

Nitrogen uptake dynamics, yield and quality as influenced by nitrogen fertilization in 'Piel de sapo' melon

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Abstract

The need to reduce nitrogen (N) fertilizer pollution strengthens the importance of improving the utilization efficiency of applied N to crops. This requires knowledge of crop N uptake characteristics and how fertilization management affects it. A three-year field experiment was conducted from May to September in central Spain to investigate the influence of different N rates, which ranged from 11 to 393 kg ha⁻¹, applied through drip irrigation, on the dynamics of N uptake, nitrogen use efficiency (NUE), fruit yield and quality of a 'Piel de sapo' melon crop (*Cucumis melo* L. cv. Sancho). Both N concentration and N content increased in different plant parts with the N rate. Leaves had the highest N concentration, which declined by 40-50% from 34-41 days after transplanting (DAT), while the highest N uptake rate was observed from 30-35 to 70-80 DAT, coinciding with fruit development. In each year, NUE declined with increasing N rate. With N fertilizer applications close to the optimum N rate of 90-100 kg ha⁻¹, the fruits removed approximately 60 kg N ha⁻¹, and the amount of N in the crop residue was about 80 kg N ha⁻¹; this serves to replenish the organic nutrient pool in the soil and may be used by subsequent crops following mineralization.

Additional key words: *Cucumis melo*; fertilization; N distribution; N use efficiency; N removal; N in crop residues.

Resumen

Influencia de la fertilización nitrogenada en la dinámica de absorción de nitrógeno, producción y calidad del melón 'Piel de sapo'

La necesidad de reducir la contaminación procedente de la aplicación de fertilizantes nitrogenados refuerza la importancia de mejorar la eficiencia de utilización del nitrógeno aplicado a los cultivos. Durante tres años se realizaron ensayos de campo al aire libre en los meses de mayo a septiembre en la zona centro de España para investigar la influencia de distintas dosis de N, en la dinámica de absorción de N, eficiencia del uso del N (NUE), producción y calidad de un cultivo de melón (*Cucumis melo* L. cv. Sancho) 'Piel de sapo'. Las dosis de N variaron desde 11 a 393 kg ha⁻¹ y se aplicaron a través del riego por goteo. Tanto la concentración como el contenido de N aumentaron en las distintas partes de la planta a medida que la dosis de N aumentó. La hoja fue el órgano con la mayor concentración de N, decreciendo un 40-50% a partir de los 34-41 días después del trasplante (DAT). La tasa de absorción de N más alta se observó desde los 30-35 hasta los 70-80 DAT, coincidiendo con el desarrollo del fruto. En cada año, el NUE descendió con el incremento de la dosis de N. Con aplicaciones de N cercanas a la dosis óptima de 90-100 kg ha⁻¹, los frutos extrajeron aproximadamente 60 kg N ha⁻¹, y la cantidad de N en el residuo del cultivo estuvo alrededor de 80 kg N ha⁻¹. Este residuo sirve para rellenar la reserva de nutrientes orgánicos del suelo y puede ser usado por los cultivos posteriores después de su mineralización.

Palabras clave adicionales: *Cucumis melo*; distribución de N; eficiencia del uso del N; fertilización; N exportado; N en residuo del cultivo.

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Abbreviations used: DAT (days after transplanting); ETc (crop evapotranspiration); ET_o (reference evapotranspiration); Kc (crop coefficient); FY (fruit yield); Nap (nitrogen applied); Nc (nitrogen content); NUE (nitrogen use efficiency); TSS (total soluble solids content).

Introduction

Melon is an important horticultural crop that is grown throughout the world, mainly in Asia, America, and Europe, with an overall production of 27.7 million tonnes and about 1.3 million hectares planted (FAO-STAT, 2011). The 'Piel de sapo' melon is cultivated mainly in Spain, with about 40,000 ha and production close to 1.2 million tonnes (MARM, 2011). Its importance is growing in South American countries such as Brazil, which is one of the ten largest melon producers in the world (Silva *et al.*, 2005).

Nitrogen is often considered the most important limiting factor, after water, for crop yields. Formation of each yield component depends strongly on the N supplied at each developmental stage throughout the life cycle of the plant (Zhang *et al.*, 2007). In melon, as in other cucurbit crops (Tanemura *et al.*, 2008), the indeterminate growth habit makes it necessary to apply N during the harvest period. For this reason, it is important to know not only the total N requirement but also the dynamics of N uptake, according to the plant phenology, in order to achieve the maximum N use efficiency.

The introduction of nutrient management legislation in central and southern Spain, the area where melon crops are grown, and increased fertilizer costs are forcing growers to reduce N application. They usually apply greater amounts of N than the crop requires, in the belief that the potential yield is guaranteed in different climatic conditions. Also, the amount of N that is returned to the soil in the residues of the previous crop is usually not taken into account (Lemaire *et al.*, 2008). Excess N can have a negative impact from the economic point of view, because excessive N can reduce fruit yield and quality and increase input costs (Pérez-Zamora *et al.*, 2004; Wang *et al.*, 2007; Cabello *et al.*, 2009), and the environmental point of view, because N is very mobile in the soil and can cause groundwater contamination (Gastal & Lemaire, 2002). To minimize the loss of N by leaching, the fertilizer application should be optimized, with regard to both timing and rate, in accordance with the N uptake by the crop.

Optimal N rates of field grown cucurbits vary depending on cucurbit species, location, climate, soil characteristics, and crop management (Van Eerd & O'Reilly, 2009). In melon the fertilizer N rates depend on its different types. Crops differ substantially in the amount of N in the crop residue and N available for

use by subsequent crops. Availability of N from a previous crop depends on the amount of crop residue, its N concentration and mineral N that remains in the soil after the crop. Of the N taken up by the crop, that accumulated in the harvested fruit is removed from the field while the rest is returned to the soil in the vegetative part of the plant and in the unmarketable fruits which have not been harvested. Nitrogen budget research has been reported for different cucurbits, such as zucchini squash (Zotarelli *et al.*, 2008) and cucumber (Van Eerd & O'Reilly, 2009), but a review of the literature has not shown studies about crop N balance in field grown melon.

