Journal of Agricultural Science (2014), **152**, 177–187. © Cambridge University Press 2013
doi:10.1017/S0021859612000998

CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

The effect of temperature, water input and length of growing season on sugar beet yield in five locations in Greece

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(*Received 17 February 2012; revised 17 November 2012; accepted 30 November 2012; first published online 7 January 2013*)

SUMMARY

From 1999 to 2006, 36 field experiments were conducted in five sugar beet growing areas in Greece (Larissa, Plati, Serres, Xanthi and Orestiada) to monitor yield. Locations differed significantly regarding thermal variables during the growing season with Xanthi having the most favourable thermal conditions (T_{max}, average daily maximum temperature; T_{mean}, average daily mean temperature; GDD, growing degree days) for sugar beet growth. From early June to the end of the harvesting campaign, successive harvests were conducted. Over the years, fresh root weight and sugar yield at the last harvest of the season (FRW_{LH}, SY_{LH}) did not differ significantly among locations. Also, there were no significant differences among locations regarding GDD for maximum FRW and SY (GDD_{MFRW}, GDD_{MSY}), with the means over location estimated at 2639·9 and 2792·5 °C, respectively. Days after seeding (DAS) necessary for maximum yield (DAS_{MFRW}, DAS_{MSY}, respectively) differed among locations, with the longest period (DAS_{MFRW} 206·4 days, DAS_{MSY}: 204·5 days) occurring in the northernmost location (Orestiada). Means for DAS_{MFRW} and DAS_{MSY} at the five locations were estimated at 190·4 and 188·9·days, respectively. Excluding Xanthi and combining the remaining locations, FRW_{LH} and SY_{LH} were negatively correlated with the average temperatures (T_{mean}, T_{max} and T_{min}, daily minimum temperature) over the growing season. The opposite was evident for Xanthi where sugar beet was grown under sub-optimal temperatures. The optimum mean T_{max} of the five locations was estimated at 25·5 and 25·1 °C for FRW_{LH} and SY_{LH}, respectively. Elongation of the growing season, by means of early sowing, would increase yield by decreasing average temperatures (T_{mean}, T_{max}) over the growing season in locations with the highest recorded temperatures (Larissa, Plati, Serres and Orestiada). In Xanthi, the projected temperature increase, as a result of climate change, is expected to have a positive effect on yields.

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) provides *c*. 0·35 of the world white sugar (Hergert 2010). In Europe, sugar beet is grown on diverse soils and under various climatic conditions, which determine yield (Märländer *et al*. 2003; Hoffmann *et al*. 2009) and result in low yield stability (Chloupek *et al*. 2004). Sugar beet growers aim for both high fresh root weight (FRW) and sucrose content (SC,% in fresh roots) that produce high sugar yield (SY).

In Greece, sugar beet is grown in the central (Thessaly) and northern (Macedonia and Thrace) parts of the country where erratic and low rainfall during summer is the main constraint on productivity (Morillo-Velarde & Ober 2006). Thus, the sugar beet crop is irrigated and irrigation water needs are estimated at 200–550 mm, descending from the northern to central areas (Analogides 1993). However, sugar beet is mostly grown under water deficit conditions due to irrigation water shortages, mainly in central Greece.

Under Mediterranean conditions, water shortages during the summer are accompanied by air temperatures much higher than the optimum (25 °C) for sugar beet growth and yield (D'Ambrosio *et al*. 2006; Kenter *et al*. 2006). In Greece, maximum air temperatures higher than 30–35 °C are common from June till mid-September. High temperatures decrease photosynthetic rate and increase photorespiration, thus

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Table 1. *Comparison of thermal variables and rain during the PGS (March–mid November) from 1999 to 2006. The CV% is given in parenthesis*

	GDD_{PGS} (°C)	$T_{meanPGS}$ (°C)	T_{maxPGS} (°C)	T_{minPGS} (°C)	ΔT_{PGS} (°C)	CT_{25PGS} (°C)	$Rain_{PGS}$ (mm)
Larissa 39° 33′N, 22° 27′E, 93 m asl clay	3322·5 (3)	19·2 (3)	25·7 (3)	12·7 (3)	13·1 (6)	1237·9 (15)	264·5 (34)
Plati 40° 35′N, 22° 33′E, 3 m asl clay	3424·4 (2)	18·7 (2)	25·3 (3)	13·2 (3)	12·1 (7)	976·8 (15)	363·3 (32)
Serres 41° 01′N, 23° 34′E, 23 m asl clay	3484·3 (6)	19·3 (5)	25·1 (2)	13·8 (10)	11·3 (9)	1044·3 (17)	322·6 (33)
Xanthi 41° 05′N, 24° 50′E, 36 m asl sandy loam	3564·3 (2)	18·4 (2)	22·8 (2)	13·9 (3)	8·9 (4)	483·3 (19)	311·3 (47)
Orestiada 41° 30′N, 26° 32′E, 20 m asl clay	3366·4 (3)	19·3 (3)	23·5 (2)	12·9 (4)	10·6 (7)	758·2 (18)	271·9 (51)

GDD, growing degree days; T_{mean}, average mean temperature; T_{max}, average maximum temperature; T_{min}, average minimum temperature; ΔT, $T_{max} - T_{min}$; CT_{25}, cumulative temperatures above 25 °C.

retarding growth (D'Ambrosio *et al.* 2006; Tsialtas & Maslaris 2008). Irrigation could potentially compensate for the negative effects of thermal stress on plant growth (Mahan *et al.* 1995) but it offers only a partial alleviation of high temperature stress in sugar beet (Qi & Jaggard 2006).

