High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield

P. Muñoz, A. Antón, A. Paranjpe, J. Ariño, J.I. Montero

Agron. Sustain. Dev. 28 (2008) 489–495
© INRA, EDP Sciences, 2008
DOI: 10.1051/agro:2008024

Available online at:
www.agronomy-journal.org

Agronomy
for Sustainable Development

Research article

High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield

P. Muñoz[1]*, A. Antón[1], A. Paranjpe[1], J. Ariño[2], J.I. Montero[1]

[1] IRTA, Carretera de Cabrils km 2, 08348 Cabrils, Barcelona, Spain
[2] SELMAR, Masía de can Ratés s/n, 08348 Santa Susanna, Barcelona, Spain

(Accepted 29 April 2008)

Abstract – Nitrate pollution due to excessive N fertirrigation in greenhouse tomato production is a persisting environmental concern in the Mediterranean region. Driven by productivity rather than sustainability, growers continue to use very high N concentrations of more than 11 mM in greenhouse tomato production. A greenhouse study was conducted in Barcelona, Spain, over two growing seasons to analyze the effect of N concentrations from 5 mM to 11 mM (control) on tomato yield and physical quality. The relative environmental impact was calculated by using the life cycle assessment method (LCA). Our results show that N concentration in the nutrient solution can be reduced from 11 mM (control) to 7 mM under a daily mean drainage volume of 30%. This finding implies a 70% decrease in nitrate leaching without reducing tomato yield or quality. According to life cycle assessment, a reduction of 36% in N fertilizers leads to a 60% decrease in the potential impact of eutrophication, 50% decrease in the potential impact of climate change, and 45% decrease in the potential impact of photochemical oxidants.

***Lycopersicon esculentum* L. / water-use efficiency / LCA / hydroponics**

1. INTRODUCTION

Nitrogen in nutrient solution discharges, leachates, from protected and open-field horticulture is an important contributor to groundwater pollution and eutrophication. Nutrient supply in soil-based as well as soilless cultivation systems tends to be excessively high in southern European countries, where evaporation and water demands are relatively greater than nutrient demands (Siddiqi et al., 1998; Le Bot et al., 2001; Muñoz et al., 2006). In the case of soilless cultivation, the irrigation strategy consists of providing a quantity of nutrient solution that is 30 to 50% in excess of the crop requirements (Runia et al., 1998; Kläring, 2001; Ehret et al., 2001) in order to avoid salt build-up near the root zone, and the problem of excessive fertirrigation is compounded. In the case of soilless tomato crops in France, for example, Le Bot et al. (2001) have estimated that about 50% of the nutrient solution applied is leached out, the remaining 50% being absorbed partly by plants and partly by the substrate, but ultimately ending up in the environment. In northern European countries, annual nitrogen losses from soilless cultivation are known to approach 1000 kg/ha (Duchein et al., 1995; Van Noordwijk, 1990, as cited in Le Bot et al., 2001). A study of 140 ha of greenhouses in the region of Brest harbor, Brittany, France, indicated that 500 000 m^3 of nutrient solution containing at least 560 tons of fertilizers are leached annually into the sea (Méar and de Brest, 1998, as cited in Le Bot et al., 2001).

In the Netherlands, pioneering "fertirrigation" practices for protected vegetable cultivation were developed to ensure high productivity under low temperatures and sub-optimal light conditions. Since crop water demand under such conditions is significantly reduced as compared with southern Europe, the concentration of fertilizers in the nutrient solution needs to be augmented considerably in order to ensure adequate nutrient supply. On the other hand, in the Mediterranean region, due to higher temperatures and solar radiation, the crop water demands are significantly greater than those in north-western Europe, and logically, the nutritional needs of crops could be met using nutrient solutions with relatively lower fertilizer concentrations. However, Mediterranean growers seem to have adopted the north-European fertirrigation practices without making significant modifications relevant to local climate or plant requirements, and thus, the nutrient concentrations used in practice in the Mediterranean region are practically as high as those used in north-western Europe. Fertirrigation practices in the Mediterranean have changed very little in the past 15 years, and the majority of growers continue to use very high nitrogen concentrations ranging from 14 to 15 mM (Pardossi,

* Corresponding author: pere.munoz@irta.es

2005) for greenhouse production of tomato and other vegetables. Excessive fertirrigation is also used as a strategy to compensate for the variation in transpiration and nutrient demands of individual plants and the variations in efficiency of the nutrient solution supply system (Runia et al., 1998; Ehret et al., 2001). Thompson et al. (2007) have pointed out the importance of management practices, manure and excessive irrigation in the first weeks as main important factors in lixiviation.