The objectives of this study were: 1) to determine the effects of N supply on the dynamics of N uptake by a 'Piel de sapo' melon crop; 2) to evaluate the effect of N supply on melon yield and quality; 3) to quantify the N exported with the harvested fruit and the N content in the crop residue that may be used by the following crops.

Material and methods

Experimental design

Field trials were conducted in different and adjacent plots at *La Entresierra* field station, Ciudad Real, in central Spain (3° 56' W; 39° 0' N; 640 m of altitude) during the May- September seasons of 2005, 2006, and 2007. The soil of the experimental site is a shallow sandy-loam, classified as Petrocalcic Palexeralfs (Soil Survey Staff, 2010), with very low variability in the first 60 cm of depth from which a fragmented petrocalcic layer is localized. Soil characteristics of trial plots are showed in Table 1. The mineral N content was 88, 67 and 34 kg ha⁻¹ in 2005, 2006 and 2007, respectively. The area is characterized by a Mediterranean climate, with a strong continental character and contrasting daily temperatures. In the three years previous to the experiment, the plots received no organic or fertilizer amendments and were used to grow non-irrigated wheat (*Triticum aestivum* L.).

The 'Piel de sapo' type of melon (*Cucumis melo* L. cv. Sancho) was used. In every year of experimentation, the melon seeds were germinated in April under greenhouse conditions, in individual wells of trays containing a mixture of 75% peat, 15% perlite and 10% vermiculite. The seedlings were transplanted to soil covered with transparent plastic mulch on 26 May

Table 1. Physicochemical properties of the soil (0-35 cm) and the irrigation water used in 2005, 2006 and 2007

| Property | 2005 | 2006 | 2007 |
|---|---------|---------|---------|
| Soil | | | |
| pH | 7.9 | 7.9 | 7.9 |
| Electrical conductivity (mS cm ⁻¹) | 0.2 | 0.2 | 0.2 |
| Organic matter (g kg ⁻¹) | 22.6 | 22.1 | 22.2 |
| Available P (mg kg ⁻¹) | 19.4 | 16.4 | 17.9 |
| Available K (mg kg ⁻¹) | 398.9 | 347.0 | 342.5 |
| Available Ca (mg kg ⁻¹) | 2,302.1 | 1,811.8 | 2,016.9 |
| Available Mg (mg kg ⁻¹) | 815.1 | 728.9 | 759.0 |
| N (Kjeldahl) (g kg ⁻¹) | 1.2 | 1.0 | 1.1 |
| Irrigation water | | | |
| pH | 7.9 | 7.9 | 8.2 |
| Electrical conductivity (mS cm ⁻¹) | 2.0 | 2.5 | 0.3 |
| NO ₃ ⁻ (mg L ⁻¹) | 5.6 | 80.6 | 10.9 |
| NH ₄ ⁺ (mg L ⁻¹) | 0.1 | 0.1 | 0.1 |
| SO ₄ ⁻² (mg L ⁻¹) | 790.7 | 1,376.5 | 56.1 |
| K ⁺ (mg L ⁻¹) | 1.4 | 3.6 | 2.5 |
| Mg ²⁺ (mg L ⁻¹) | 16.5 | 176.0 | 10.9 |
| Na ⁺ (mg L ⁻¹) | 163.3 | 138.0 | 17.5 |
| Ca ²⁺ (mg L ⁻¹) | 193.1 | 323.3 | 34.8 |
| Cl ⁻ (mg L ⁻¹) | 240.1 | 185.8 | 44.5 |

2005, 24 May 2006, and 28 May 2007 with a density of 4,444 plants ha⁻¹ (1.5 m × 1.5 m). The experimental design was a randomized complete block, with four N treatments in 2005 and 2007 and three in 2006. The treatments were replicated four times in plots measuring 10.5 m × 12 m. The plots had seven rows of eight plants each. Each row was irrigated by a drip line and emitters of 2 L h⁻¹, 0.5 m apart: the water was applied as required (100% of crop evapotranspiration [ETc = reference evapotranspiration (ETo) × crop coefficient (Kc)]; Doorenbos & Pruitt, 1977). The ETo was estimated by the Penman-Monteith method (Allen *et al.*, 1998) using daily data from a meteorological station sited 200 m from the experimental field. The Kc used during the crop season was obtained in previous years in the same conditions, with daily measurements of ETc from a lysimeter together with ETo. The treatments consisted of different N doses: 30 (N₃₀), 85 (N₈₅), 112 (N₁₁₂), and 139 kg ha⁻¹ (N₁₃₉) in 2005. In 2006, water without nitrates was not available and the minimum N rate was 93 kg ha⁻¹, which was the N amount in the irrigation water. Moreover, the negative effect of excessive N was not clearly observed in the previous year and therefore, it was decided to apply 93 (N₉₃), 243 (N₂₄₃), and 393 (N₃₉₃) kg ha⁻¹. In 2007, the N doses were 11 (N₁₁), 61 (N₆₁), 95 (N₉₅), and 148 (N₁₄₈) kg ha⁻¹. The N fertilizer was applied daily by fertigation, as ammonium

nitrate (34.5% N): from 19 to 84 days after transplanting (DAT) in 2005, from 16 to 86 DAT in 2006, and from 25 to 86 DAT in 2007. In the three years, the total amount of N applied in each treatment was the sum of the N fertilizer and the amount of N in the irrigation water. All the treatments received 120 kg of phosphorus fertilizer (phosphoric acid) for the season, added to the irrigation water and injected daily, from three weeks after transplanting until the last week of August. The irrigation water quality was measured weekly (Table 1). It was not possible to use the same source of the water in the three years. Therefore, the chemical composition of the irrigation water was affected by the composition of the soils where it was obtained: surface water in 2005 and 2007 and groundwater in 2006.

