

## Onion yield as affected by plant density, nitrogen level and loss of leaf area

### Producción de cebolla determinada por la densidad de plantas, nivel de nitrógeno y pérdida de área foliar

Siliquini OA<sup>1</sup>, GA Orioli<sup>2</sup>, JC Lobartini<sup>2</sup>

**Abstract.** Onion (*Allium cepa*) is an important horticulture crop because of its value as a food with a long shelf life being a relatively non-perishable product. It is very helpful to understand the growth response of the seeded onion crop to conduct appropriate field practices in attaining the highest or optimum yields. A three year field experiment was conducted using a variety of onion Valcatorce INTA, in a randomized block design with five replicates. Treatments were two plant densities and three rates of N application. The bulb growth followed a classical sigmoid curve. During the rapid growing period, the crop had the greatest leaf area (LA) with at least six leaves per plant. Increasing plant density increased yield in kg/ha, but decreased bulb size. Defoliating 40 to 60% of the LA had a significant impact on bulb production only at early growth stages. Late in the growing period, the remaining LA was apparently large enough for producing sufficient amounts of metabolites to feed new leaves, increasing their photosynthesis efficiency for the benefit of bulb production.

**Keywords:** Defoliation; Bulb production; Onion fertilization.

**Resumen.** La cebolla es un importante cultivo debido a su valor como alimento con una vida relativamente larga siendo así un producto no perecedero. Es muy útil entender las respuestas del crecimiento del cultivo de cebolla para realizar las prácticas a campo que conduzcan a un mayor y óptimo crecimiento. Se realizó un experimento a campo usando una variedad Valcatorce en un diseño de bloques al azar con cinco replicas a dos densidades de siembra y tres niveles de fertilización nitrogenada. El crecimiento del bulbo siguió una clásica curva sigmoidea. Durante el rápido período de crecimiento, el cultivo tuvo la mayor área foliar (AF) con al menos seis hojas por planta. Con el aumento de la densidad de plantas aumentó la producción en kg/ha pero disminuyó el tamaño del bulbo. Defoliaciones del 40 al 60% del AF tuvieron un fuerte impacto en la producción de bulbos sólo en los primeros estadios de crecimiento. En los últimos estadios, el AF remanente fue aparentemente lo suficientemente grande para producir metabolitos que alimentaron nuevas hojas, aumentando la eficiencia de fotosíntesis para la producción de bulbos.

**Palabras clave:** Defoliación; Producción de bulbos; Fertilización de cebolla.

<sup>1</sup> Facultad de Agronomía, Universidad Nacional de la Pampa, Santa Rosa, La Pampa, Argentina.

<sup>2</sup> Departamento de Agronomía, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina.

Address Correspondence to: Dr Juan Carlos Lobartini, e-mail: lobartini@uns.edu.ar

Recibido / Received 1.III.2015. Aceptado / Accepted 17.III.2015.

---

## INTRODUCTION

---

Plants growing together as a crop compete with each other for light, nutrients and available soil water. Of these factors, the most important for agronomic crop production is the amount of radiation intercepted by the leaf surface area (Williams et al., 1965). Since leaf area (LA) determines the amount of incident solar radiation that can be intercepted by the crop canopy, yields of many crops are often closely related to LA and duration of canopy radiation (Dale et al., 1980; Engel et al., 1987; Waggoner & Berger, 1987). The LA, related to a unit area of soil, is often termed leaf area index (LAI), which is an expression of canopy density of a crop (Hay & Walker, 1989). The canopy density is defined as half of the foliage life (all-sided included) per unit of projected ground surface area (Fernandes et al., 2003). It is generally accepted that either a too large or too small LAI at any growth stage is of no benefit for yield improvement. However, at a high LAI, mutual shading of lower leaves becomes usually a limiting factor, but the economic yield per area may still increase due to the high LAI, even though the increase in plant density might decrease plant growth (Cardinali et al., 1985). As density increased onion yield also increased both in plants grown from seeds (Bleedsdale, 1966) and from transplants (Russo, 2008), but the number of large bulbs decreased (Shock et al., 2004). On the other hand, high LAI initiates bulb scales and matures sooner than those with low LAI due to a decrease in the R:FR spectral ratio as LAI increases (Mondal et al., 1986).

