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The response of Valencia orange trees to irrigation in Uruguay

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Abstract

The effects of different drip irrigation regimens on mature Valencia orange trees growing in southern Uruguay were studied over a five year period (1995-2000). These treatments were: no irrigation (T1), irrigation at 50% ETc (T2), 100% ETc (T3), 150% ETc (T4), and irrigation-stress-irrigation (T5, equal to T3 except during the period from approximately mid-December to mid-February, when no irrigation was provided). Trunk cross-sectional area and crown volume increased linearly with the amount of water applied. Flower number and fruit setting were not affected by the treatments. T3 gave the best yield, which on average was 31% higher than that obtained with T1. Fruit size was the yield component most affected by irrigation treatment. The exportable yield of the T3 trees was almost double that of the T1 trees (36.7 and 19.2 t ha^{-1} $year^{-1}$ respectively). T2 allowed a seasonal water saving of 738 m^3 ha^{-1} $year^{-1}$ but produced smaller trees; nonetheless, the reduction in exportable yield was only moderate (14%). T4 used more water than T3 and produced larger trees, but led to no improvement in yield. The complete restriction of irrigation during the initial phases of fruit enlargement (T5) led to a smaller water saving than that provided by the T2 regime (547 m^3 ha^{-1} $year^{-1}$) and a greater reduction (22%) in the exportable yield.

Key words: Citrus fruits, production, fruit quality.

Resumen

Respuesta al riego de naranjos 'Valencia' en Uruguay

Se realizó un experimento durante cinco años consecutivos (1995-2000) en la zona sur del Uruguay, en naranjos 'Valencia' adultos regados por goteo. Los tratamientos aplicados fueron: secano (T1), riego 50% ETc (T2), 100% ETc (T3), 150% ETc (T4), riego-estrés-riego (T5, a igual dosis que el T3, pero se cortó el riego desde el fin de la caída de frutos, a mediados de diciembre, hasta mediados de febrero). El incremento de la sección del tronco y del volumen de copa tuvieron una respuesta lineal y positiva a la dosis de agua aplicada. Ni el número de flores producidas ni el porcentaje de cuajado fueron afectados por los tratamientos. En promedio, el rendimiento con T3 fue un 31% superior que con T1. El tamaño del fruto fue el componente de la producción total más afectado por el riego. El rendimiento de frutos de tamaño exportable fue casi el doble en el tratamiento regado que en el secano (36,7 y 19,2 t ha^{-1} $año^{-1}$ respectivamente). El T3 dio los mejores resultados productivos. El T2 significó, en promedio, un ahorro de 738 m^3 ha^{-1} $año^{-1}$ de agua, produjo árboles de menor tamaño, y una reducción moderada (14%) de la producción de tamaño exportable. El T4 utilizó más agua que el T3, produjo árboles de mayor tamaño, pero no mejoró la producción. El T5 significó un menor ahorro de agua que el T2 (547 m^3 ha^{-1} $año^{-1}$), pero una mayor reducción (22%) de la producción exportable.

Palabras clave: cítricos, producción, calidad de fruta.

Introduction

More than 20,000 ha are given over to citrus production in Uruguay, where mean annual production is some 360,000 t. Citrus fruit consumption in the country is currently some 28 kg per person per year. Given the slow growth of the population, this is not likely to rise significantly in the short term. The goal of new plantations is therefore to export fresh, high quality fruit to the markets of the northern hemisphere at times of year when local production cannot meet demand (Bentancur, 1988).

In a recent review, du Plessis (2000) discusses the use of water in citrus plantations, and indicates that research results can only be extrapolated from one area

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to another if basic factors such as the quantity and distribution of rainfall are taken into account. This suggests that a distinction needs to be made between research undertaken in areas with rainy winters, areas with summer drought, areas with scant rainfall year round, and areas with abundant rain and supplementary irrigation.

The literature is rich in material discussing the beneficial effects of irrigation in arid and semi-arid areas (Shalhevet and Levy, 1990), but less is available on its effects in more rainy areas. A better understanding is also required of how growth and yield are affected in the long term by water availability if the efficiency of irrigation is to be improved (Hsiao *et al*., 1976).

Parsons and Wheaton (2000) state three reasons why it is still beneficial to irrigate even in areas of high rainfall such as Florida: 1) rain does not always come at the time when it is needed, 2) soils may have low water retention capacities, and 3) the technology and management of irrigation has improved.

The aim of the present work was to assess the productive response of orange trees to irrigation in an area of Uruguay with high rainfall and where the soil has a high water retention capacity, and to determine the agricultural parameters to be assessed for the optimum design and correct management of irrigation regimens.

Material and Methods

This study was undertaken over a period of five consecutive years (August 1995-August 2000) at an orchard belonging to the Milagro S.A. company in Kiyú (34°39' S, 56°46' W, altitude 30 m, 5 km from the River Plate coast), San José, Uruguay.

The experimental orchard had 15 rows of 32 orange trees, *(Citrus sinensis* (L.) Osb.), cv. Valencia grafted onto *Poncirus trifoliata* (L.) Osb. stocks. All the trees had been planted (6 m apart, 4 m between rows) in the winter of 1981.

According to the Uruguayan classification, the soil was a *Brunosol Subéutrico Lúvico* [equivalent to a typical Argiudoll (USDA, 2003) or Phaeozem (FAO-UNESCO, 1990)] of the Kiyú unit, with a 25 cm-thick clay-silt loam horizon followed by a Bt clay-lime horizon down to 70 cm.

A randomised complete block design with four repetitions was used for the experiment. Each block was formed by three rows of 32 contiguous trees. Each plot was formed by 18 or 21 trees (6 or 7 in each row respectively). The responses of the central four trees of the centre row of each plot were assessed; the remainder acted as «guards».

Five irrigation treatments were tested:

T1. Rainfed. No irrigation at any time during the experimental period.

T2. Irrigation to cover 50% of crop evapotranspiration (ETc), always with a dose equal to 50% of T3.

T3. Irrigation to cover 100% ETc, always with a dose equal to the estimated water consumption of the trees.

T4. Irrigation to cover 150% ETc, always with a dose equal to 150% of T3.

T5. Irrigation-Stress-Irrigation with the same dose as in T3, but cutting off irrigation to create a period of stress during phase II of fruit growth (approximately 15th December-mid February).