Closed or re-circulating hydroponic systems can significantly reduce fertilizer runoff but not eliminate it, and the spent nutrient solution has to be ultimately collected and treated at the end of the crop cycle. Also, closed systems involve greater installation and running costs, need a high degree of automation and technical skill, and their economic viability is a question of debate in southern Europe (De Pascale and Maggio, 2005). As a consequence, the majority of the high-value horticultural production in Mediterranean countries is done using 'open' systems. Therefore, the most practical way to reduce pollution from fertilizer runoff from 'open' systems would be to employ a production strategy based on optimal fertilizer input, especially N fertilizers.

Life cycle assessment (LCA) has become a popular tool, also used in agriculture, which tries to be the most objective and transparent methodology to quantify and assess environmental burdens of products and services (Antón et al., 2005; Audsley, 1997). The ISO standards (ISO-14040, 2006; ISO-14044, 2006) identify guidelines to be followed in a LCA study in order to guarantee this objectivity.

Previous studies using LCA in agriculture have compared different production systems involving open air, organic, integrated and conventional crops (Cowell and Clift, 1997; Cowell, 1998; Mattsson, 1999; Milà, 2003; Wegener Sleeswijk et al., 1996). Several works carried out using LCA have examined the "bottleneck" of greenhouse horticulture (Antón, 2004; Antón et al., 2005; Jolliet, 1993; Nienhuis et al., 1996; Russo and Scarascia-Mugnozza, 2004; Van Woerden, 2001). Among these, Nienhuis et al., 1996 did a study comparing different cropping systems, hydroponic and soil. Nevertheless, none of them have applied LCA to quantifying the environmental impact that different fertirrigation programs could have.

Thus, the aim of this study was to analyze the effect of high, medium and low N doses on greenhouse tomato yield, and to evaluate their respective impacts on the Mediterranean environment.

2. MATERIALS AND METHODS

2.1. Greenhouse experimental set-up and climate data measurement

Experiments were carried out in a passively ventilated multi-span single-layer polyethylene greenhouse, 250 m^2 surface area, located at the IRTA research facility in Cabrils, Barcelona, Spain. Rockwool plug transplants of the tomato cultivar Bond® were planted in white-on-black polyethylene bags; in Agroperl™, filled with perlite of particle size 0–5 mm. Planting was done on 23 February in the 2004 season and on 3 March in the 2005 season at a plant density of 2.2 plants/m^2, achieved by using a 33-cm plant-spacing and 135-cm row-spacing. Each treatment was replicated five times, with 12 plants per replication in 2004 and 18 plants per replication in 2005. Plants were drip-irrigated using an emitter-and-stake assembly with one drip emitter of 4.0 L/h per plant. Climate data inside and outside the greenhouse were recorded every minute using a CR-10 datalogger (Campbell Scientific®). Air temperature and relative humidity were measured using a HMP45C sensor (Vaisala®) and global solar radiation was measured using a CM6 sensor (Kipp & Zonen®).

Table I. Monthly mean outdoor global radiation, temperature and vapor pressure deficit (VPD) during the daytime (0700–1900 h) and in a 24-h period, during the crop period for the years 2004 and 2005.

2004	March	April	May	June	July
Outdoor Global Radiation (MJ/m^2/day)	13.6	19.1	22.9	26.3	25.9
Day Temp. (°C)	17.2	20.5	21.9	26.3	26.4
Day VPD (kPa)	0.7	0.82	0.88	1.04	1.03
24 h Temp. (°C)	14.3	17.1	19.2	23.6	24.1
24 h VPD (kPa)	0.42	0.44	0.51	0.55	0.60
2005					
Outdoor Global radiation (MJ/m^2/day)	15	21.3	24.8	25.7	24.3
Day Temp. (°C)	20.9	24.3	25.1	29.6	30.6
Day VPD (kPa)	1.2	1.03	1.02	1.12	0.7
24 h Temp. (°C)	15.5	18.6	21.4	25.4	26.5
24 h VPD (kPa)	0.62	0.81	0.66	0.81	0.93

Table I summarizes monthly mean outdoor global radiation, temperature and vapor pressure deficit (VPD) during the daytime (0700–1900 h) and in a 24-h period, during the crop period for the years 2004 and 2005. It can be seen that spring of 2005 was warmer than 2004 for the same period, which will affect the production in quantity and quality.