For a given environmental condition, crop yield seems to increase until an optimal LAI value is reached. Such a relationship between LAI and yield before harvest time can be used to predict yield in advance. Hence, this will be useful for strategic planning enabling a more accurate determination of crop yields at harvest time (Doraiswamy et al., 2003). Because LA determination under field conditions is subject to time, labor restrictions and the need of investments of expensive, sophisticated equipment, non-destructive models based on leaf dimensions have been proposed currently to overcome the above-mentioned restrictions (Bosco et al., 2012).

Another important factor in crop production is the effect of defoliation on plant growth and in this research of particular importance on the growth and yield of onion bulbs. Leaf area loss is a typical damage resulting from fungal and arthropod attacks or hail, and several studies have been performed to describe the effect of defoliation on herbaceous and woody plants (Moriondo et al., 2003) but not on onion plants. Some of the plants investigated have shown the ability to recover from defoliation treatments but the recovery process was reported to be inversely related to the time to harvest and the intensity of defoliation (McNaughton, 1983). With sunflower crops, the loss of foliage was most detrimental to yield when defoliation treatments were applied during anthesis; however, little, if any, effects were observed when defoliation was applied during the vegetative and post-anthesis

phases (Schneitner et al., 1987; Schneitner & Johnson, 1994; Cardinali et al., 1982). No information about the issue above is available in the literature on onion crops.

Crop yields are in addition affected by genotype, plant density, climate and soil fertility (Tethio-Kagho & Gardner, 1988a; Tollernar et al., 1994). Thereafter, the fertility of soils, and especially the soil mineral nutrition aspect, will also determine the yield of any crop. In this respect, a number of scientists consider nitrogen as perhaps the most growth limiting nutrient in soil ecosystems (Chapin, 1980; Marschner, 1995). Fertilization with nitrogen has often been reported to play a crucial role in particularly enhancing onion yields (Maier et al., 1990a, 1990b; Bezic et al., 1998; Halvorson et al., 2002) even though Shock et al. (2004) found that nitrogen fertilization did not affect yield. Application of N was noted to enhance development of LA, leading to the improvement of the so called leaf area duration (LAD), which allegedly contributed to higher bulb yields. The results of a number of investigations indicated photosynthesis rate to be related to various nitrogen treatments or to leaf nitrogen concentrations. This is because most of the leaf-nitrogen is believed to be used for synthesis of photosynthetic components, and differences in nitrogen nutrition may cause physiological and morphological changes which perhaps affect the possible optimization of gas exchange rates (Novoa & Loomis, 1981).

The aim of this work was to examine and analyze seeded onion crop responses to variations in plant density, nitrogen fertilization and defoliation at different growth stages, focusing the attention on the dynamics of leaf area and yield.

---

## MATERIALS AND METHODS

---

A three-year study was carried out at the experimental fields of the "Facultad de Agronomía, Universidad Nacional de La Pampa," La Pampa, Argentina. The soil was an Entic Haplustol with low fertility. The physico-chemical characteristics of the soil are shown in Table 1.

The onion (*Allium cepa*) variety used was Valcatorce INTA, a common cultivar preferred by farmers due to its commercial value and excellent performance in the region. New seeds, harvested in the same year, were used to insure good germination. Seeding was done in two rows in 0.80 m wide beds, with the rows separated at 0.30 m distance in the center. In the first week of September, a band application of 100 kg/ha of DAP (diammonium phosphate) was made before seeding using a precision machine. Weed control was done by hand or using recommended herbicides, and the plots were maintained relatively weed-free during the study period. Furrow irrigation was applied when soil water tension dropped to approximately -20 to -30 kPa. For this purpose, water was applied to every furrow (0.80 m spacing) by 3.2 cm diameter siphon tubes to achieve uniform wetting of both the onion rows in the bed. Over the three-year period, onions received a total application of 40-50 cm of water using 20 irrigations.

**Table 1.** Physicochemical characteristics of an Entic Haplustol.  
**Tabla 1.** Características físico-químicas de un Haplustol Entico.