ETc was estimated using a class A evaporation pan multiplied by the corresponding coefficients for adult trees proposed by the FAO (Allen *et al.,* 1998).

Irrigation was applied daily throughout the corresponding periods, the duration of irrigation being the same in all treatments (except, of course, in T1). The irrigation period began between the end of September and the beginning of November, and ended between the end of March and mid May, depending on the year.

The irrigation system was equipped with pressure compensated drippers set 1 m apart (one line per row, 4 drippers per tree). The different doses were supplied using drippers with different discharge rates: 2 L h^{-1} for T2, 4 L h^{-1} for T3 and T5, and one dripper of 2 L h^{-1} plus one of 4 L h^{-1} set 5 cm apart for T4.

Over the five year experimental period, the trunk circumferences and crown volumes of the four central trees of each plot (16 trees for each treatment) were measured every three months.

To study the effect of irrigation on flower and fruit fall, two 4 × 1.5 m nets were positioned on each side of the trunk to form a 4 × 3 m rectangle (two trees per plot). The content of these nets was periodically collected and the number of flowers or fruits counted.

Four branches with a minimum of two and maximum of five fruits were selected from two trees in each plot. Twice-weekly from mid December until harvest, the equatorial diameter of all these fruits was recorded.

At harvest, the individual production of each of the 80 monitored trees was weighed and their number of fruits counted. Samples were taken from each plot and the fruits assigned to four marketing categories depending on their diameter: < 63 mm, > 63 mm, > 69 mm, > 72 mm and > 76 mm.

Fruit quality (peal thickness, Brix value and acidity) was determined in 10 oranges (belonging to the predominant size category) from each plot.

Results were analysed using the SAS statistical package (SAS Institute, 1997).

Results

Climate and total irrigation water supplied

Table 1 shows the annual rainfall and class A evaporation pan data. The ensuing analysis naturally focuses on summer, which is practically the only season during which drought of any importance occurs in Uruguay. The summer of 1995 was moderately dry-conditions that are repeated approximately every four years. That of 2000 was very dry, conditions that are repeated approximately once every seven years. The summer of 1997 saw rainfall around the historical mean. Finally, the rainfall record was broken in 1998 and then again in 1999; the probability of breaking the record is less than once every 35 years.

Table 1 also shows the total amount of irrigation water provided. Between February and March of 2000, 69 L of water were applied per day to each tree in T3 (covering 100% ETc).

Vegetative growth

Vegetative growth (Table 2) was examined by analysis of covariance, taking initial size as the covariable (in this case represented by trunk section).

In September 1996, after only one year of treatment, significant differences between treatments had already developed with respect to trunk size. The mean relative increase in trunk section (Y, recorded as a percentage) for the five years of the experiment corresponded directly to the volume of irrigation water supplied (X, in m^3 $tree^{-1}$), according to the following relationship:

$$Y = 38.48 + 4.71 * X$$

When corrected for the variation between plots and trees, an R^2 value of 0.54 was established (highly significant at $p < 0.01$; 75 degrees of freedom).

This relationship indicates that, within the irrigation dose range employed, no negative effect on vegetative growth was caused by excess water. Indeed, vegetative growth increased by approximately 5% for every extra m^3 of water per tree. The growth of the crown volume showed the same tendency but the results were not as clear (results not shown).

Number of flowers and flower fall

Over the four years in which these variables were monitored, no significant differences were seen, either in the number of flowers or newly set fruits collected, or in the totals accumulated (data not shown).

Fruit growth

During the two wettest seasons (1997/98 and 1998/99), the growth curves for the fruits (Fig. 1) were almost equal; no significant differences were seen between treatments. However, very clear differences in behaviour were seen for the other seasons, with T1 fruits always smaller than those of the other treatments. They were significantly smaller ($p < 0.05$) from December

Table 1. Rainfall, evaporation from a class A pan (Eo), and irrigation water supplied to each treatment during the different seasons, as well as the means for the whole experimental period)[1]

	Rainfall	Eo	Irrigation			
			T2	T3	T4	T5
1995/96	796	1,417	153	306	446	197
1996/97	1,083	1,494	131	254	384	192
1997/98	1,311	1,149	85	146	227	117
1998/99	1,362	1,260	145	234	360	147
1999/00	1,319	1,441	244	372	606	248
Means	1,174	1,352	152	262	405	180

[1] All values in mm. Rainfall calculated for a planting area of 16 m^2.

Table 2. Trunk cross section (in cm^2) at harvest of each season corrected by covariance (taking the values measured in year 1995), and the relative increase in trunk section (%) from one year to the next and for the five years as a whole (1995-2000)[1]

	Corrected trunk cross section (cm^2)										
	1995	**1996**		**1997**		**1998**		**1999**		**2000**	
T1	125.8	142.7	c	142.1	d	157.2	c	163.6	c	169.3	c
T2	126.4	146.5	c	148.0	cd	162.9	bc	174.1	b	180.3	b
T3	123.3	152.5	ab	155.5	ab	170.4	ab	177.7	b	188.8	b
T4	115.6	158.3	a	162.2	a	179.4	a	188.6	a	200.0	a
T5	121.2	146.9	bc	151.6	bc	167.7	bc	174.3	b	185.7	b
p	ns	< 0.001		< 0.001		0.001		< 0.001		< 0.001	
CV		2.24		2.03		3.49		4.06		2.36	
MSD		5.0		7.0		11.5		7.0		10.0	

	Relative increase in trunk cross section (%)									
	1995-96		**1996-97**		**1997-98**	**1998-99**	**1999-00**		**1995-00**	
T1	9.37	c	6.80	b	10.54	4.27	3.45	b	39.25	c
T2	12.15	bc	8.68	ab	9.16	8.10	5.13	ab	48.44	bc
T3	18.32	ab	6.86	b	9.47	4.26	6.22	a	52.80	bc
T4	23.34	a	10.12	ab	10.95	5.04	6.00	a	67.79	a
T5	13.00	bc	12.07	a	10.63	4.29	6.25	a	55.31	ab
p	0.001		0.036		ns	ns	0.004		0.002	
CV	40.54		60.30				47.77		18.53	
MSD	7.19		4.62				1.82		14.76	
LIN	< 0.001		ns		ns	ns	ns		< 0.001	
QUAD	ns		ns		ns	ns	ns		ns	
T3-T5	0.009		ns		ns	ns	ns		ns	

[1] Values are means of 16 trees per treatment. Values followed by the same letter are not significantly different at the 10% level according to the Tukey test. p: level of statistical significance of covariance analysis. CV: coefficient of variation. MSD: minimum significant difference in the Tukey test at the 10% level. LIN, QUAD: level of significance of the linear and quadratic effects, respectively. T3-T5: level of significance of the contrast analysis. ns: not significant.

and January of 1999/00 and 1995/96 respectively, and from April of 1996/97. The greatest reduction in T1 fruit volume occurred in 1999/00, which had the driest summer of the experimental period.