Plant nitrogen uptake

Four plants per treatment were harvested in the middle of each plot at 15, 34, 53, 70, and 91 DAT in 2005, at 20, 41, 62, and 83 DAT in 2006, and at 22, 36, 50, 64, 78, and 92 DAT in 2007. Leaves, stems, and fruits were separated and weighed to obtain the fresh weight. The dry weights of the different aboveground plant organs were determined following oven drying at 80 °C to constant weight. The dry weight of the melon plant

was the sum of the different plant parts. A sub-sample of the oven-dried material was ground to a fine powder to determine the N content, using the Kjeldahl method (AOAC, 1990). The N accumulation in every organ was obtained as the product of N concentration and dry biomass. The total N uptake of the melon plant was determined as the sum of the N uptakes of every above-ground organ of the plant.

Nitrogen content in the fruit yield

Weekly, from 68 to 110 DAT in 2005, from 63 to 106 DAT in 2006, and from 66 to 108 DAT in 2007, fruit samples were taken from each plot and the dry weight and N content were determined in order to calculate the N in harvested fruits.

Fruit yield and quality

The harvests started at 68, 64, and 66 DAT in 2005, 2006, and 2007, respectively, with a total of seven harvests in every year. At each harvest, each melon was weighed to determine the mean fruit weight. Fruit number per square meter and total fruit yield (FY) per hectare were obtained. The N use efficiency (NUE) was determined by dividing FY by total above ground N uptake. For each harvest, four representative ripe fruits from each plot were taken to determine flesh firmness, flesh ratio, skin ratio, and total soluble solids content (TSS). The flesh firmness was measured at four zones of the cut equatorial surface, using a Penefel penetrometer (Agro-Technologie, Tarascon, France) with a 0.5-cm² punch to measure the force necessary to penetrate into the flesh. The flesh and skin ratios were calculated using the formulae: $2 \times \text{flesh thickness} \times \text{equatorial diameter}^{-1}$ and $2 \times \text{skin thickness} \times \text{equatorial diameter}^{-1}$, respectively. The TSS was determined with a hand-held Atago refractometer (Mod. PR-101 α) and expressed as °Brix.

Statistical analysis

The data for each year were analyzed separately using ANOVA: when this showed significant differences among treatments, Tukey's test was applied. Significance levels were defined at $p < 0.05$ and $p < 0.01$. Linear regressions were performed using the statistical analysis software SPSS 12.0.

Results

Nitrogen concentration in the aerial plant parts

The amount of N applied had a positive effect ($p < 0.05$) on leaf, stem, and fruit N concentrations (Fig. 1). Higher rates of N resulted in the highest values from an early stage of the vegetative cycle. The leaves were the organs with the highest N concentration. From 34, 41, and 36 DAT in 2005, 2006, and 2007, respectively, the leaf concentration decreased between 40 and 50%, depending on the treatment and year (Fig. 1a, d, g).

Stem N concentration showed a slight increase at the beginning of crop development in 2005 (Fig. 1b), reaching its maximum value at 34 DAT. In the next two years, the highest values were in the first sampling, at 20-22 DAT. Later, in all three years, stem N concentration decreased by 37 or 57%, depending on the treatment, until about 56 DAT, and then exhibited little change until the end of the cycle in 2006 and 2007 (Fig. 1e, h). In contrast, in 2005, stem N concentration increased slightly, especially in the treatments involving greater N addition.

Fruit N concentration increased slightly during the crop development in the first year (Fig. 1c). However, in 2006, the values decreased gradually until the end of the cycle and, in 2007, they declined until 60 DAT and later remained more or less constant (Fig. 1f, i).

Nitrogen uptake

Applied N significantly affected ($p < 0.05$) N content of the different plants parts and of the whole plant in 2005 and 2007 (Fig. 2a, b, c, d, i, j, k, l). This effect was evident from about 50 DAT, when the majority of fruits had already set and the first set fruits were in the second half of the development period. In 2006, no significant differences were observed; although in leaves, stems, and the whole plant, the N accumulation showed a tendency to increase with the amount of N applied (Fig. 2e, f, g, h). In the leaves, the N content increased continuously in most treatments in 2006 and 2007. In 2005, the N accumulation increased until 53 DAT (treatments N₃₀ and N₈₅) and 70 DAT (treatments N₁₁₂ and N₁₃₉) and later became constant or decreased. The leaf N content in the N₉₃ treatment was similar to the highest values in the N₁₃₉ and N₁₄₈ treatments (close