Organic Matter (%)	1.52
Clay (%)	13.20
Loam (%)	17.80
Sand (%)	65.00
pH	6.62
EC/dsm	0.64
CEC (meq/100 g)	13.08
Ca (meq/100 g)	8.18
Mg (meq/100 g)	1.59
Na (meq/100 g)	0.43
K (meq/100 g)	2.03
P (ppm) (Bray & Kurtz)	19.90
N (%)	0.11

Source: Chemistry Laboratory of the Facultad de Agronomía UNLPam.

**Experimental design.** The experiment was done in a randomized block design with five replicates, using two plant densities and three rates of N application as treatments. Each plot was 0.8 x 15 meters, long enough to determine yield, foliar area, growth rate, and defoliation treatment effects. A base fertilization was done for all treatments with 100 kg/ha of diammonium phosphate (18-20-0) before planting. The three doses of nitrogen were: N0 = none; N1 = 100 kg/ha of urea applied in band at 0.05 m distance from the side of each row when the plants had four leaves; and, N2 = another application of 100 kg/ha of urea when the plants had 8 leaves.

Plant densities were: (D1) 500000-520000 plants/ha and (D2) 31000-320000 plants/ha at harvesting time (Table 2).

Every 15 days, ten (10) plants were taken at random from each treatment to determine the number, length and diameter of

leaves; LA, and diameter and fresh weight of bulbs. At harvesting time (i.e.: 15 days after *top-over*), whole plants were taken from the soil for LA, bulb (fresh) weight and diameter measurements. Two methods were used to measure LA: (1) determination with a "Licor-3000 portable area meter" and (2) with an "A 3000 A-01 readout console." Leaf length and leaf diameter at half-length were measured every 15 days in the field, and the LA calculated by assuming that the down middle half leaf was a cylinder, and the upper middle half leaf was a cone. The LA obtained by adding the cylinder (Ci) and cone (Co) surfaces was highly correlated with the one determined by the Licor method; this can be noticed in the regression curve below:

$$y = 1.2149 (Co + Ci) - 0.1303 \quad R^2 = 0.9973$$

Due to this high correlation, and the advantage of the method above being a non-destructive procedure, the LA was estimated by measuring weekly the leaf length and diameter on ten plants.

During the final year, the study involved the effects of loss of LA on onion yields using the following treatments. Three different percentages of defoliation at three different growth stages were applied to plants cultivated at the higher density (D1) and higher N fertilization (N2). The percentage was calculated for each leaf after which the distal part was clipped. The three different treatments stated above were: R0 = no (zero) reduction of LA; R1 = minus 20% of LA; R2 = minus 40% of LA; and, R3 = minus 60% of LA. Defoliations were applied at the following three stages of bulb development: E1 = at the beginning of bulb formation; E2 = 30 days after the start of bulb formation, which is the period of rapid growth; and, E3 = 45 days after the beginning of bulb formation.

## RESULTS

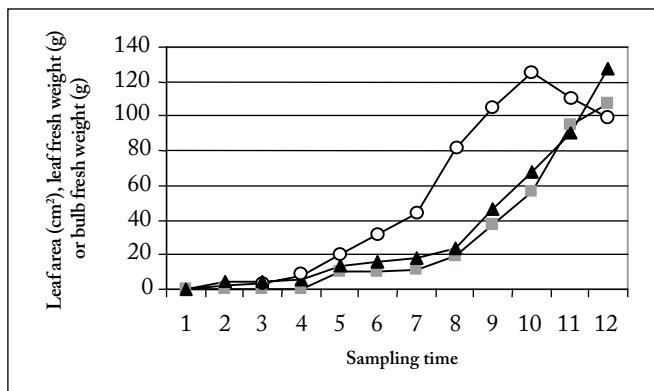
**Variation of leaf and bulb weight, and leaf area during the growing season.** The accumulation of leaf and bulb fresh weights during the growing season showed the classic biphasic curve (Fig. 1). On the other hand, the increase of the leaf

**Table 2.** Number of seeds planted, number of seedling emergence, number of bulbs at harvest, yield, and average bulb weight. Numbers are averages of five replicates.