With respect to fruit growth rate, T1 growth stopped for approximately one and a half months in the driest summer (1999/00), and showed two pauses in the autumn of 1996/97. T5 fruit growth was only detained completely in the last season at the end of the no-irrigation period. With the exception of this year, which had the greatest water deficiency, the stress induced by cutting off the irrigation supply was never sufficient to totally stop fruit growth.

Fitting of a model of fruit growth

With the aim of generalising the effects of the irrigation treatments on fruit growth, the following logistic model was fitted to the points on the growth curve:

$$Volume\ (cm^3) = \frac{A}{1 + e^{(B - GxT)}}$$

T = time elapsed in days since the 1st September

A = Upper asymptote, coinciding with the final potential size of the fruit in cm^3.

B = Related to the value of the function (*the above logistic model)* when T = 0.

This equation was fitted to the mean volume change of the fruits on the four branches monitored per tree (eight trees per treatment). The Nlin procedure of the SAS package was used to obtain the best fit parameters: *A, B* and *G*. These were then used to calculate the maximum growth rate for each fruit and the time needed to achieve this rate.

The maximum potential size of the fruit (variable *A*, Table 3), only showed significant differences

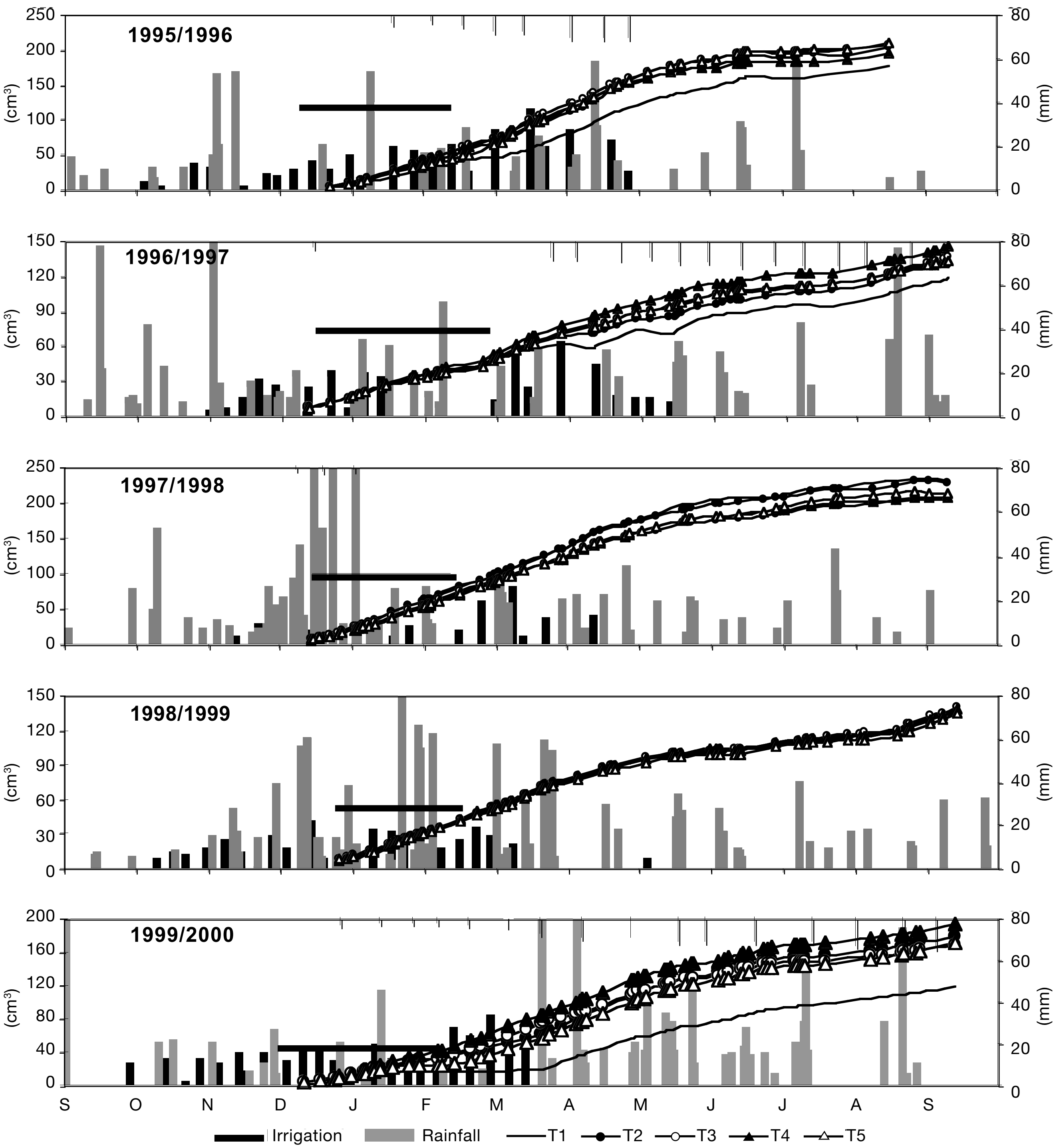

Figure 1. Fruit growth curves (volume, cm^3) over the five year experimental period. Total values for rainfall and weekly irrigation water supplied (mm) are also shown. The horizontal bar in each figure indicates the period over which irrigation was detained in T5. The vertical lines indicate the Tukey MSD at 0.10 on those dates for which there were significant differences between treatments.

between treatments in 1999/00, when that of the T1 fruits was smaller than that of the irrigated treatments.