The length of growing season affects yield, with better yields from crops sown early (Durrant *et al.* 1993; Richter *et al.* 2006). As a biennial species, sugar beet grows as long as the growing season lasts (Launay *et al.* 2009). The putative growing season (PGS) of sugar beet in Greece extends from early March to mid-November. Plants sown early, in February, can be damaged by late-season frosts, while autumn rainfall restricts the use of harvesters on heavy, mineral soils and therefore inhibits late harvesting. Moreover, late in autumn, yield increments decline due to low temperatures and irradiance interception (Scott *et al.* 1973). Climate change, with increasing summer temperatures and decreasing rainfall, is likely to affect crop development, change agronomic practices such as sowing date and is expected to affect sugar beet growth and yield even in central and northern Europe (Jones *et al.* 2003; Estrella *et al.* 2007; Kaukoranta & Hakala 2008).

GDD (the sum of the daily maximum (T_{max}) and minimum (T_{min}) air temperatures compared with a base temperature) is a thermal index related to plant development, yield and maturity in determinate crops (Swan *et al.* 1987; Klepper *et al.* 1988). In sugar beet, a crop without a specific phenological stage of maturity, GDD have been related to growth stages, i.e. canopy closure and root growth (Kenter *et al.* 2006; Bellin *et al.* 2007) but they have not been used for harvest time determination.

Factory campaign planning and length are very important for the profitable operation of sugar industries. Monitoring, by periodic harvests in commercial fields, is commonly used to assess seasonal yield trends but it is both money- and time-consuming. For those reasons and in order to simulate climate change effects on sugar beet, yield forecasting models based on weather and soil parameters (nutrients and soil water availability) have been evolved (Spitters *et al.* 1990; Qi *et al.* 2005; Richter *et al.* 2006; Jaggard *et al.* 2007).

Greece is characterized by its fragmented terrain, which affects pedo-climatic conditions and leads to significant variation of GDD climatology in the main agricultural areas (Matzarakis *et al.* 2007). The aims of the present work were to: (a) define the optimum harvest time, in terms of DAS (DAS_{MFRW}, DAS_{MSY}) and GDD (GDD_{MFRW}, GDD_{MSY}), of sugar beet grown in the main growing areas and (b) relate yields of the last harvest of season (FRW_{LH}, SY_{LH}) with climatic variables (temperatures and water availability).

MATERIALS AND METHODS

Locations and experimentation

Field experiments, aimed at monitoring yield formation during the growing season, were conducted from 1999 to 2006, in the main sugar beet growing areas in central (Larissa) and northern Greece (Plati, Serres, Xanthi and Orestiada). Table 1 presents information on soil type and climatic conditions during the PGS for each location.

Randomized complete-block design experiments with six replications for each harvest were sown at the time when *c.* 0·50 of growers' fields had been sown in each location and growing season. Plots consisted of six rows (8 m long), 0·45–0·50 m apart, where seeds were drilled mechanically at 0·10–0·15 m spacing in the row. The cultivars used (Corsica, Creta, Dorothea, Palma, Rival and Rizor) were rhizomania-tolerant and well adapted to each location. Fertilization was applied as both basal (110 kg N/ha, 90 kg P/ha and 265 kg K/ha) and top-dressing (40 kg N/ha). Supplemental irrigation was provided according to irrigation water availability and standard practices applied by growers in each location. Water input (WI) was calculated as the sum of rain and irrigation water applied to each experiment. Chemical spraying and hand weeding were employed to suppress the weeds. Full protection against insects, *Cercospora* and powdery mildew was provided by spraying.

Beginning in early June and depending on year and location, 7–12 successive harvests were conducted during the growing season and completed by the end of the harvest campaign. In each harvest, three internal rows of 7 m long, for each of six plots were harvested by hand (10·5 m^2 harvested area). Sugar beet plants were topped by hand, number of roots was counted and FRW per plot was recorded. In all cases, root number was higher than 75 000 roots/ha. A random sub-sample of 25–30 roots per plot was transferred to the factory's tare house for root quality assessment (SC,% in fresh roots, K, Na and α-amino N concentration). Measurements were conducted using a Venema automatic beet laboratory system (Venema Automation b.v., Groningen, The Netherlands) connected to a BETALYSER® analysing system (Dr Wolfgang Kernchen GmbH, Seelze, Germany). SY per plot was calculated as the product of FRW and SC. Yields at the last harvest (FRW_{LH}, SY_{LH}) were used for comparisons between locations and for plotting against thermal and water variables recorded over the growing season.