**Tabla 2.** Número de semillas sembradas, número de plántulas emergidas, número de bulbos al momento de la cosecha, rendimiento y peso promedio del bulbo. Las cifras son promedios de n=5.

Treatments	Number of seeds planted/ha	Number of seedlings/ha	Number of bulbs/ha	Yield (kg/ha)	Average bulb weight (g)
D1	1003100 a	747300 a	511450 a	42100 a	82 b
D2	627300 b	456300 b	315751 b	30350 b	96 a

area began well before the steep increase of the other two parameters. As a consequence, four months after emergency the LA/Bulb-weight ratio (amount of leaf area necessary to produce one gram of bulb fresh weight) decreased from 4.22 cm<sup>2</sup>/g to 0.92 cm<sup>2</sup>/g at harvesting time.



**Fig. 1.** Evolution of leaf area in cm<sup>2</sup> (-O-); leaf fresh weight in g (-▲-) and bulb fresh weight in g (-■-) from plants sown in the first week of September. Samples from the plot D1N2 were taken every 15 days during the 6 month growing season in the plot of high density and nitrogen level.

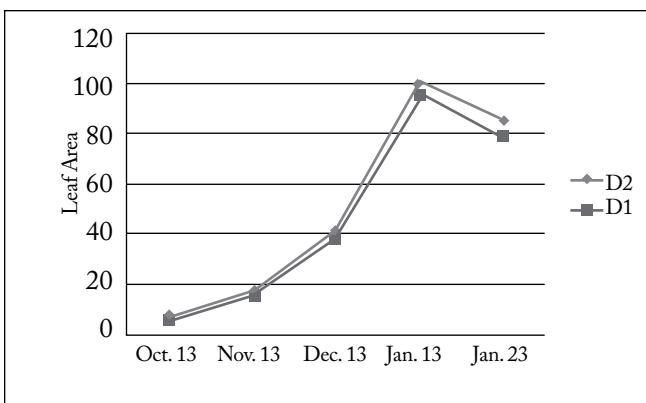
**Fig. 1.** Variación del área foliar en cm<sup>2</sup> (-O-); peso fresco foliar en g (-▲-) y peso fresco de bulbo en g (-■-) en plantas cuya siembra se efectuó en la primera semana de septiembre. Las muestras de la parcela D1N2 se tomaron cada 15 días durante 6 meses de la estación de crecimiento en la parcela de alta densidad y nivel de N.

**Effects of plant density at three nitrogen levels.**

*On Leaf Area.* The development of LA, expressed as a percentage of the maximum value reached during the cycle, is shown in Figure 2. Despite of the differences in the LA absolute values, the response of the plants growing at two densities was the same. An increase of 60% in LA was observed in January, the month with the maximum LA. Thereafter, the value of LA decreased as a result of the foliage to start toppling over to finally die in the final growth stage of the crop.

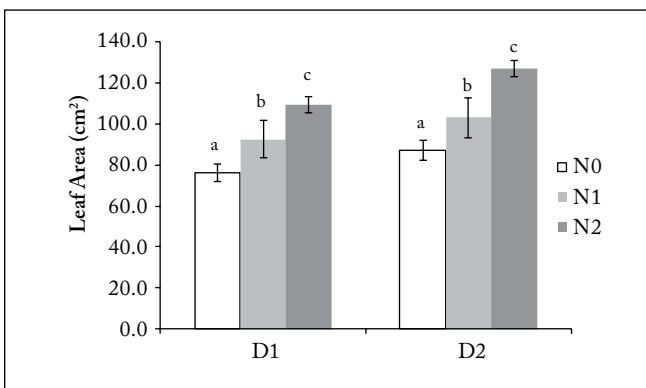
The effects of plant density and N fertilization on LA are shown in Figure 3. The value of LA increased with N addition in both plant density treatments.

*On bulb yield and quality.* The effect of plant density and N fertilization on bulb production is shown in Table 3. The crop appeared to have responded to N fertilization, since bulb yields were higher at high plant density. In the soil with low N fertility, the treatment at low plant density but with the highest dose of N (N2D2) yielded more bulbs than the treatment at high



**Fig. 2.** The variation of the leaf area on onion plants sown at two densities (D1 and D2) and high nitrogen level (N2). The values of leaf area are expressed as a percentage of the maximum obtained value (118 cm<sup>2</sup>) and leaf area was measured every 30 days.