2.2. Nitrogen fertirrigation treatments, drainage collection and analysis

The different N concentrations in the nutrient solution were 7, 9 and 11 mM in 2004. In 2005 the N concentrations tested were also three treatments: 5 mM, 7 mM and a dynamic nutrient solution, starting the first month with 5 mM, with 7 mM during the next two months and ending the crop cycle with 5 mM again, 5-7-5. The maximum N concentration used in this study of 11 mM is slightly lower than the typical range, 14 to 15 mM, identified by Pardossi (2003) for greenhouse vegetable cultivation. However, this study considered 11 mM as 'control' since it represents the typical N concentration used in protected vegetable cultivation in the Maresme region near Barcelona (Muñoz et al., 2005). The concentration of all other micro- and macro-elements (except sulfur) in the nutrient solution was identical for all treatments (Tab. II). Since K^+ concentrations in the drainage during 2004 were high (data not shown), in 2005, the concentration of K^+ in the nutrient solution was reduced from 7 to 5 mM (Tab. II). Table III shows the concentration and total amount of the different inorganic salts used in the preparation of nutrient solutions: Potassium Nitrate, Nitric Acid, Monopotassium Phosphate and Magnesium Sulfate. In order to maintain the same level of potassium in the different treatments Potassium Sulfate was preferred instead of Potassium Chloride due to the significant content of clorures in the water.

Table II. Nutrient concentration, mMol, and electrical conductivity, dS/m, in the fertirrigation solution for different treatments during summer 2004 and 2005.

Treatment	Nutrient concentration (mean mM)								E.C. (dS/m) (mean values)
	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	Cl^-	K^+	Ca^{2+}	Mg^{2+}	Na^+	
(2004)									
7 mM	7	1	4	3	7	4.5	1	2	1.87
9 mM	9	1	3	3	7	4.5	1	2	1.96
11 mM	11	1	2	3	7	4.5	1	2	2.00
(2005)									
5 mM	5	1	4	3	5	4.5	1	2	1.63
7 mM	7	1	3	3	5	4.5	1	2	1.63
5-7-5 mM	5-7-5	1	3	3	5	4.5	1	2	1.64

Table III. Concentration and total amount of the different inorganic salts in the nutrient solutions for different treatments during summer 2004 and 2005.

Fertilizer	Concentration			*Nitrogen fertirrigation* treatments			
	% N	% P_2O_5	% K_2O	11 mM g m^{-2}	9 mM g m^{-2}	7 mM g m^{-2}	5 mM g m^{-2}
Potassium Nitrate	13.5		46.2	270.56	181	77	22
Potassium Sulfate			51.0	0	77	166	115
Nitric Acid	60			281	281	281	188
Monopotassium Phosphate		22.47	34.0	60	60	60	60

Fertirrigation decisions were primarily based on solar radiation and temperature, but the overriding factor was a target drainage volume of approximately 30%. The quantity of nutrient solution supplied to each treatment was monitored daily with water-meters. Also, the drainage from each treatment was collected separately in 100 L tanks, and the volume of drainage was measured with a separate set of water-meters connected to a submersible pump triggered by a ball-cock assembly which emptied the collection tanks every time the drainage volume reached 80 L. Samples of nutrient solution and drainage solution from each treatment were collected daily in 100 mL PE containers and frozen. Every week, samples were pooled and sent for laboratory analysis.

2.3. Fruit yield and size (caliber) measurement

Tomato fruit with light red color were harvested at 3- to 4-day intervals, with a total of 23 harvests from 28 May to 2 August during the 2004 season, and 22 harvests from 17 May to 28 July during the 2005 season. Fruit that were deformed or showed symptoms of blossom-end rot were weighed separately as "non-marketable yield". Marketable fruit yield consisted of tomato fruit that showed no signs of disease or deformation, and were graded according to their diameter. Fruit yield data were subjected to analysis of variance and the Duncan's multiple range test was used to compare treatment means at *P* of 0.05 using SAS version 2002.