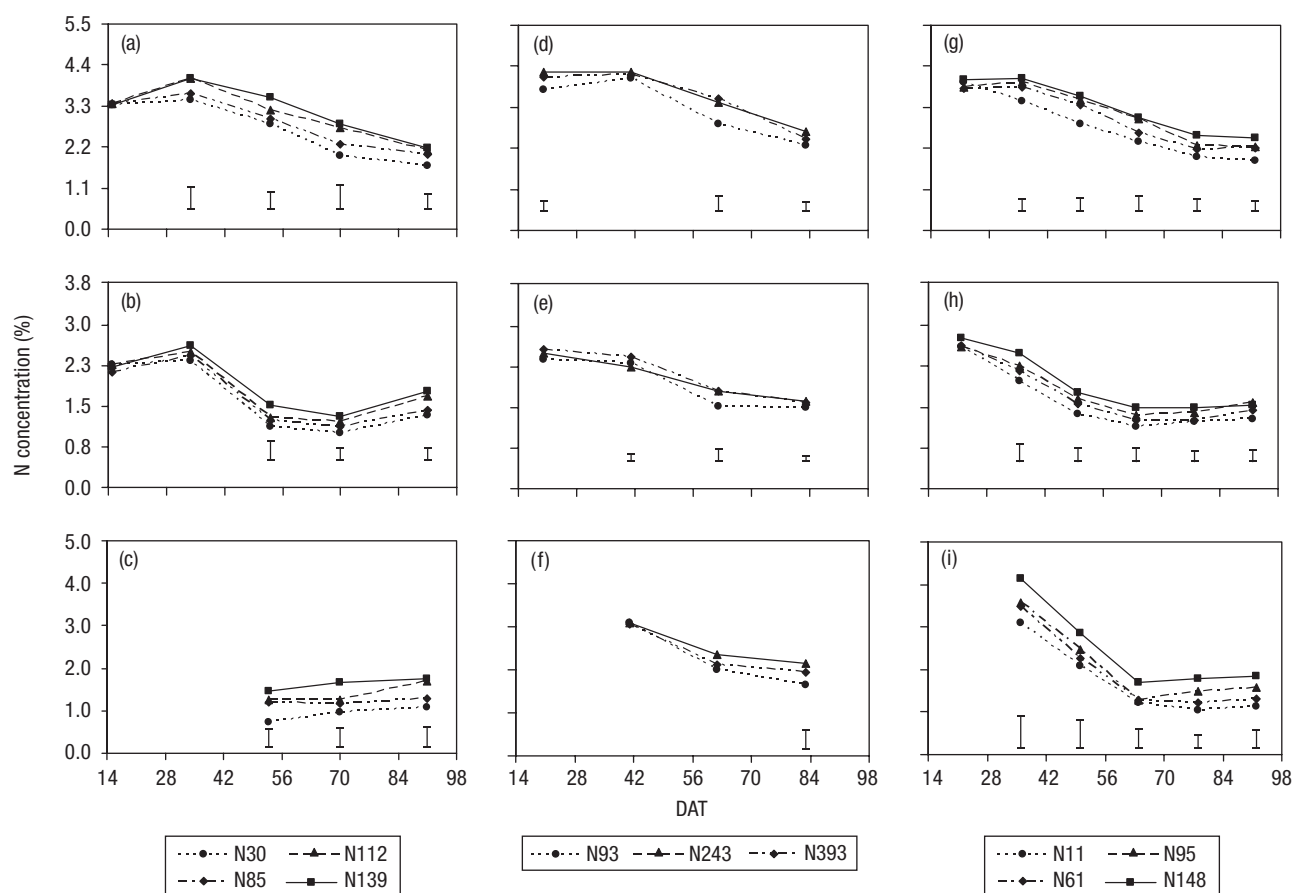


Figure 1. Effect of N application rate on the concentration of N (dry wt basis) in the different melon plant parts: leaves (a, d, g), stems (b, e, h), and fruits (c, f, i) in 2005 (a, b, c), 2006 (d, e, f) and 2007 (g, h, i). The bars represent the least significant difference ($p < 0.05$).

to 7 g m^{-2}). Nitrogen uptake by the other organs and the whole plant increased continuously as the vegetative cycle progressed. Total N uptake in N_{93} (14.27 g m^{-2}) was similar to that obtained in N_{95} (13.84 g m^{-2}) and slightly higher than in N_{85} (12.79 g m^{-2}). In all three years, higher values were obtained as N fertilizer rates increased (18.87 g m^{-2} in N_{139} , 16.75 g m^{-2} in N_{393} , and 16.50 g m^{-2} in N_{148}).

Nitrogen distribution

The applied N rate did not significantly affect N concentration in the leaves, stems, and fruits in relation to the whole plant at any sampling date in the three years.

At the beginning of crop growth, the leaves were the organs that contributed the most to the total N uptake. These values decreased with increasing plant age, ranging between 83% at 15 DAT and 28% at 91 DAT in

2005, and 88% at 20 DAT and 50% at 83 DAT in 2006. The stem contribution was more or less constant over the crop development, with an average of 9% in 2005 and 11% in 2006, except at 34, 41, and 36 DAT in 2005, 2006, and 2007, respectively, where the contribution was higher. In 2005, from 70 DAT, the fruits were the organs that contributed most to the total N in the whole plant, with an average of 63% at the end of the cycle. In 2006, the fruits contribution (40%) was lower than that of the leaves, while in 2007 it was slightly higher (47%).

Yield, yield components and quality

Nitrogen fertilizer application significantly affected FY in all three years (Table 2). In 2005, the largest FY was obtained with 112 kg ha^{-1} , decreasing by 22% in the N_{30} treatment. In 2006, the largest FY was obtained with 93 kg ha^{-1} , decreasing by 23% at