**Fig. 2.** Variación del área foliar en plantas de cebolla cuya siembra se efectuó a dos densidades (D1 y D2) y alto nivel de nitrógeno (N2). Los valores del área foliar se expresaron como porcentaje del valor máximo obtenido (118 cm<sup>2</sup>); el área foliar se midió cada 30 días.



**Fig. 3.** Leaf Area at the final growth and developmental morphology stages of onion plants grown at two plant densities (D1 and D2) and different nitrogen doses (N0, N1, and N2). The results are expressed as an average of a three-year experiment.

**Fig. 3.** Área foliar en los estados finales de crecimiento y desarrollo de plantas de cebolla que crecieron a dos densidades de planta (D1 y D2) y diferentes dosis de N (N0, N1 y N2). Los resultados se expresan como el promedio de un estudio de tres años.

density without fertilization (N0D1). The efficiency of N fertilization appeared always greater in the high plant density plots. Bulb weight increased with increased N applications either at low or high plant densities (Table 3). Bulb size was approximately 20% larger in plots with low plant densities with similar N treatments. However, a difference started to be noticed when the maximum LA was obtained (Fig. 4). The development of fresh bulb weight during the crop cycle (N2D2) was similar in all treatments, but exhibited two different phases (Fig. 1). During the first 60 days, there was a slow growth phase but a second phase of exponential growth was observed afterwards.

**Table 3.** Effect of nitrogen fertilization and plant density on number of harvest bulbs, yield (kg/ha) and average bulb fresh weight (g).

**Tabla 3.** Efecto de la fertilización con N y la densidad de planta sobre el número de bulbos cosechados, el rendimiento (kg/ha) y el peso fresco promedio del bulbo (g).

Treatments	Number of bulbs/ha	Average yield (kg/ha)	Average bulb weight (g)
N0D1	506100 a	25623 c	50
N1D1	517330 a	33627 b	65
N2D1	512366 a	43225 a	84
N0D2	320264 b	20479 d	64
N1D2	316494 b	25366 c	80
N2D2	310495 b	31275 b	101

Values in the same column followed by the same letter are not significantly different at the 90% probability level. The average bulb weight was calculated, respectively, as the ratio between the values of average yield and number of bulbs.

**Table 4.** Effect of N fertilization and plant density on the percentage of bulbs in the different size groups (diameters in mm).

**Tabla 4.** Efecto de la fertilización con N y la densidad de plantas en el porcentaje de bulbos en los diferentes grupos de tamaño (diámetro en mm).

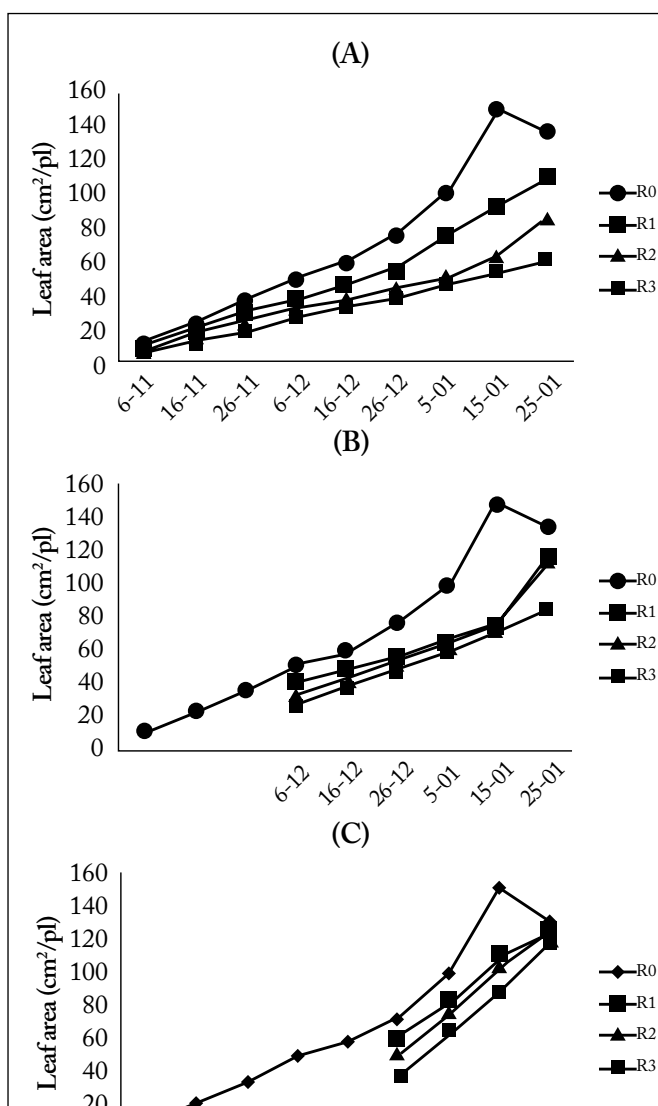
Treatments	Size Groups (diameter in mm)			
	35 - 50	50 - 60	60 - 70	>70
N0.D1	8 a	44 a	42 a	6 a
N2.D1	8 a	20 b	70 b	2 a
N2.D2	2 b	12 b	62 b	24 b