2.4. Environmental impact assessment

Life cycle assessment (LCA) was used to assess the environmental impact associated with fertilizer use. The following impact categories typically used in LCA (Audsley, 1997; Guinée et al., 2002) were assessed: CML2000-Air Acidification g eq. SO_2; CML2000-Depletion of abiotic resources g eq. Sb; CML2000-Eutrophication g eq. PO_4 and g eq. of NO_3; IPCC-Greenhouse Effect g eq. CO_2; CML2000-Photochemical oxidant formation g eq. ethylene. Tomato production in kg was selected as the functional unit to compare and standardize input and output (ISO 14040, 1997; Antón et al., 2005). TEAM® 3.0 Software (1999) was used for calculating environmental impact. Mineral fertilizer doses, fertilizer production, water consumption and fertirrigation pump energy consumption were considered in this study. The method presented by Audsley (1997) was followed to calculate the emissions of the applied fertilizers.

Data relating to fertilizer manufacture and transport, and management of water were obtained from the DEAM® 1999 database. The effect of N input reduction on the different impact indices was compared for all treatments and the avoided impact quantified and evaluated. Other phases of crop management are out of scope because they do not change from one fertilizer treatment to another.

3. RESULTS AND DISCUSSION

3.1. Fruit yield and physical quality

In summer of the 2004 season, there were no significant differences in marketable fruit yield per m^2 or the mean fruit weight among the three N treatments (Tab. IV). However, the percentage of fruits over 9 cm diameter from the 7 mM treatment was significantly greater than that from higher nitrogen fertilizer treatments, 9 or 11 mM. These results suggest that the concentration of N could be reduced to 7 mM (~ 64% of the control) under Mediterranean climatic conditions without any adverse effects on fruit yield or quality. These results were also similar to those observed in previous studies (Steiner, 1966; Wilcox et al., 1985; Larouche et al., 1989), wherein threshold concentrations for N were reported to be in the range of 7 to 8 mM.

Table IV. Influence of different N concentrations in the nutrient solution on the marketable and non-marketable fruit yield and quality of tomato cv. Bond grown in perlite bags under a passively ventilated greenhouse during summer 2004 and 2005.

Treatment	Marketable fruit	Fruit quality		
		Marketable fruit	Non-marketable fruit	
	Yield	Mean fruit weight	BER†	Malformed
	(kg/m^2)	(g/fruit)	(% kg/m^2 of total fruit yield)	
(2004)				
11 mM	20.0	157.7	6.2	0.05
9 mM	20.1	155.5	5.8	0.06
7 mM	19.7	154.9	6.5	0.11
	N.S.	N.S.	N.S.	N.S.
(2005)				
7 mM	16.5	189.6a	14.5	1.01
5-7-5 mM	16.2	191.3a	13.7	1.02
5 mM	14.8	169.8b	8.9	1.27
	N.S.	S.	N.S.	N.S.

† Fruit with blossom-end rot.
S.: significant according to Duncan's Multiple Range Test ($P < 0.05$).
N.S.: Not significantly different according to Duncan's Multiple Range Test ($P < 0.05$).

In the 2004 season, although satisfactory yields were obtained at a moderately low N concentration (7 mM), the concentrations of both N and K observed in the drainage solution were still quite high (data not shown), sometimes approaching the input concentration. Therefore, in the 2005 season, the N concentration in the nutrient solution was further reduced to 5 mM, about 45% of the control, and a dynamic treatment starting the first month after planting with 5 mM, 7 mM for the next 30 days and 5 mM to the end of the crop cycle (5-7-5) was included to observe plant response to varying levels of N within the low to intermediate range.

The summer of 2005 was notably hotter and dryer than that of 2004, with significantly greater values for all climatic parameters measured (Tab. I). A mean temperature increase of 3.6 °C during the entire cropping period and a mean vapor pressure increase of 0.5 kPa at the beginning of the crop, as well as a two-week reduction in the net cropping period (one harvest less than 2004) could explain the significant increase in blossom-end rot and a corresponding decrease in marketable fruit yield in 2005 (Tab. IV). Interestingly, the mean marketable fruit weight in the 2005 season was significantly greater than in 2004, indicating that fruit quality improved at the cost of yield, wherein the 7 mM treatment produced 16.5 kg/m^2 in 2005, a reduction of 16.2% as compared with the 19.7 kg/m^2 produced in 2004 (Tab. IV). Marketable fruit yield from the treatments 7 mM and 5-7-5 mM was not significantly different; however, the 5 mM treatment showed a significant decrease in the marketable fruit yield as well as mean fruit weight (Tab. IV).

