Several studies have shown that yield can be affected by an uneven distribution of irrigation water [18, 36, 43,

53, 54, 57]. However, it seems that in our experimental situation, this non-uniformity did not have any direct effect on lettuce growth. No water stress was simulated, even in zone A, which received least water (results not shown, see [14]).

This structuring of spatial non-uniformity by cropping techniques is specific to greenhouse cropping systems. It is possible to compensate for the negative effects of non-uniformity in water distribution and structural soil condition by managing irrigation and N fertilisation in such a way that even the most disadvantaged lettuces do not suffer water or N stress. On the other hand, spatially irregular radiation cannot be compensated for; whence its major effect on the variability of the weight of the harvested lettuces.

4.3. Consequences of non-uniformity on N pollution

Greenhouse lettuce crops seem to generate considerable nitrate pollution, both in terms of the quantity of nitrogen (33 and 46 kg N/ha over two months) and in the nitrate content of the percolating water (300 mg/l to over 600 mg/l). Further, the simulation predicted quite a high level of mineral nitrogen residue in the soil at the end of the sequence of lettuce crops (46 kg N/ha). This residue is liable to leaching during the drip-irrigated summer crop that usually follows [14], further increasing the risk of N pollution due to lettuce growing in these cropping systems.

And yet, these simulations were not carried out under conditions of over-irrigation or over-fertilisation. The simulation results for zone E show that the N supply was just enough to meet the needs of the lettuces in this zone (Tab. VI). Also, the low water application efficiency values estimated in our trials are not due to poor irrigation management but to the very uneven distribution of the water. To demonstrate this, we used the results of a theoretical study by Clemmens [9] to establish a relationship between application efficiency (Ea), the proportion of the crop area sufficiently irrigated (A) and the variation coefficient of this distribution (Cd), on the hypothesis that the water applied was normally distributed (Fig. 1). From Clemmens' equations 1, 2 and 4, we have:

$$Ea = \frac{1 + rCd(A - 1)}{1 + zCd}$$

where r and z are the parameters deriving from statistical tables for Gaussian distribution (see Clemmens [9]: Tab. I).

With the variation coefficient of 28% obtained in our trials, the application efficiency so calculated is 73%

where A=90% (90% of the crop area sufficiently irrigated), 68% where A=95% and 60% where A=99%. So one can see that the low application efficiencies simulated in our trials can be explained by the need to keep the proportion of insufficiently irrigated crop area below 10%, because of the lettuce's high sensitivity to water stress [18, 37, 43, 52–54]. Reducing the amount of irrigation applied would no doubt have increased the effect of the variability of supply [57].

So the N pollution under plastic was essentially due to environmental non-uniformity, which mainly affected the N demand of the crop and the quantities of water draining out. Of the other items in the nitrogen budget in these simulation conditions, mineralisation seems to vary little and denitrification hardly at all. Also, these simulation results show that N pollution is cumulative: it is greater during the second lettuce crop owing to the mineral N residue accumulated during the first crop. This illustrates the need to consider N pollution on the scale of the entire cropping system [45].

5. CONCLUSION

This study has revealed a high degree of non-uniformity in the greenhouse environment, structured by cropping techniques and liable to affect both the environmental supply of water and nutrients and the crop stand's demand. This non-uniformity results in lower quality in the harvested lettuces (more variable weight) and a greater risk of N pollution. The excessive mean irrigation and fertilisation of lettuce crops observed by many authors is therefore probably due not only to the lack of adequate input management tools but also to the high degree of spatial variability of the environment. If this non-uniformity is ignored in designing the schedule of technical operations, the solutions proposed may not produce the desired results in terms of product quality and environmental protection. But how can a non-uniform area be managed in a uniform way? There are two possible solutions: reducing the non-uniformity by changing the greenhouse architecture, the irrigation system, or taking account of this in designing the technical schedule. In any case, a model of cropping system functioning that incorporates environmental non-uniformities will be an essential tool for understanding that functioning and proposing innovative solutions.

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