The maximum growth rate (*Vmax*) and the date when this was reached (*Tmax*) were different in three seasons; only in the wettest seasons (1997/98 and 1998/99) were no differences seen. With respect to these three seasons, T1 fruits always had the lowest *Vmax*, while no differences were seen between the

Table 3. Fitting of the logistic model to fruit growth for the five years as a whole

	Fitted variables						**Calculated variables**				
	A		***B***		***G***		***Vmax***		***Tmax***		**Date**
1995/96											
T 1	178.1		6.31	b	0.0289	c	1.28	b	218	a	06 Apr
T 2	201.4		6.38	b	0.0309	b	1.55	ab	207	b	25 Mar
T 3	209.0		6.32	b	0.0311	b	1.63	ab	203	bc	21 Mar
T 4	192.0		6.46	b	0.0325	ab	1.55	ab	198	c	17 Mar
T 5	210.3		6.89	a	0.0330	a	1.73	a	209	b	27 Mar
p	ns		0.001		< 0.001		0.084		< 0.001		
CV			6.34		6.15		17.35		2.24		
MSD			0.31		0.0020		0.39		7.2		
1996/97											
T 1	120.6		3.46	c	0.0159	d	0.48	c	219	a	08 Apr
T 2	129.4		3.98	b	0.0184	c	0.60	bc	214	ab	03 Apr
T 3	133.3		4.11	b	0.0197	bc	0.65	ab	210	b	30 Mar
T 4	140.6		4.47	a	0.0217	a	0.77	a	207	b	27 Mar
T 5	130.4		4.39	a	0.0210	ab	0.69	ab	209	b	29 Mar
p	ns		< 0.001		< 0.001		< 0.001		0.019		
CV			7.07		10.34		19.98		6.83		
MSD			0.22		0.0015		0.12		9.1		
1997/98											
T 1	232.5		5.06	b	0.0255	b	1.19		198		18 Mar
T 2	228.1		5.08	b	0.0259	ab	1.47		197		16 Mar
T 3	203.8		5.08	b	0.0260	ab	1.33		196		15 Mar
T 4	206.8		5.32	a	0.0268	a	1.39		198		18 Mar
T 5	212.2		5.33	a	0.0270	a	1.43		198		17 Mar
p	ns		0.009		0.033		ns		ns		
CV			5.65		5.63						
MSD			0.23		0.0013						
1998/99											
T 1	126.6		4.89		0.0242		0.77		203		22 Mar
T 2	125.0		4.70		0.0235		0.73		200		20 Mar
T 3	127.7		4.80		0.0240		0.77		201		20 Mar
T 4	125.9		4.80		0.0242		0.76		199		18 Mar
T 5	121.9		4.76		0.0238		0.73		200		20 Mar
p	ns		ns		ns		ns		ns		
1999/00											
T 1	124.6	b	6.06	a	0.0238	ab	0.73	b	256	a	14 May
T 2	179.2	a	5.36	b	0.0237	b	1.07	a	227	bc	14 Apr
T 3	167.0	a	5.29	b	0.0244	ab	1.02	a	217	bc	04 Apr
T 4	190.0	a	5.17	b	0.0242	ab	1.15	a	214	c	02 Apr
T 5	169.9	a	5.78	a	0.0253	a	1.06	a	230	b	17 Apr
p	0.002		< 0.001		0.087		0.004		< 0.001		
CV	21.05		7.63		9.03		22.28		5.08		
MSD	34.9		0.39		0.0016		0.24		13.0		

A (cm^3), *B* and *G* are the fitted variables. *Vmax:* maximum growth rate (cm^3 day^{-1}). *Tmax:* days elapsed since 1st September until *Vmax* is reached. Values are the means of 32 replicates per treatment. Values followed by the same letter are not significantly different according to the Tukey test at the 10% level. ns: not significantly different.

irrigated treatments. In these same seasons, T1 fruits always reached *Vmax* the latest. At the other extreme, T4 was the fastest to reach *Vmax* (some 2-6 weeks ahead of T1, and 3-5 days ahead of the other treatments, depending on the season).

Effects on yield

The effect of irrigation on annual yield was significant in four of the five seasons, as well as on the average yield over the five seasons. Only in 1998/99 —the second summer with exceptionally high rainfall— were no significant differences seen. For the entire experimental period, the mean yield of the T3 treatment (covering 100% ETc) was 31% greater than that of T1 (Table 4).

The linear and quadratic components (Table 4, LIN and CUAD) for each of the five seasons, as well as their means for all five years, were significantly different between treatments. In all cases, the quadratic component significantly increased the coefficient of determination for the relationship between yield and irrigation supplied. These results show that, despite the high annual rainfall of Uruguay, these variables are closely related (Fig. 2).

The maximum for each yield–irrigation function for the seasons 1995/96 to 1999/00 and for the means for the five years was obtained with 5.1, 4.8, 1.4, 2.0, 8.7 and 4.2 m^3 of irrigation water per tree per year (320, 303, 86, 127, 544 and 262 mm on a 16 m^2 area).

With respect to the total restriction of irrigation during phase II of fruit growth, contrast analysis of T3 and T5 showed there to be a significant reduction in yield in the three seasons in which rainfall was not greatly above normal. This effect was highly significant ($p < 0.001$) when the five years were taken as a whole, the mean T5 value showing a 10% reduction compared to the mean for T3.

With respect to the number of fruits, a clear biannual alternate bearing cycle was seen, with high and low numbers of fruits harvested in alternate years. The irrigation treatments significantly affected the number of fruits per tree only in seasons 1997/98 and 1999/00 (Table 4).

Taking the five seasons as a whole, T2 and T3 produced the highest mean number of fruits while T1 and T4 produced the lowest. T5 gave an intermediate value.

Mean fruit weight was also affected by alternate bearing. In years with high fruit loads, these fruits were small, while in years with low fruit loads they were large, independent of the irrigation treatment.

Significant differences were seen in the mean fruit weight achieved with the different treatments in the three seasons in which rainfall was not greatly above normal. Taking the five years together, significant differences in this variable were also seen. T4 fruits were the largest. This may be the result of a direct effect of irrigation, or the fact that T4 gave significantly fewer fruits than T3 or T2. T3 gave the second largest fruits despite the fact that this treatment, along with T2, led to the highest number of fruits. T1 gave even smaller fruits than those obtained with T5.