Values in the same column followed by the same letter are not significantly different at the 90% level of probability.

The effects of plant density and N applications on bulb diameter (in percentage) are shown in Table 4. Bulb size is very important from a commercial point of view; the most valuable bulbs are those with a diameter of 60-70 mm. At the highest amount of N applications, no differences in percentages were obtained for this size group at both plant densities. The highest percentage of large bulbs (>70%) and the lowest percentage of small bulbs were obtained at low plant density. The opposite was found for high N dose and high plant density.

**Effect of LA-reductions on bulb yield.** The defoliation treatments were applied at three stages of bulb development, as shown in Figure 4, in a crop with high N dose and plant density (D2N2). The development of LA of undefoliated plants (Fig. 4) exhibited a curve with a sharp increase from the middle of October to the end of January when the crop started to top over.

Figure 4 A shows the development of LA when defoliations were applied on plants with LA = 11 cm<sup>2</sup> which occurred just at the beginning of bulb formation (E1). A poor recovery was noted at any percentage of defoliation. The most affected plants were those receiving the R3 treatment, which at the end of the cycle had a LA value of 45% of the control plants. At the second defoliation (E2), conducted 30 days after bulb formation when plants had a LA of 51 cm<sup>2</sup> (Fig 4 B), the most affected plants were those receiving the R3 treatment. The plants at the other two treatments were not statistically different and at the end of the cycle had only 15% less



**Fig. 4.** Rate of LA growth every ten days at three different defoliation times and different defoliation intensities (R0=control; R1=20%, R2=40%, and R3=60% defoliation).

**Fig. 4.** Tasa de crecimiento del área foliar cada diez días en tres momentos diferentes de defoliación y diferentes intensidades de defoliación (R0=control; R1=20%, R2=40%, y R3=60% defoliación).

LA than the control. When defoliation was done 45 days after bulb formation (E3) no significant differences in LA were observed at the final stage in treatments R1 and R2 with respect to the control. Plants receiving R3 were able to recover until 90% (Fig. 4 C).

The data in Table 5 show the values of LA and bulb weight at the final crop stage in the treatments with different defoliation percentages. In general, a large LA corresponded with a large bulb weight. In no treatment was the bulb weight smaller than in the control if the LA was lower than 100 cm<sup>2</sup>. In the control plants the ratio of LA/Bulb-weight = 1.3. When defoliation was 20%, as in the E1

and E2 treatments, the ratio was 1.15. It seemed that plants with a ratio lower than 1.2 exhibited an increased efficiency in photosynthesis.

**Relationship between leaf area and yield.** A correlation was made between yield and LA with the data obtained in the different fertilization treatments and those resulting from plant the densities in the three-year period. As a result, a high correlation was obtained between LA and bulb yields (Fig. 5).