3.2. Threshold N concentrations, N fertilizer use and water -use efficiency

The results explained in the previous section suggest that a N concentration of 5 mM was insufficient for obtaining the same level of production as the rest of the treatments under the experimental and climatic conditions of the 2005 season. Furthermore, considering that such climatic conditions as experienced in summer 2005 are a fairly common occurrence in the Mediterranean region, a 5 mM concentration may not be recommendable. Thus, a N concentration of 7 mM or a combination of 5-7-5 mM could be used without adverse effects on fruit yield or quality, and would represent a N fertilizer input reduction of 45% and 54%, respectively, as compared with the control (11 mM) (Tab. V).

During this study, fertirrigation decisions were made based on a 30% mean target drainage volume. The summer of 2005 was more severe than 2004 (Tab. I) and plant growth was adversely affected, wherein the leaf area in 2005 was considerably smaller than in 2004 (Tab. V). This was reflected in the relatively smaller quantity of water supplied in 2005 as compared with 2004. In the 2004 season, water-use efficiency in terms of conversion of water supplied into marketable fruit yield (WUE^f) for the treatments 11 mM and 9 mM was similar and greater than for the 7 mM treatment, whose fruit yield as well as leaf area were slightly lower than, but not significantly different to, the 11 mM and 9 mM treatments (Tab. V). In the 2005 season, WUE^f for the 7 mM and 575 mM treatments was similar to and greater than that for the 5 mM treatment, whose fruit yield as well as leaf area were slightly lower than (but not significantly different to) the 7 mM and 5-7-5 mM treatments (Tab. V). During both seasons, similar results were obtained for water-use efficiency in terms of conversion of water supplied into fresh biomass, and the sum of fresh weight of stem, leaves and fruit (WUE^p).

The results of this study need to be viewed in the context of efficient irrigation management, an aspect which is often difficult to implement in practice. In other words, a 45 to 54% reduction in N fertilizer input (Tab. V) could be achieved without compromising fruit yield or physical quality if the mean daily drainage volume does not exceed or fall short of 30%. Having said that, it must be mentioned that if mean drainage volume exceeds 30% the fruit yield and physical quality may still be similar to that obtained with 30% drainage; however, the environmental impact burden would be considerably greater.

3.3. Environmental impact analysis

Nutrient solution runoff from greenhouse crops generally contains a high concentration of nitrogen, which is one of the important causal factors of environmental pollution. This study has shown that N fertilizer input for a greenhouse tomato crop can be reduced by 45 to 54% as compared with the standard N fertilizer input used at present in the Mediterranean region without reductions in fruit yield or physical quality, provided water management is done efficiently by maintaining a mean drainage volume not exceeding 30%. A reduction in N

Table V. Water supplied to crop, water-use efficiency, leaf area index and N input per hectare with respect to different N concentrations in the nutrient solution for tomato cv. Bond grown in perlite bags under a passively ventilated greenhouse during summer 2004 and 2005.

Treatment	Water supplied to crop	**Water-use efficiency**		Leaf Area Index	N input
	(L/m^2/season)	(L/kg of marketable fruit) (WUE^f)	(L/kg of fresh biomass§) (WUE^p)		(kg/ha)
(2004)					
11 mM	604.9	30.2	24.0	3.91	788 control
9 mM	700.8	34.9	27.7	4.56	645 (18%)
7 mM	618.4	31.4	24.9	4.27	501 (36%)
				N.S	
(2005)					
7 mM	534.5	32.4	27.2	2.51	431 (45%)
5-7-5 mM	535.3	33.0	28.3	1.92	359 (54%)
5 mM	535.3	36.2	31.5	1.75	308 (60%)
				N.S	

Plant density = 2.2 plants/m^2.
§Fresh biomass = sum of fresh weight of stem, leaves and fruit (marketable and non-marketable).
WUE^f: water-use efficiency in terms of conversion of water supplied to marketable fruit yield.
WUE^p: water-use efficiency in terms of conversion of water supplied to fresh plant biomass.
Numbers in parentheses represent percent reduction in N fertilizer input as compared with control.
N.S.: Not significantly different according to Duncan's Multiple Range Test ($P < 0.05$).