To quantify the effect of the different treatments on alternate bearing, the variable *I* proposed by Monselise and Goldshmidt (1982) was calculated as follows:

$$I = \frac{1}{n-1}\left(\frac{a_2 - a_1}{a_2 + a_1} + \frac{a_3 - a_2}{a_3 + a_2} + \ldots + \frac{a_{(n-1)} - a_n}{a_{(n-1)} + a_n}\right) * 100$$

where *n* is the number of years studied (5 in this case), and $a_1, a_2, \ldots, a_n$ the yield for each year.

The values obtained were: T1-28.9%, T2-17.5%, T3-16.0%, T4-21.1%, and T5-25.0%.

Effect on fruit category and market destination

The fruits produced were assigned to five different commercial categories depending on their diameter: Categories 1-5 corresponded to fruits of diameter > 76 mm, 72-76 mm, 69-72 mm, 63-69 mm, and < 63 mm respectively.

Category 5 fruits can only be used for the production of orange juice concentrate or other by-products; the price they can command is substantially lower than those of other categories, and the costs of their harvesting and transport to factories is only just covered. Category 4 fruits cannot be exported either, although they can command a somewhat higher price than category 5 fruits when sold on the Uruguayan market.

The different irrigation treatments had a direct effect on market destination percentages (i.e., depending on the commercial categories of the fruits produced) in three of the five seasons studied (Table 5). No effect was seen in the very rainy years of 1997/98 and 1998/99. However, in the former three seasons, T1 produced a larger number of category 5 fruits than any other treatment-approximately three times as many as

Table 4. Total yield, number of fruits harvested per tree, and mean fruit weight (for each of the five seasons plus means for the whole period)[1]

	1995-96		**1996-97**		**1997-98**		**1998-99**	**1999-00**		**Mean**	
Total yield (kg tree⁻¹)											
T 1	85	b	113	b	80	ab	180	66	c	105	b
T 2	121	a	129	a	95	a	190	131	b	133	a
T 3	133	a	133	a	84	ab	179	162	a	138	a
T 4	127	a	132	a	61	b	164	163	a	129	a
T 5	111	a	130	a	68	ab	180	131	b	124	a
p	< 0.001		0.016		0.052		ns	< 0.001		< 0.001	
CV	16.0		13.4		28.7			13.9		12.4	
MSD	22		15		29			28		15	
LIN	< 0.001		0.003		0.029		0.057	< 0.001		< 0.001	
QUAD	< 0.001		0.058		0.002		0.038	< 0.001		< 0.001	
T3-T5	0.003		ns		0.066		ns	< 0.001		0.015	
Number of fruits per tree											
T 1	491		1,084		401	ab	1,300	497	b	755	b
T 2	609		1,137		487	a	1,350	745	a	866	a
T 3	646		1,055		450	ab	1,257	923	a	866	a
T 4	584		1,012		302	b	1,134	838	a	774	b
T 5	559		1,096		346	ab	1,298	819	a	824	ab
p	ns		ns		0.029		ns	0.001		0.010	
CV					32			17.4		11.9	
MSD					148			209		87	
LIN	0.067		0.053		0.056		0.008	< 0.001		ns	
QUAD	0.022		ns		< 0.001		0.055	< 0.001		< 0.001	
T3-T5	0.100		ns		0.028		ns	0.052		ns	
Mean fruit weight (g)											
T 1	177	b	105	d	201		138	135	c	139	d
T 2	206	ab	114	cd	198		141	181	ab	154	bc
T 3	210	ab	126	ab	189		143	177	ab	160	b
T 4	223	a	132	a	208		145	196	a	167	a
T 5	204	ab	119	bc	198		139	162	b	151	c
p	0.078		< 0.001		ns		ns	< 0.001		< 0.001	
CV	11.3		5.7					9.2		3.8	
MSD	40		10					23		7	
LIN	< 0.001		< 0.001		ns		0.020	< 0.001		< 0.001	
QUAD	ns		ns		0.019		ns	0.005		0.029	
T3-T5	ns		0.022		ns		ns	0.014		< 0.001	

[1] Values are the means of 16 trees per treatment. Values followed by the same letter are not significantly different at the 10% level according to the Tukey test. p: level of statistical significance of variance analysis. CV: coefficient of variation. MSD: minimum significant difference in the Tukey test at the 10% level. LIN: level of significance of the linear correlation coefficient. QUAD: level of significance of the quadratic relationship. T3-T5: level of significance of the contrast analysis. ns: not significant.

produced by T3 in 1995/96 and 1996/97, and eight times as many as in the driest year (1999/00).

Citrus cultivation in Uruguay revolves around the export of high quality fresh fruit. Therefore, the yield of exportable fruit is more important than the overall yield. To determine which treatment gave the best results in this respect, the total fruit production of each plot in each year was examined to determine the percentage of fruits greater than 69 mm in diameter (categories 1, 2 and 3).

The different irrigation treatments very significantly ($p < 0.001$) affected the production of exportable fruit in three of the five study seasons as well as the means for the period as a whole. Only in 1998/99 (the second

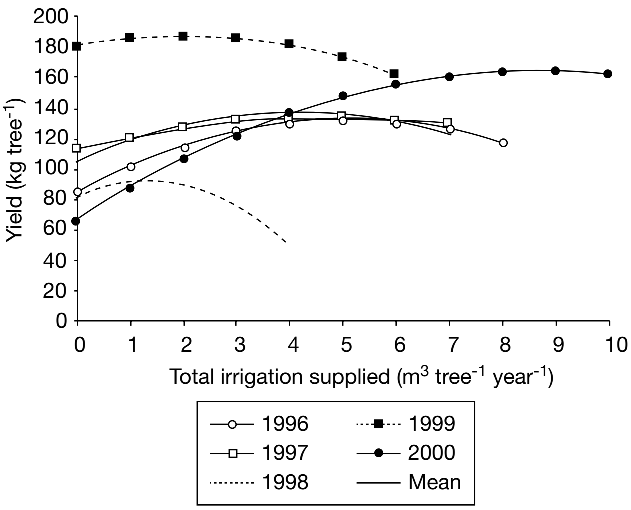

Figure 2. Response to total irrigation water supplied per year (for each season and mean for all seasons).

year with summer rainfall well above the mean) was no effect observed ($p > 0.10$). In 1997/98, the effect was only significant at $p < 0.08$ and was therefore not clearly related to differences in irrigation supply (Table 6).