## DISCUSSION AND CONCLUSIONS

The development of bulb weights followed a classical sigmoid curve, showing at first a slow growth from the beginning of bulb formation to the middle of December. Following this period, bulb weights showed a continuous increase until the top over of the crop. At this rapid period of growth, the crop exhibited the largest LA, consisting of at least six green leaves, which were considered vital for bulb production.

Nitrogen fertilization had a strong impact on onion production, and proved to be necessary to obtain high yields. The second N application (N2) at the start of bulb formation was the stage when the increase of growth rate and translocation of photosynthates to bulbs occurred. This is in agreement with reports by Bezic et al., (1998), who found that fertilization with N was efficient from the beginning of bulb formation to the early stage of the exponential phase, whereas no responses were obtained with late applications. The average bulb size and weight diminished by increasing plant density. This negative effect was perhaps attributed to the competition among plants for light, water and nutrients. Assuming that the harmful effect was not caused by water restriction, since irrigation was applied every time it was needed and no mutual shading occurred among leaves, it was concluded that evidently the limiting factor was nutrient availability.

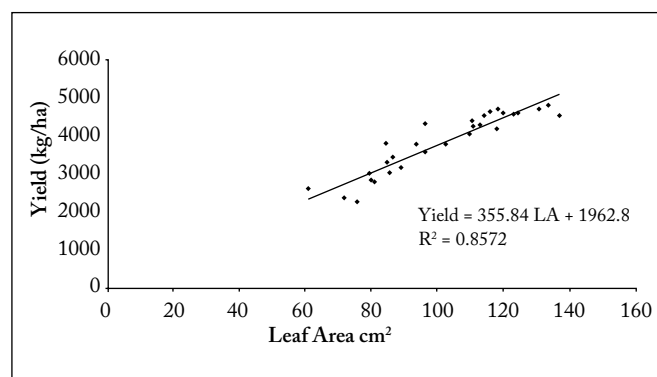
A direct linear relationship between LA and bulb fresh weight was showed at a density of at least 500000 seeded plants/ha. As a result, defoliation had an impact on bulb production when it was done in the early stages at 40 and 60 percent foliage removal. The latest the reduction of LA, the better the recovery observed. At this late growing state, the remaining or residual LA was apparently sufficiently large to produce enough metabolites to feed new leaves and the bulb by increasing photosynthesis efficiency. Because of the high statistical correlation obtained with R values, indicative of a 90% level of probability between LA and onion yield, a method was obtained for predicting onion yields several days before harvest, when values are available for LA at the top-ping-over stage and plant density.

**Table 5.** Leaf area (cm<sup>2</sup>) and bulb weight (g) at the end of the cycle of plants treated with different percentages of defoliation at different time (E).

**Tabla 5.** Área foliar (cm<sup>2</sup>) y peso de bulbo (g) al final del ciclo de crecimiento de las plantas tratadas con diferentes porcentajes de defoliación en diferentes momentos (E).

Time	E1		E2		E3	
	cm <sup>2</sup>	g	cm <sup>2</sup>	g	cm <sup>2</sup>	g
0	137 a	104 a	134 a	101 a	131 a	101 a
20	111 b	95 a	116 b	102 a	124 ab	100 a
40	85 c	74 b	114 b	96 a	123 ab	98 a
60	61 d	59 b	84 c	80 b	118 b	90 ab

Values in the same column followed by the same letter are not significantly different at the 90% level of probability.



**Fig. 5.** Relationship between leaf area (cm<sup>2</sup>) at the top over stage and onion yield (kg/ha).

**Fig. 5.** Relación entre el área foliar (cm<sup>2</sup>) en el estado más avanzado de crecimiento y desarrollo versus el rendimiento (kg/ha) en plantas de cebolla.