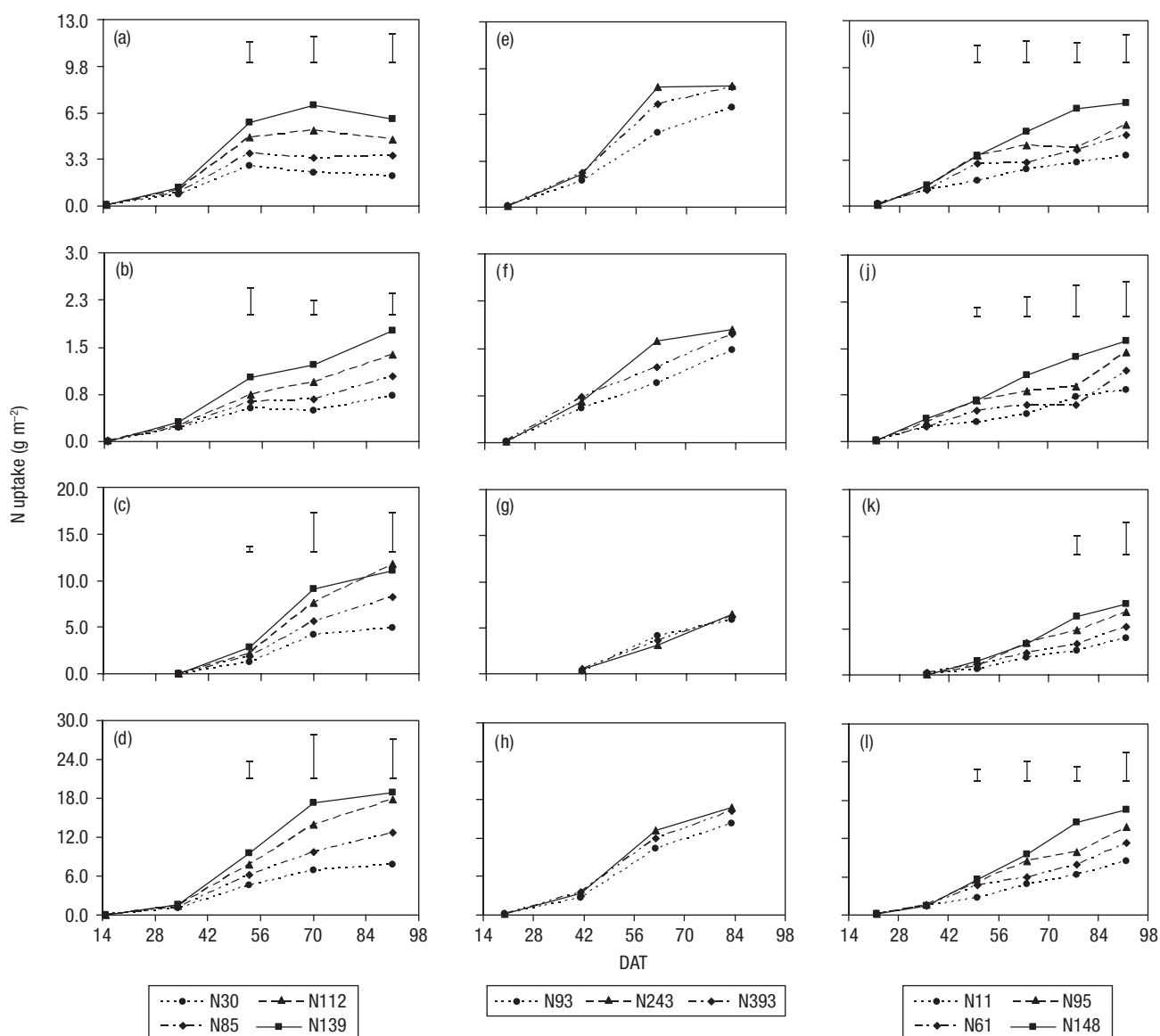


Figure 2. Effect of N application rate on the N uptake (g m^{-2}) of the different melon plant parts: leaves (a, e, i), stems (b, f, j), fruits (c, g, k), and whole plant (d, h, l) in 2005 (a, b, c, d), 2006 (e, f, g, h), and 2007 (i, j, k, l). The bars represent the least significant difference ($p < 0.05$).

the maximum amount of N applied. In 2007, the FY rose by 26% and 32% when the N rate increased from 11 to 95 and 148 kg ha^{-1} , respectively. In 2005 and 2007, FY was correlated positively with the applied N although in the first year r was lower (0.53). In 2006, this correlation was negative and highly significant (Table 3).

With regard to the fruit N content, in the three years the correlations were highly significant with r ranging between 0.74 (2005) and -0.94 (2006). The FY was also correlated with the N accumulation of the whole

plant: the coefficients were 0.67 (2005), -0.87 (2006), and 0.84 (2007), and in all cases they were highly significant. In 2006, the fruit number per square meter was correlated negatively with the applied N and with both the fruit and whole plant N uptake. On the contrary, in 2007, the fruit number was correlated positively with applied N and with the N uptake by the whole plant. In all three years, the fruit weight showed a high correlation with both the applied N and N uptake. The NUE showed a strong negative correlation with both the applied N and N uptake, in the three years. In 2006,

Table 2. Fruit yield of melon grown at different N rates in 2005, 2006 and 2007

| Year | Treatment | Fruit yield (t ha ⁻¹) |
|------|--------------------|-----------------------------------|
| 2005 | N ₍₃₀₎ | 40.6 a |
| | N ₍₈₅₎ | 49.4 ab |
| | N ₍₁₁₂₎ | 52.0 b |
| | N ₍₁₃₉₎ | 45.5 ab |
| 2006 | N ₍₉₃₎ | 41.8 a |
| | N ₍₂₄₃₎ | 38.3 a |
| | N ₍₃₉₃₎ | 32.4 b |
| 2007 | N ₍₁₁₎ | 34.5 a |
| | N ₍₆₁₎ | 39.2 ab |
| | N ₍₉₅₎ | 43.1 bc |
| | N ₍₁₄₈₎ | 44.9 c |

For each year, values followed by the same letter are not significantly different at $p < 0.05$.

significant correlations were found for the flesh and skin ratios. The flesh ratio was correlated negatively ($p < 0.01$) with the applied N and with N content in the fruit and N uptake by the aerial parts of the plant. In contrast, the skin ratio showed a strong positive correlation ($p < 0.01$). In 2007, only the flesh ratio was correlated negatively ($p < 0.05$) with the applied N. The TSS was not correlated with the applied N in any year.

Nitrogen in ripe fruits and nitrogen in crop residue

The concentration of N in ripe fruits increased significantly with applied N in all three years and at each harvest (Fig. 3a, c, e). The N concentration for each treatment was relatively constant until 96, 77, and 80 DAT in 2005, 2006, and 2007, respectively. From that time until the last harvest, the N concentration increased markedly: by 43% in N₁₃₉, 81% in N₃₀, 50% in N₉₃, and 73% in N₃₉₃, and between 55 and 62% in the N₁₁ and N₁₄₈ treatments.

In 2005 and 2007, N accumulation in ripe fruits increased with increasing N rate (Fig. 3b, f). In 2006, the N accumulated in treatment N₉₃ was lower than in the other two treatments, although the differences were not significant (Fig. 3d). The N accumulation rate was always higher at the first harvests and with the advancement of the vegetative cycle there was a slowdown, reaching values between 46.8 and 80.8 kg N ha⁻¹ in treatments N₃₀ and N₁₁₂, 59.4 and 68.9 kg N ha⁻¹ in N₉₃ and N₃₉₃ and 34.2 y 72.3 kg N ha⁻¹ in N₁₁ and N₁₄₈.