Taking the five years as a whole (here it should be remembered that one was moderately dry, one very dry, one had mean rainfall, and two were very rainy), T3 and T4 gave the maximum amount of exportable fruit-both close to 37 t ha^{-1}; T5 produced a significant 22% less exportable fruit, mainly because of the stress-induced reduction in the size of the fruits; T2 yielded 86% of the amount of exportable fruit produced by T3, its efficacy was therefore intermediate; T1 produced the fewest exportable fruits, only some 50% of the production achieved with T3: in other words, irrigation that covered 100% ETc led to 17.5 t ha^{-1} $year^{-1}$ more exportable fruits than no irrigation at all.

The function between yield of exportable size fruit and the irrigation supply for each year were analysed. For the three seasons in which rainfall was not greatly above normal, and for the five years as a whole, the quadratic relationship between these variables was significant. In 1996/97, their relationship was linear. Only in the wettest season (1998/99) was no significant relationship seen (Table 6).

The maximum for the above mentioned function in 1995/96, 1997/98 and 1999/00 (the years when the response was quadratic), and for the entire study period as a whole, was achieved with irrigation doses of 5.6, 1.4, 10.4 and 5.5 m^3 per tree (349, 87, 652 and 343 mm respectively on a 16 m^2 area).

Comparing these values with those of Figure 2 shows that to obtain the maximum yield of exportable fruit, more irrigation is necessary than that required simply to achieve maximum production. In 1996/97 the response was linear, therefore the range of irrigation doses used led to no negative effects in this respect.

With respect to cutting the supply of irrigation water during phase II of fruit growth, contrast analysis of T3 and T5 shows that in the three drier years this significantly reduced the production of exportable fruit. Taking the five seasons as a whole, this effect remained very significant ($p = 0.008$), leading to a reduction of 22% exportable fruit compared to that obtained with T3. This reduction is much greater than that seen with respect to overall yield.

Effects on fruit quality

Irrigation treatment significantly affected peal thickness in two of the four years in which this was measured, as well as the quantity of juice obtained in one of these four years (data not shown). The Brix value and acidity were affected in three of these four years: both tended to decrease as the amount of water supplied increased. The maturity index was therefore never affected. Taking the study period as a whole, only the Brix value and acidity were affected by irrigation. The former fell from 10.2 in T1 to 9.7 in T4 (the most irrigated treatment), while acidity fell from 1.43 to 1.32% in these same treatments.

Discussion

Several authors report that increasing irrigation water supply increases vegetative growth, both in areas of scant rainfall (Hilgeman and Sharp, 1970; Metochis, 1989; Castel, 1993; Eliades, 1994; Chartzoulakis *et al.,* 1999) and heavier rainfall (Koo, 1969, 1979; Koo and Hurner, 1969; Fouqué, 1980). Wiegand and Swanson (1982b) found the increase in tree trunk circumference to be almost linearly related to the total amount of water (rainfall plus irrigation) supplied. This agrees with the present results, which show a very significant linear relationship between irrigation dose and trunk section or crown volume.

The fruit growth results for 1999/00 show that moderate water stress (T5: detaining irrigation and

Table 5. Fruit size distribution by category (CAT). Values are percentages of fruit on each category with respect to total kg of fruit produced on each of the five seasons. [1] CAT1, fruit diameter > 76 mm; CAT2, 72-76 mm; CAT3, 69-72 mm; CAT4, 63-69 mm; and CAT5, < 63 mm

	CAT 1		CAT 2		CAT 3		CAT 4		CAT 5	
1995/96										
T 1	24.2	b	17.1		33.5	a	21.1	a	4.2	a
T 2	42.9	ab	18.1		25.8	ab	11.9	ab	1.3	b
T 3	49.4	ab	19.0		20.3	ab	10.0	ab	1.3	b
T 4	57.2	a	18.3		17.4	b	6.9	b	0.3	b
T 5	50.3	ab	21.0		20.8	b	7.5	b	0.5	b
p	0.064		ns		0.052		0.051		0.005	
CV	32.59				29.97		55.47		80.73	
MSD	28.6				13.8		12.5		2.4	
1996/97										
T 1	0.2		0.0	c	4.7	c	27.7	b	67.5	a
T 2	0.7		1.5	bc	10.5	c	42.0	a	45.2	b
T 3	2.3		4.1	ab	24.8	ab	45.5	a	23.3	c
T 4	2.9		7.4	a	28.6	a	37.7	ab	23.4	c
T 5	0.9		2.8	bc	21.1	ab	41.6	a	33.6	bc
p	ns		0.002		< 0.001		0.005		< 0.001	
CV			62.69		20.19		13.72		16.71	
MSD			3.9		7.1		10.5		12.6	
1997/98										
T 1	60.0		17.1		15.8		6.4		0.7	
T 2	62.9		18.4		13.5		4.6		0.6	
T 3	45.2		23.6		23.0		7.3		0.9	
T 4	58.3		17.9		19.1		4.3		0.5	
T 5	49.0		22.2		21.4		6.8		0.7	
p	ns		ns		ns		ns		ns	
1998/99										
T 1	3.1		6.5		25.4		37.7		27.3	
T 2	2.2		6.5		28.5		39.2		23.6	
T 3	4.6		8.9		28.7		37.0		20.8	
T 4	6.0		5.7		30.8		39.7		17.8	
T 5	3.6		5.5		27.2		40.3		23.4	
p	ns		ns		ns		ns		ns	
1999/00										
T 1	5.8	c	7.4	b	22.9	b	32.3	a	31.6	a
T 2	26.7	b	15.2	ab	33.1	ab	20.5	ab	4.4	b
T 3	24.6	b	22.3	a	33.6	ab	16.0	bc	3.7	b
T 4	48.5	a	16.7	ab	25.0	ab	7.9	c	1.9	b
T 5	11.1	bc	13.5	ab	36.2	a	28.6	a	10.7	b
p	< 0.001		0.015		0.027		< 0.001		< 0.001	
CV	39.10		32.87		19.39		29.45		55.74	
MSD	17.9		9.7		11.5		12.2		11.4	

[1] Values are the means of four replicates per treatment. Values followed by the same letter are not significantly different at the 10% level according to the Tukey test. p: level of statistical significance of variance analysis. CV: coefficient of variation. MSD: minimum significant difference in the Tukey test at the 10% level. ns: not significant.