---

## REFERENCES

---

- Bezic, C.R., A. Dall Armelina, O. Gajardo, S.B. Polo & M. Abramoto (1998). Dosis, fuente y momento de aplicación de nitrógeno en el ajuste del programa de fertilización para cebolla en el Valle Inferior del Río Colorado. XXI Congreso Argentino de Horticultura. San Pedro, Buenos Aires, Argentina.
- Bosco, L.C., H. Bergamaschi, L.S. Cardoso, V.A. De Paula & B. Casamali (2012). Seleção de Modelos de Regressão Para Estimar a Área Foliar de Macieiras 'Royal Gala' e 'Fuji Suprema' Sob Tela Antigranizo e em Céu Aberto. *Revista Brasileira de Fruticultura* 34: 504-514.
- Brewster, J.L. (1997). Physiology of Crop Growth and Bulbing. In: H.D. Rabinowich and J.L. Brewster (Ed.), *Onion and Allied Crops*, Vol. I, pp 53-88.
- Cardinali, F., V.R. Pereyra, C. Farizo & G.A. Orioli (1982). Effects of defoliations during filling of sunflowers. Proceeding 10th International Sunflower Conference, Surfers Paradise, Australia, pp. 26-28.
- Cardinali, F.J., G.A. Orioli & V.R. Pereyra (1985). Comportamiento de dos híbridos de girasol a bajas densidades de siembra. *Revista de la Facultad de Agronomía* 6: 131-139.
- Chapin, F.S. III. (1980). The mineral nutrition of wild plants. *Annual Review of Ecology & Systematic* 11: 233-260.
- Dale, R.F., D.T. Coelho & K.P. Gallo (1980). Prediction of daily green leaf area index for corn. *Agronomy Journal* 72: 999-1005.
- Doraiswamy, P.C., S. Moulin, P.W. Cook & A. Stern (2003). Crop yield assessment from remote sensing. *Photogrammetric Engineering & Remote Sensing* 62: 665-674.
- Engel, R.K., L.E. Moser, J. Stubbendieck & S.R. Lowry (1987). Yield accumulation, leaf area index, and light interception of smooth bromegrass. *Crop Science* 27: 316-321.
- Fernandes, R.A., C. Butson, S. Leblanc & R.A. Latifovic (2003). Landsat-5TM and Landsat-7 ETM+ based accuracy assessment of leaf area index products for Canada derived from SPOT-4 vegetation data. *Canadian Journal of Remote Sensing* 29: 241-258.
- Halvorson, A.D., R.F. Follett, M.E. Bartolo & F.C. Schweissing (2002). Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn. *Agronomy Journal* 94: 442-449.
- Hay, K.M.R. & A.J. Walker (1989). An introduction to the physiology of crop yield. Longman Scientific & Technical, Essex, UK.
- Marschner, M.H. (1995) Mineral Nutrition of higher plants. Academic Press, NY.
- McNaughton, S.J. (1983). Compensatory plant growth as a response to plant herbivory. *Oikos* 40: 329-336.
- Moriondo, M., S. Orlandini & F.J. Villalobos (2003). Modelling compensatory effects of defoliation on leaf area growth and biomass of sunflower (*Helianthus annuus* L.). *European Journal of Agronomy* 19: 161-171.
- Natr, L. (1975). Influence of mineral nutrition on photosynthesis and the use of assimilates. In: J.P. Cooper (ed), *Photosynthesis and Productivity in Different Environments*. International Biological Programme, Vol 3. Cambridge University Press, Cambridge, pp 537-555.
- Novoa, R. & R.S. Loomis (1981). Nitrogen and plant production. *Plant and Soil* 58:177-204.
- Schneitner, A. & B.L. Johnson (1994). Response of sunflower plants to physical injury. *Canadian Journal of Plant Science* 74: 763-766.
- Schneitner, A., J.M. Jones & J.J. Hammond (1987) Simulated hail research in sunflower defoliation. *Agronomy Journal* 79: 431-434.
- Tethio-Kagho, F.P. & F.P. Gardner (1988). Responses of maize to plant population density. I Canopy development, light relationships, and vegetative growth. *Agronomy Journal* 80: 930-935.
- Tollernar, M., A.A. Dibop, A. Aguilera, S.F. Wiese & C.J. Swanton (1994). Effect of crop density on weed interference in maize. *Agronomy Journal* 86: 591-595.
- Waggoner, P.E. & R.D. Berger (1987). Defoliation, disease, and growth. *Phytopathology* 77: 393-398.
- Williams, W.A., R.S. Loomis & C.R. Lepley (1965). Vegetative growth of corn as affected by population density: productivity in relation to interception of solar radiation. *Crop Science* 5: 211-215.