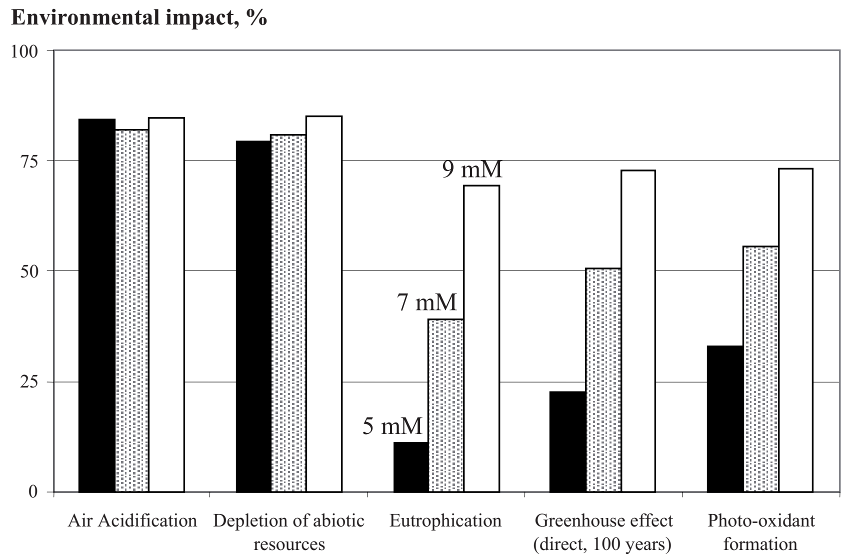

Figure 1. Ratios of the different fertilizer treatments, 5 mM, 7 mM and 9 mM for five different environmental categories, air acidification, depletion of abiotic results, eutrophication, greenhouse effect and photo-oxidant formation. Ratios are expressed as percentages with respect to the 11 mM treatment.

fertilizer input can significantly reduce environmental impact from a Mediterranean greenhouse tomato crop with respect to parameters such as air acidification, depletion of abiotic resources, eutrophication, greenhouse effect and photo-chemical oxidant formation. In Figure 1, values for each one of these environmental categories as influenced by different levels of N fertilization, are expressed as a percentage of the control (N11) treatment.

The two types of compounds mainly involved in air acidification are sulfur and nitrogen compounds. The diminution of nitrogen fertilizers used in crop production decreases the emissions of ammonia and nitrogen oxides to air. Correspondingly, there is a decrease in air acidification impact when N concentration in the nutrient solution is reduced from 11 mM to 9 mM (Fig. 1). However, in the case of the 7 mM and 5 mM treatments, the reduction in air acidification impact was not proportional, since the only way to reduce N level in the nutrient solution while maintaining the same potassium level as that of 11 mM and 9 mM treatments was to use a greater quantity of K_2SO_4, resulting in greater SO_2emissions (and greater air acidification values) from the 5 mM and 7 mM treatments (Fig. 1).

Resource depletion can be defined as the decreasing availability of natural resources. Only abiotic resources such as fossil and mineral resources were considered for this analysis. The main resource depleted was natural gas, which is used

Table VI. Quantity of nitrogen leached (kg ha^{-1}) and avoided nitrate leaching for the different nitrogen concentration treatments.

	Concentration of N in nutrient solution			
	5 mM	7 mM	9 mM	11 mM
Qty. of nitrates leaching out (kg N ha.)	29.31	86.72	202.39	290.28
Avoided nitrate leaching with respect to N11 (%)	89.9	70.1	30.2	0.0

mainly in the production of KNO_3 or K_2SO_4, giving similar results to those of the air acidification category (Fig. 1).

According to Andersen et al. (2006) eutrophication is defined as "the enrichment of water by nutrients, especially nitrogen and/or phosphorus and organic matter, causing an increased growth of algae and higher forms of plant life to produce an unacceptable deviation in structure, function and stability of organisms present in the water and to the quality of water concerned, compared to reference conditions". Fertilizer runoff from agricultural activities is a major causal factor of eutrophication, and coastal Mediterranean ecosystems in the vicinity of intensive agriculture zones are especially vulnerable. In Spain, the maximum permissible limit for nitrates in potable water is established at 50 mg/L (0.81 mM) (Royal Decree 140/2003) in congruence with the Food and Agricultural Organization and and the World Health Organization recommendations. The maximum permissible limit for nitrates in subterranean water is also set at 0.81 mM (Royal Decree 261/1996 and the Council Directive 91/676/EEC), and the regions, including el Maresme, Barcelona, where groundwater nitrate concentrations may be greater than the above stated maximum permissible limit are declared as "vulnerable zones". In the present study, nitrate concentrations, seasonal mean values, in the leachate ranged from 1.6 mM for the N5 treatment to as high as 13.4 mM for the 11 mM treatment. The LCA conducted in this study was done with the assumption that the leachates were not re-used for fertilizing the same crop or a cascade (Incrocci et al., 2003; Muñoz et al., 2005) crop. The LCA analysis indicated that the treatment with the highest N content produced the highest environmental damage (resulting from eutrophication) and vice versa (Fig. 1). The corresponding values for avoided nitrate leaching for the different N treatments are presented in Table VI, wherein the 7 mM treatment, which produced similar fruit yield to the 11 mM treatment, led to a 70% reduction in nitrate leaching as compared with the 11 mM treatment.