Table 6. Yield of exportable fruit (> 69 mm in diameter, categories 1, 2 and 3) for each year of the study and means for the whole study period[1]

	Yield of exportable fruit (kg tree^{-1})									
	1995-96		1996-97		1997-98		1998-99	1999-00		Mean	
T 1	63	b	6	c	74	ab	62	25	c	46	c
T 2	105	a	16	c	90	a	70	96	b	76	ab
T 3	117	a	41	ab	77	ab	75	130	a	88	a
T 4	117	a	51	a	58	b	70	147	a	89	a
T 5	103	a	32	b	64	ab	65	80	b	69	b
p	< 0.001		< 0.001		0.080		ns	< 0.001		< 0.001	
CV	10.3		23.6		21.0			15.8		11.6	
MSD	20		14		30			30		17	
LIN	< 0.001		< 0.001		ns		ns	< 0.001		< 0.001	
QUAD	< 0.001		ns		0.022		ns	0.001		0.002	
T3-T5	0.069		0.089		ns		ns	< 0.001		0.008	

[1] Values are the means of four replicates per treatment. Values followed by the same letter are not significantly different at the 10% level according to the Tukey test. p: level of statistical significance of variance analysis. CV: coefficient of variation. MSD: minimum significant difference in the Tukey test at the 10% level. LIN: level of significance of the linear correlation coefficient. QUAD: level of significance of the quadratic relationship. T3-T5: level of significance of the contrast analysis. ns: not significant.

then restarting it) allows the fruits to recover the size they would have reached if irrigation had been continuous, whereas more severe stress that prolongs the detainment of growth (T1) prevents fruits from attaining their potential size. González Altozano and Castel (1999) found that summer water stress led to a reduction in fruit growth rates, but that growth was accelerated when the normal provision of water was resumed. The final size of the fruits at harvest was therefore not greatly affected. The same results were obtained with the present T5 treatment. Goldhamer and Salinas (2000) indicated that the increased growth rate on resumption of the water supply is likely to be due to the rehydration of the fruits. However, the maintenance of such high rates (for several weeks in the present study) suggests that there is also a rapid accumulation of dry matter, and that this is at least partially responsible for the phenomenon. Guardiola (1992) indicates that reduced fruit growth caused by a short term lack of water has no effect on the final size achieved. However, prolonged water deficits can affect this: Mostert (1999; cited by du Plessis, 2000) found that after an almost negative fruit growth rate during phase II caused by water stress, resuming the water supply led to final sizes smaller than controls (even though the growth rate increased dramatically). This was seen in the present T1 treatment, especially in the 1999/00 season.

Working in Texas, Wiegand and Swanson (1984) determined the growth curves and growth rates of Valencia oranges (very similar to those of the present study in terms of slope, the maximum values obtained, and the times when these were obtained). However, they found that 85% of the total variation in fruit size was reached by 1st August (1st February in the southern hemisphere); in the present study, significant differences were not seen until early April in the 1996/97 season.

Hales *et al.* (1967) studied the correlation between fruit growth rate and ten environmental variables, of which the only one found to be significant ($p < 0.01$) was soil water tension. Braun *et al.* (1989) assessed the use of physiological indicators of water stress for use in citrus irrigation programs and concluded that fruit growth was the most reliable. The present results also show that the measurement of fruit growth is a sensitive indicator of the need to irrigate. However, for this methodology to be valid, a large number of fruits would have to be measured regularly, which might be impractical at a commercial level.

Significant differences in maximum potential fruit size were only seen between treatments in one season, while maximum growth rates and the dates on which these were reached were significantly different in three of the five years studied. This indicates that these are the factors of the growth curve most directly affected by irrigation.

Irrigation has a beneficial effect on citrus fruit yield in all of the main production areas of the world where rainfall is insufficient or almost absent, e.g., in

Valencia (Castel and Buj, 1993), Israel (Shalhevet and Levy, 1990), Arizona (Hilgeman and Sharp, 1970), Texas (Wiegand and Swanson, 1982a) and California (Ali and Lovatt, 1996). For this last location, Goldhamer and Salinas (2000) report a rather strong linear relationship ($r^2 = 0.56$) between overall yield and the amount of water provided. However, even in the more rainy production areas where fruit can be cultivated without extra water, irrigation is still beneficial. Constantin *et al.* (1975), who worked in Louisiana, and Koo (1979), who undertook research in Florida, report increased yields of 23% and 29% respectively. In Uruguay, García Petillo (1995), who worked on Valencia oranges and for a mean of four or five years per experiment, reports irrigated trees to provide yields some 36% higher than those obtained by non-irrigated cultivation. Further, Goñi and Otero (2000) report increases of 27% in marketable fruit. These results are similar to the 31% increase obtained in the present work, but rather less than the 91% increase obtained in exportable fruit yield (Table 6).

Ginestar and Castel (1996) who worked with young clementines, report a period of stress similar to that induced by T5 in the present study to be the most critical in the reduction of yields.

Alternate bearing in Valencia orange trees is well known (Wiegand and Swanson, 1982a). The values calculated for variable *I* infer that irrigation (T3) reduces alternate bearing compared to non-irrigated cultivation (T1). Similarly, moderate stress over the whole season (T2) reduces its effects compared to shorter but more intense stress (T5). The beneficial effect of irrigation on alternate bearing is not well documented, although Monselise and Goldschmidt (1982) mention that drought might effect it.

The low number of fruits produced in T1 in the last season, and the low mean number for the five years as a whole, is owed to low crown volume (analysed above). The same effect was reported by Koo and Hurner (1969). However, this was not seen for T4; these trees showed almost the largest crown volumes and the greatest increase in trunk and crown size. There is therefore an antagonistic effect between vegetative growth and fruit production.