In 2005 and 2007, the amount of N applied had a significant effect on the N in the plants and in the total FY, and also on the amount of N returned in the crop

Table 3. Pearson correlation coefficients (r) and linear relationships (when $r > 0.5$ or $r < -0.5$) of fruit yield, fruit number m⁻², fruit weight, nitrogen use efficiency (NUE), flesh ratio and skin ratio *versus* nitrogen applied (N_{ap}), nitrogen content in the fruit (fruit N_c), and nitrogen uptake by the aerial part of the plant (TP N_{up}) in 2005, 2006 and 2007

| Dependent variable | Independent variable | 2005 | | 2006 | | 2007 | |
|-----------------------------------|---|---------|-------------------------|---------|-------------------------|---------|-------------------------|
| | | r | Equation | r | Equation | r | Equation |
| Fruit yield (t ha ⁻¹) | N _{ap} (kg ha ⁻¹) | 0.53* | $y = 0.0626 x + 41.14$ | -0.86** | $y = -0.0314 x + 45.11$ | 0.88** | $y = 0.0775 x + 34.33$ |
| Fruit number m ⁻² | | -0.02 | - | -0.78** | $y = -0.0008 x + 1.263$ | 0.57* | $y = 0.0009 x + 1.184$ |
| Fruit weight (kg) | | 0.91** | $y = 0.0021 x + 3.225$ | -0.59* | $y = -0.0006 x + 3.609$ | 0.87** | $y = 0.0038 x + 2.782$ |
| NUE (t kg ⁻¹) | | -0.94** | $y = -0.0027 x + 0.610$ | -0.85** | $y = -0.0003 x + 0.323$ | -0.73** | $y = -0.0010 x + 0.423$ |
| Flesh ratio | | -0.47 | - | -0.76** | $y = -0.0002 x + 0.567$ | -0.54* | $y = -0.0005 x + 0.746$ |
| Skin ratio | | -0.15 | - | 0.80** | $y = 0.00006 x + 0.092$ | 0.28 | - |
| Fruit yield (t ha ⁻¹) | Fruit N _c (g m ⁻²) | 0.74** | $y = 0.9931 x + 37.91$ | -0.94** | $y = -11.799 x + 109.9$ | 0.71** | $y = 1.6825 x + 30.51$ |
| Fruit number m ⁻² | | 0.19 | - | -0.83** | $y = -0.2845 x + 2.825$ | 0.41 | - |
| Fruit weight (kg) | | 0.86** | $y = 0.0229 x + 3.214$ | -0.75** | $y = -0.2575 x + 5.050$ | 0.74** | $y = 0.0869 x + 2.570$ |
| NUE (t kg ⁻¹) | | -0.83** | $y = -0.0267 x + 0.606$ | -0.96** | $y = -0.1344 x + 1.067$ | -0.90** | $y = -0.0343 x + 0.544$ |
| Flesh ratio | | 0.07 | - | -0.85** | $y = -0.0703 x + 0.954$ | -0.38 | - |
| Skin ratio | | 0.00 | - | 0.91** | $y = 0.0250 x - 0.046$ | 0.03 | - |
| Fruit yield (t ha ⁻¹) | TP N _{up} (g m ⁻²) | 0.67** | $y = 0.6366 x + 37.76$ | -0.87** | $y = -2.8674 x + 82.73$ | 0.84** | $y = 1.0760 x + 26.97$ |
| Fruit number m ⁻² | | 0.09 | - | -0.78** | $y = -0.0703 x + 2.186$ | 0.53* | $y = 0.0124 x + 1.100$ |
| Fruit weight (kg) | | 0.94** | $y = 0.0179 x + 3.165$ | -0.86** | $y = -0.0782 x + 4.702$ | 0.83** | $y = 0.053 x + 2.419$ |
| NUE (t kg ⁻¹) | | -0.94** | $y = -0.0215 x + 0.672$ | -0.96** | $y = -0.0353 x + 0.798$ | -0.94** | $y = -0.0196 x + 0.587$ |
| Flesh ratio | | -0.14 | - | -0.76** | $y = -0.0164 x + 0.782$ | -0.45 | - |
| Skin ratio | | -0.06 | - | 0.95** | $y = 0.0069 x - 0.0010$ | 0.11 | - |

* Significant at the 0.05 level, ** significant at the 0.01 level.