Greenhouse gases, CO_2 and nitrous oxide, which are released mainly during the production of KNO_3, are the main factors contributing to the greenhouse effect. Since KNO_3 is one of the major sources of nitrogen used in fertirrigation, the increase in N concentration of the nutrient solution translates into a significant impact for the "greenhouse effect" category (Fig. 1).

Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level, where they react with sunlight to produce photochemical smog. One of the components of smog is ozone, which is not emitted directly, but rather produced through the interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). The emission of methane during the production of nitrogen fertilizers (HNO_3 and KNO_3) can significantly increase photo-oxidant formation. Thus, a reduction in the use of these fertilizers can considerably reduce photo-oxidant formation (Fig. 1).

4. CONCLUSION

Our results show that for soilless tomato cultivation under Mediterranean climatic conditions, the concentration of N in the nutrient solution can be reduced to 7 mM without reducing fruit yield or physical quality. Nitrogen concentration of 7 mM in the nutrient solution can reduce the quantity of nitrates leached out by 70% as compared with the control (11 mM). More N input was reduced, the environmental impact decreased, and the environmental burden avoided was especially pronounced for the eutrophication, greenhouse effect and photo-chemical oxidant formation categories than for the air acidification or abiotic resource depletion categories. Although this study demonstrated that N input can be substantially reduced without adversely affecting yield, its environmental sustainability could be improved further. Considering the economic constraints to conversion to "closed" systems, future research could focus on other alternatives such as 'cascade' cropping for improving the overall environmental sustainability of protected horticulture in the Mediterranean region.

Acknowledgements: This work was supported by MCYT (Ref.: 95-0848.OP) and INIA (Ref.: RTA2005-00142-C02-02.).

REFERENCES

Antón A. (2004) Utilización del Análisis del Ciclo de Vida en la Evaluación del Impacto ambiental del cultivo bajo invernadero Mediterráneo, Tesis doctoral Thesis, Universitat Politècnica de Catalunya, Barcelona.

Anton A., Montero J.I., Muñoz P., Castells F. (2005) Identification of the main factors affecting the environmental impact of passive greenhouses, Acta Hort. 691, 489–494.

Andersen J.H., Schluter L., Gunni A. (2006) Coastal eutrophication: recent developments in definitions and implications for monitoring strategies, J. Plankton Res. 28, 621–628.

Audsley E. (1997) Harmonisation of environmental life cycle assessment, in: Final Report Concerted Action AIR3-CT94-2028, European Commission DG VI Agriculture.

Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC).

Cowell S.J. (1998) Environmental Life Cycle Assessment of Agricultural Systems: Integration Into Decision-Making, Ph.D. Thesis, University of Surrey, Guildford.

Cowell S.J., Clift R. (1997) Impact assessment for LCAs [Life Cycle Assessments] involving agricultural production, Int. J. Life Cycle Assessment 2, 99–103.

De Pascale S., Maggio A. (2005) Sustainable protected cultivation at a Mediterranean climate: perspectives and challenges, Acta Hort. 691, 29–42.

DEAM® (1999) Data for Environmental Analysis and Management, Écobilan, France.

Duchein M.C., Baille M., Baile A. (1995) Water use efficiency and nutrient consumption of a greenhouse rose crop grown in rockwool, Acta Hort. 408, 129–135.

Ehret D.L., Alsanius B., Wohanka W., Menzies J.G., Utkhede R. (2001) Disinfection of recirculating nutrient solutions in greenhouse horticulture, Agronomie 21, 323–339.

Guinée J.B., Gorrée M., Heijungs R., Huppes G.R.K., de Koning A., Wegener Sleeswijk A., Suh S., Udo de Haes H., Bruijn H., Duin R.V., Huijbregts M.A.J. (2002) Handbook on life cycle assessment, Operational guide to the ISO standards. Dordrecht, Kluwer, The Netherlands.

Incrocci L., Pardossi A., Malorgio F., Maggini R., Campiotti C.A. (2003) Cascade cropping system for greenhouse soilless culture, Acta Hort. 609, 297–300.