Some authors (Hilgeman and Sharp, 1970; Metochis, 1989; Ali and Lovatt, 1996; Ginestar and Castel, 1996; Eliades, 1994; Chartzoulakis *et al.,* 1999) reported irrigation to increase the number of fruits produced, although Wiegand and Swanson (1982a) and Castel and Buj (1993) reported no important effect in this respect.

The results obtained confirm reports made by other authors (Wiegand and Swanson, 1982a; García Petillo, 1995) that fruit size is the production component most affected by irrigation. T2 fruits were intermediate in size between those of T3 and T5, which agrees with the results of González Altozano and Castel (1999) who indicate that moderate, permanent drought is less detrimental to final fruit size than shorter periods of more intense drought.

With regard to fruit quality, the majority of published results agree with those of the present study in that the main effect of increasing the amount of irrigation water is a simultaneous reduction of the Brix value and acidity (the maturity index is therefore not affected) (Koo and Sites, 1955; Koo, 1969; Hilgeman and Sharp, 1970; Levy *et al.,* 1979; Cruse *et al.,* 1982; Koo and Smajstrla, 1984 and 1985; Metochis, 1989; Castel and Buj, 1990; Eliades, 1994). Hockema and Etxeberría (2001) found increased acid and soluble solid concentrations in fruits suffering water stress, as well as an increase in the activity of the enzyme sucrose synthase and a reduction in the pH of the juice. They concluded the activity of this enzyme and the vacuolar pH to be factors controlling the accumulation of photoassimilates in fruits under conditions that increase the sink strength*,* caused by the induction of moderate water stress.

In T3 (100% ETc covered), between 2.3 and 5.6 m^3 water were supplied every year (mean 4.2 m^3 per tree per year, i.e., 1750 m^3 ha^{-1}). The maximum doses in this treatment were almost 70 L $tree^{-1}$ day^{-1}, which, in fact, did not completely cover maximum daily ETc needs. The total volume supplied was comparable to those recommended for Florida (IFAS, no date), less than that used in areas of little rainfall (Wiegand and Swanson, 1982a; Domingo *et al.,* 1996) and very much less than that used in arid areas (Hilgeman and Sharp, 1970; Levy *et al.,* 1979). The total volume of irrigation water supplied in a season was, therefore, very dependent on rainfall. However, the maximum daily dose does not depend on rainfall and is comparable to that estimated by Pizarro Checa (1989) and greater than that applied by Domingo *et al.* (1996). Comparison of the mean effects of each treatment over the five years of the study with those of T3 (Table 7) shows that non-irrigated cultivation (T1) restricts vegetative growth (both in terms of trunk section and crown volume). The overall yield of T1 trees was reduced, both in terms of number of fruits and mean fruit weight (T1 trees produced more non-exportable fruits, and only half as

Table 7. Responses of the main vegetative and productive variables under the different irrigation regimens, relative to those of T3 trees (irrigated at 100% ETc), for the entire study period

	Trunk[a]	Canopy[b]	Yield[c]	Number[d]	Weight[e]	Export[f]	Efficiency[g]
T1	71	64	76	87	87	52	80
T2	87	86	96	100	96	86	97
T3	100	100	100	100	100	100	100
T4	117	109	93	89	104	100	93
T5	95	113	90	95	94	78	92

[a] Increase in trunk cross section. [b] Increase in canopy volume. [c] Yield. [d] Number of fruits. [e] Mean fruit weight. [f] Exportable fruit yield. [g] Productive efficiency.

many fruits of exportable size as those produced by T3 trees). Productive efficiency was also reduced.

Restricting irrigation to cover 50% of ETc over the whole season (T2) led to no significant differences in terms of vegetative growth, although a clear tendency towards the trees being smaller was seen (smaller increase in crown volume and trunk section). Overall yield was significantly lower only in the driest season; the mean for the five years as a whole showed only a 4% decrease compared to T3. This was because the number of fruits produced was not reduced and their mean weight was lower only in the driest seasons, not over the five years as a whole. The exportable fruit yield was significantly down in 1996-97 and 1999-00, and a trend towards reduction (14%) was seen for the five years as a whole. Productive efficiency, however, was not affected. This treatment used a mean 738 m^3 ha^{-1} $year^{-1}$ less water than the T3 regimen. Uruguay has abundant water resources, but in certain regions they are limited- and this affects many orchards. Under these conditions, the T2 regimen might be a reasonable alternative.

These results agree with those of Mostert (1999; cited by du Plessis, 2000), who, in South Africa, found that optimum results could only be obtained by irrigating for the entire season and covering the evapotranspiration losses of the crop. They also report that if only 60% of annual water needs can be met, irrigation should still be supplied throughout the season at smaller doses. In principle, this does not agree with the existence of critical periods widely reported in the literature. Nonetheless, it does reflect one of the main differences between arid and damp areas: in the latter, irrigation is complementary, and its reduction may not create irreversible stress damage. This behaviour was reported in Uruguay by García Petillo (1995).

Excess irrigation over the entire season (T4) significantly increased the size of the trees. There was a trend towards a fall in yield owing to the lower number of fruits produced, but more of these belonged to category 1 in the driest season. The mean production of exportable fruit was, however, not affected. Productive efficiency was lower in two seasons and there was a trend for the mean to fall. The resource partitioning was reduced and trees began to show more vegetative growth and less fruit production. Therefore, even when water is unlimited, it would not seem wise to irrigate excessively.

Cutting off the water supply in summer (mid December-mid February,T5) led to a trend towards greater crown volume since the reduction in growth was more than compensated for once the water supply was reconnected. Although the number of fruits remained the same, they were smaller: more fell into the poorest categories. Exportable fruit production was down by 22% compared to T3 (much more than total yield). Productive efficiency was reduced. The resource partitioning was not significantly affected though there was a trend towards a reduction. The water saving made by applying this treatment was 547 m^3 ha^{-1} $year^{-1}$, therefore not only was production negatively affected but less water was saved than with the T2 treatment. There is therefore little justification for the commercial use of this irrigation regimen.

In conclusion, irrigation that covers 100% of the trees evapotranspiration needs gives the best results. However, where water supplies are limited, irrigating to cover 50% of needs is a strategy worth considering. In the present study, the latter regimen led to the production of smaller trees, but these provided yields similar to those of trees whose ETc was completely covered and they produced only 14% fewer exportable fruits.

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