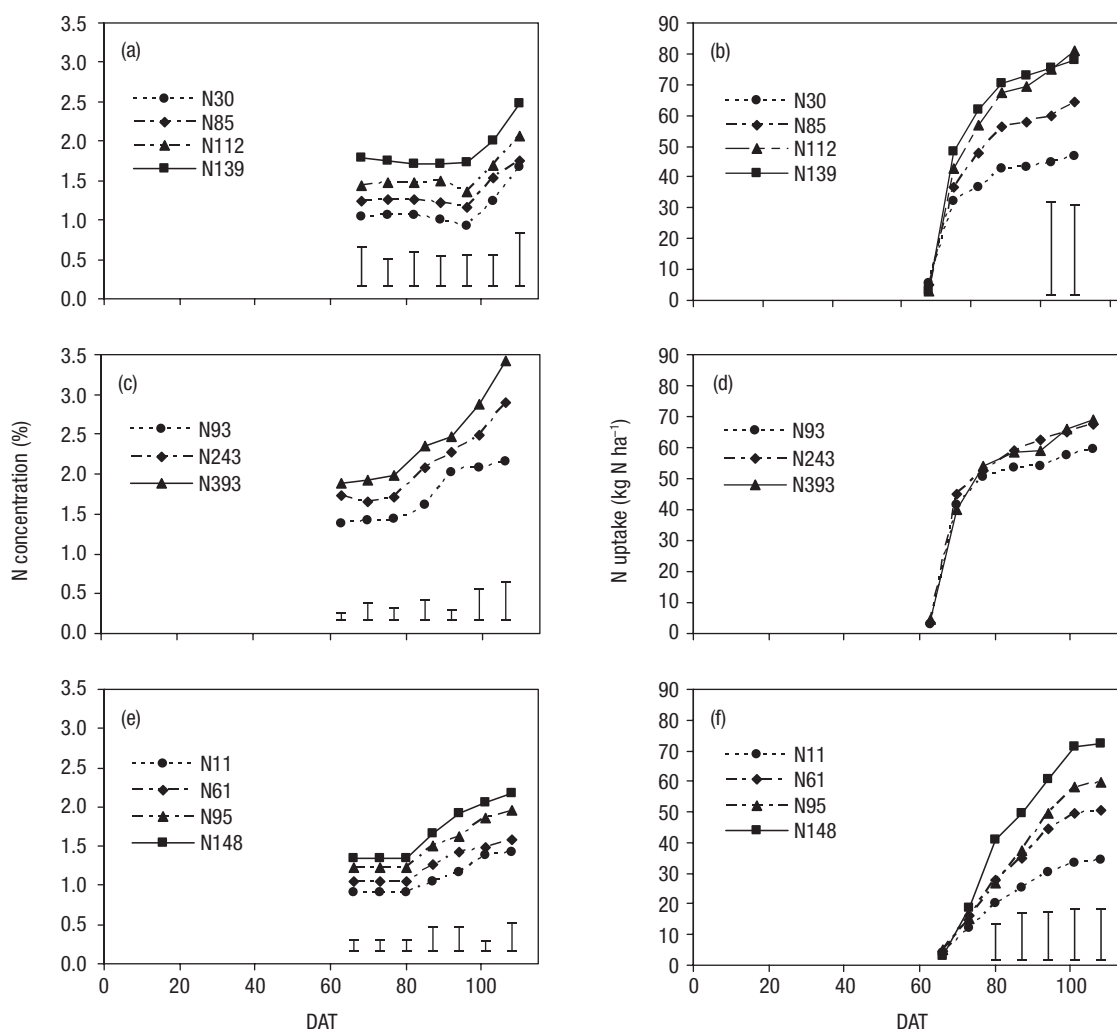


Figure 3. Effect of N application rate on the N concentration (a, c, e) and the accumulated N uptake (b, d, f) of the ripe fruit in 2005 (a, b), 2006 (c, d), and 2007 (e, f). The bars represent the least significant difference ($p < 0.05$).

residue (Table 4). In the three years, the highest amounts of N removed from the crop by the fruit were in treatments N₃₉₃ and N₁₁₂ and ranged between 69.0 and 80.8 kg ha⁻¹, respectively.

Discussion

Nitrogen concentration in the different plant parts

As N application increased, the N concentration was enhanced in each part of the plant, as found also by Panagiotopoulos (2001) and Kirnak *et al.* (2005) in melon. In contrast, in our trials, even though some N treatments were higher, the leaf N concentration was

lower, especially compared with that obtained by Kirnak *et al.* (2005) at the end of the crop period in cv. Polidor (7.65% with 120 kg N ha⁻¹).

Different authors (Greenwood *et al.*, 1990; Lemaire & Gastal, 1997) have stated that plant N concentration can decrease as a result of an increase of dry matter in several crops and this effect has been termed the “law of progressive decline” (Le Bot *et al.*, 1998). At the beginning of the crop development, the N concentration rose or remained more or less stable in the leaves and stems, because all plants were moved from trays, where N availability was limited, to soil, where there was more N, and also because during the first stages of plant development the growth rate was lower and therefore the reduction effect was also smaller. Later, with the rapid increase of plant biomass, N concentration de-

Table 4. N uptake in total plant, N content in marketable yield and N in crop residue in 2005, 2006 and 2007

| | Treatment | N uptake (kg ha ⁻¹) | | N in crop residue (kg ha ⁻¹) |
|------|------------------|---------------------------------|------------------|--|
| | | Total plant | Marketable yield | |
| 2005 | N ₃₀ | 77.3 a | 46.8 a | 30.6 a |
| | N ₈₅ | 127.9 ab | 64.2 ab | 63.7 ab |
| | N ₁₁₂ | 178.4 bc | 80.8 b | 97.7 bc |
| | N ₁₃₉ | 188.6 c | 77.9 b | 110.8 c |
| 2006 | N ₉₃ | 142.7 a | 59.4 a | 83.3 a |
| | N ₂₄₃ | 163.1 a | 67.6 a | 95.5 a |
| | N ₃₉₃ | 167.5 a | 68.9 a | 98.6 a |
| 2007 | N ₁₁ | 82.6 a | 34.2 a | 48.4 a |
| | N ₆₁ | 113.3 ab | 50.5 ab | 62.8 ab |
| | N ₉₅ | 138.1 bc | 59.6 bc | 78.4 bc |
| | N ₁₄₈ | 165.0 c | 72.3 c | 92.7 c |

Within each column and year, means followed by the same letter are not significantly different at $p < 0.05$.

creased according to the results found by Le Bot *et al.* (1998) and due to N translocation to the fruits, which began to set 25-30 DAT. Fruit N concentration decreased greatly until about 60-65 DAT in 2006 and 2007 as a result of fruit growth. Later, in all three years, the N concentration was relatively constant because fruits had lower growth and therefore the dilution effect decreased.

Nitrogen uptake

In the three years, between 95 and 98% of plant N was taken up after first fruit set (22-26 DAT). These values are higher than the 70% obtained by Fukutoku *et al.* (2000) and may be due to differences in the patterns of growth and fruiting between the two melon types and also to difference in growing environment -hydroponics vs. field. A period with a higher N absorption was observed from 30-55 to 70-80 DAT, coinciding with the development of most fruits. This period was much longer than that observed by da Silva *et al.* (2006), which was from 43 to 54 days after emergence, and the crop cycle only lasted 69 days. Rincón *et al.* (1996) obtained the highest N absorption rate at 65-105 DAT. The N absorption in melon and the length of the period when it is high depend not only on the variety but also on weather conditions (Pardossi *et al.*, 2004), emphasizing the importance of determining absorption dynamics for each melon type and crop area in order to establish an appropriate fertilization schedule. The amount of N applied had a clear effect on N uptake due to an increase in both the biomass and N concentration

of the plant organs (Castellanos *et al.*, 2011). Halitligil *et al.* (2002) and Kirnak *et al.* (2005) obtained the same results for melon cv. Polidor. Fukutoku *et al.* (2000) stated that the fruit functions as a large sink and accumulates a substantial amount of the total N (50%), which is derived mainly from the leaves. Therefore, the differences in fruit N content between treatments should be lower than for the leaves because both organs compete for N and the fruits have a greater demand for it.