ISO-14040 (1997) Environmental management – Life cycle assessment – Principles and framework, International Organisation for Standardisation ISO, International standard, 14040, Geneva.

ISO-14044 (2006) Environmental management – Life cycle assessment – Requirements and guidelines. 14044, International Organisation for Standardisation ISO, Geneva.

Jolliet O. (1993) Bilan écologique de la production de tomates en serre, Rev. S. Vitic. Arboric. Hortic. 25, 261–267.

Kläring H.P. (2001) Strategies to control water and nutrient supplies to greenhouse crops. A review, Agronomie 21, 311–321.

Le Bot J., Jeannequin B., Fabre R. (2001) Impacts of N-deprivation on the yield and nitrogen budget of rockwool grown tomatoes, Agronomie 21, 341–350.

Larouche R., Vezina L., Gosselin A. (1989) Nitrogen concentration and photosynthetic photon flux in greenhouse tomato production. I. Growth and development, J. Am. Soc. Hort. Sci. 114, 458–461.

Mattsson B. (1999) Life cycle assessment (LCA) of carrot puree: case studies of organic and integrated production.

Méar C., De Brest R. (1998) Les serristes visent le zéro pollution, Culture Légumière 47, 9.

Milà L. (2003) Contributions to Life Cycle Analysis for Agricultural Systems. Site-dependency and soil degradation impact assessment, Thesis doctoral, Universitat Autònoma, Bellaterra.

Muñoz P., Ariño J., Montero J.I., Antón A. (2005) Cascade crops: a method proposed for increasing sustainability in el Maresme, in: Agriculture and Energy: Case studies in the agro-industrial sector, Vol. I, pp. 468–472.

Muñoz P., Antón A., Montero J.I. (2006) Fertilización nitrogenada en un cultivo hidropónico de tomate, Hort. Int. 24, 8–13.

Nienhuis J.K., Vreede P.J.A.D., De Vreede P.J.A., Brumfield R.G. (1996) Utility of the environmental life cycle assessment method in horticulture, Proceedings of the XIIIth International Symposium on Horticultural Economics, Rutgers, New Brunswick, New Jersey, USA, pp. 531–538.

Pardossi A. (2005) The management of plant mineral nutrition in soilless culture, in: Fernández M., Minguéz P.L., Gómez I.M. (Eds.), Improvement of water use efficiency in protected crops, p. 122.

Royal Decree 261/1996, Ministerio de la Presidencia. 1996. BOE num. 11.

Royal Decree 140/2003, Ministerio de la Presidencia. 2003. BOE num. 45.

Runia W.T., Van Os E.A., Bollen G.J. (1998) Disinfection of drainwater from soilless cultures by heat treatment, Neth. J. Agr. Sci. 36, 231–238.

Russo G., Scarascia-Mugnozza G. (2004) LCA methodology applied to various typology of greenhouses, in: Bot G., Marcelis L. (Eds.), Sustainable greenhouse systems, Wageningen University and Research Centre, Leuven, Belgium.

Siddiqi M.Y., Kronzucker H.J., Britto D.T., Glass A.D.M. (1998) Growth of a tomato crop at reduced nutrient concentrations as a strategy to limit eutrophication, J. Plant Nutr. 21, 1879–1998.

Steiner A.A. (1966) The influence of chemical composition of a nutrient solution of the production of tomato plants, Plant Soil 24, 454–466.

TEAM® (1999) Tools for environmental analysis and management, Écobilan, France.

Thompson R.B., Martínez-Gaitan C., Gallardo M., Giménez C., Fernández M.D. (2007), Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey, Agr. Water Manage. 89, 261–274.

Van Noordwijk M. (1990) Synchronisation of supply and demand is necessary to increase efficiency of nutrient use in soilless horticulture, in: Van Beusichem M.L. (Ed.), Plant nutrition – physiology and applications, pp. 525–531.

Van Woerden S. (2001) The application of Life Cycle Analysis in glasshouse horticulture, International Conference LCA in Foods, Gothenburg, pp. 136–140.

Wegener Sleeswijk A. et al. (1996) Application of LCA to Agricultural Products, CML report 130, Centre of Environmental Science Leiden University (CML), Centre of Agriculture and Environment (CLM), Agricultural-Economic Institute (LEI-DLO), Leiden.

Wilcox G.E., Magalhes J.R., Silva F.L.I.M. (1985) Ammonium and nitrate concentrations as factors in tomato growth and nutrient uptake, J. Plant Nutr. 8, 989–998.