Except for fruit biomass in 2006, the biomass of different plant parts and the total aerial plant biomass increased with the applied N (Castellanos *et al.*, 2011) and, therefore, the increase in N uptake was as a result of increases in both the biomass and N concentration. In 2006, N requirements were covered by the N₉₃ treatment, which had the highest yield, while the other two (N₂₄₃ and N₃₉₃) were surplus treatments and produced more vegetative and less reproductive biomass. The total plant N uptake was higher than that obtained by Halitligil *et al.* (2002) and that found by da Silva *et al.* (2006) at 58 DAT in 'Piel de sapo' melon (3.4 g m⁻² with doses of 98 kg N ha⁻¹). However, it was similar to that obtained by Rincón *et al.* (1996) for the same melon type grown in a greenhouse (17.6 g m⁻² at 105 DAT), although with N rates above 200 kg ha⁻¹.

Nitrogen distribution

The relative contribution of each organ to the total plant N content was not influenced significantly by the N application rate, although in 2005 and 2006 the fruit percentage had a tendency to decrease in the

treatments involving greater amounts of N. This may be due to the fact that high N applications can stimulate vegetative growth at the expense of reproductive growth (Mills & Jones, 1979; Hartz & Hochmuth, 1996).

It is widely accepted that the concentration of fruit N in relation to the total plant at the end of the crop cycle is higher than that of the leaves in different crops like tomato (Scholberg *et al.*, 2000) or melon (Fukutoku *et al.*, 2000; Zotarelli *et al.*, 2008). However, in cucumber, Tanemura *et al.* (2008) obtained similar final contributions of the two organs (43% in fruits and 41% in leaves). In our case, the fruit N contribution was higher than that of the leaves in the first year, slightly lower in 2006, and similar in 2007, indicating that the relative N distribution is influenced by the edaphoclimatic conditions.

Yield, yield components and quality

In general, studies have shown that FY increases with increasing N application until reaching a maximum value. If the N application continues increasing, FY decreases, as in tomato (Wang *et al.*, 2007) or melon (Pérez-Zamora *et al.*, 2004; Kirnak *et al.*, 2005; Castellanos *et al.*, 2011). In our case, maximum yields were obtained with 112 and 93 kg N ha⁻¹ in 2005 and 2006, respectively. In 2007, the maximum FY was obtained with 148 and 95 kg N ha⁻¹, without significant differences between them. These results suggest that the maximum yield of the 'Piel de sapo' melon in our conditions is obtained with N supplies close to 90-100 kg ha⁻¹. These findings are consistent with the correlations obtained being positive in 2005 and 2007 and negative in 2006. Goreta *et al.* (2005) obtained the same response in only one of two watermelon varieties studied. In zucchini squash, Zotarelli *et al.* (2008) obtained a yield response when increasing the N dose from 82 to 145 kg ha⁻¹, but there was none above 145 kg ha⁻¹, and Van Eerd & O'Reilly (2009) found minimal cucumber yield increase per unit N applied compared with non fertilized control.

The positive correlations obtained between fruit N content and total yield in 2005 and 2007 arose because both are directly proportional to the fruit biomass, and also because the N concentration in this organ varied in the same way as the biomass. In 2006, the correlation was negative due to excessive N application, which

resulted in increasing N uptake by both the fruit and the whole plant as the N application increased, while the values of yield decreased.

The fruit weight, as well as contributing to the yield, is considered one of the main quality variables and it is very sensitive to any factor causing stress to the plant (Maynard & Clark, 1989). In our conditions and with melon cv. Sancho, this variable was more sensitive to N deficit than the fruit number, likely as a result of a minimal difference in N between treatments at the beginning of the crop cycle, at early fruit set. In 2005 and 2007, the fruit weight rose as the N application and uptake increased, while in 2006, the opposite response occurred as a result of N excess.

The NUE improved when N uptake decreased, in accordance with the findings of Zotarelli *et al.* (2008), due to the fact that when the N availability was lower than the crop N requirement, an increase in N supply resulted in yield improvement and also an increase in both the N percentage in plant organs and the N loss by leaching (Castellanos *et al.*, 2007), decreasing the efficiency. When the N supply was higher than the crop requirement, total yield decreased, fruit N concentration increased, and NUE was reduced. The results suggest that the fruit quality was affected adversely by excess N, resulting in fruits with a large seed cavity and therefore with small edible parts and greater skin thickness. The N application and N content in the fruit and whole plant were not correlated with the flesh firmness or TSS, in agreement with Ferrante *et al.* (2008). Rodríguez *et al.* (2005) found no changes in the sugar content of Galia melon when they increased N fertilizer from 80 to 240 mg L⁻¹ and Kirnak *et al.* (2005) stated that N application generally has little or no effect on the TSS. Contrasting results were found in tomato by Wang *et al.* (2007), who observed lower flesh firmness with increasing N application, while Faria *et al.* (2000) obtained a significant increase in TSS when N was raised from 0 to 80 kg ha⁻¹.

Nitrogen in ripe fruits and nitrogen in crop residue

In general, at the first harvest, the N concentration in ripe fruits remained without variation until 77-96 DAT, depending on the year, and then started to increase until the end of the cycle, likely as a result of lower fruit number at the end of the cycle and the lesser growth.

The N accumulation, especially at the first harvests, was determined by the amount of biomass, because the concentration remained very similar during the first three or four harvests. Later, the fruit N content increased only slightly, even though the N concentration in ripe fruit increased, because the fruit biomass at the end of the harvest period was very low.

In our conditions and with melon cv. Sancho, the maximum N exports were about 70-75 kg ha⁻¹ in all three years. However, the highest yields were reached with N absorptions of 64.2 kg ha⁻¹ in 2005, 59.4 kg ha⁻¹ in 2006, and 59.6 kg ha⁻¹ in 2007. Above these amounts, luxury consumption, and hence over-fertilization, occurred.

In conclusion, an appropriate N fertilization from 30 to 80 DAT should be assured because in this period, which coincides with the fruit development, is when the melon plants take up the larger amount of N. This absorption is performed almost linearly, and therefore the N fertilization could be supplied with constant daily rates. Nitrogen applications close to 90-100 kg ha⁻¹ seem to be sufficient to obtain the maximum yield and the best fruit quality. With these N amounts applied and in our conditions, approximately 60 kg ha⁻¹ are removed from the system and about 80 kg ha⁻¹ returned to the soil in the crop residue; this quantity may be available, via mineralization, for subsequent crops.

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