Thermal variable computation and estimation of harvest time for maximum yield

Tables 1 and 2 present thermal and water variables for the five locations during the putative and the actual growing seasons (PGS, March to mid-November and AGS, seeding date to last harvest, respectively). The estimation of the variables for both PGS and AGS was conducted to indicate the gap between the climatic potential and the actually exploited fraction of this potential in each location.

Hourly recorded data of rain, air maximum (T_{max}) and minimum (T_{min}) temperatures were obtained from the nearest meteorological station, which was located within 4–10 km of each experimental site.

Calculation of the GDD (°C) was according to Zalom *et al.* (1983):

$$GDD = \Sigma(T_i - T_{base}) \quad (1)$$

where T_i is the mean daily air temperature (T_{mean}), estimated by T_{max} and T_{min} as

$$[(T_{max} + T_{min})/2] \quad (2)$$

If $T_{max} > 25$ °C, $T_i = [25 - (T_{max} - 25) + T_{min}]/2$. T_{base} was set to 3 °C, below which leaf expansion rate is zero (Milford *et al.* 1985).

Cumulative temperatures above the threshold temperature of 25 °C (CT_{25}) were calculated, for a given time period, as

$$CT_{25} = \Sigma(T_{max} - 25) \quad (3)$$

The difference between T_{max} and T_{min} (ΔT) was calculated as

$$\Delta T = T_{max} - T_{min} \quad (4)$$

In each experiment, GDD were summed for each harvest occasion during the AGS. Yield data (FRW, SY), after log-transformation, were plotted against DAS and GDD. Transformation rendered variability over time more homogeneously (Mamolos 2006). The best-fitted curves (a total of 72) were quadratic functions, highly significant ($P < 0·001$) with $R^2 \geqslant 0·92$. For each experiment, the first derivative (linear function) of the best-fitted, quadratic functions was estimated. The solution of the linear function, when *y* was set equal to zero, gave the estimation of optimal harvest time in terms of DAS (DAS_{MFRW}, DAS_{MSY}) or GDD (GDD_{MFRW}, GDD_{MSY}), respectively (Snedecor & Cochran 1989).

Statistical analysis

Thermal and water variables during PGS (Table 1) were subjected to one-way ANOVA with location as the main factor and eight replications (years were set as replications).

Analysis of FRW_{LH}, SY_{LH}, AGS length (DAS_{AGS}), thermal (T_{minAGS}, T_{maxAGS}, $T_{meanAGS}$, ΔT_{AGS}, GDD_{AGS}, CT_{25AGS}) and water ($Rain_{AGS}$, $Irrigation_{AGS}$, WI_{AGS}) variables (Tables 2 and 3) was done by one-way ANOVA with location as the main factor and with unequal replications (Snedecor & Cochran 1989). The same analysis was conducted for DAS_{MFRW}, DAS_{MSY},

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Table 2. *Comparison of thermal and water variables during the AGS (from sowing to last harvest date) in each location. The CV% is given in parenthesis. n is the number of years for which experimentation was conducted in each location*

	DAS_{AGS} (days)	GDD_{AGS} (°C)	$T_{meanAGS}$ (°C)	T_{maxAGS} (°C)	T_{minAGS} (°C)	ΔT_{AGS} (°C)	CT_{25AGS} (°C)	$Rain_{AGS}$ (mm)	$Irrigation_{AGS}$ (mm)	WI_{AGS} (mm)
Larissa ($n=6$)	234·0 (3)	3140·4 (4)	20·0 (3)	26·6 (3)	13·5 (2)	13·1 (4)	1183·7 (14)	262·1 (31)	273·7 (45)	535·8 (21)
Plati ($n=8$)	205·3 (10)	2933·4 (6)	20·5 (5)	27·2 (4)	14·8 (7)	12·5 (6)	976·8 (15)	281·5 (23)	263·9 (24)	545·4 (18)
Serres ($n=7$)	215·6 (7)	3098·2 (9)	20·8 (3)	26·7 (3)	15·1 (6)	11·7 (9)	1037·8 (18)	280·3 (34)	340·0 (17)	620·2 (15)
Xanthi ($n=7$)	217·9 (4)	3267·1 (4)	20·1 (3)	24·5 (2)	15·4 (3)	9·1 (4)	505·8 (14)	254·1 (53)	381·4 (11)	635·6 (22)
Orestiada ($n=8$)	230·1 (9)	3134·1 (5)	20·4 (5)	24·7 (3)	13·8 (9)	10·9 (8)	758·2 (18)	255·3 (23)	347·5 (15)	602·8 (9)

GDD, growing degree days; T_{mean}, average mean temperature; T_{max}, average maximum temperature; T_{min}, average minimum temperature; ΔT, $T_{max}-T_{min}$; CT_{25}, cumulative temperatures above 25 °C; WI, water input (rain + irrigation).

GDD_{MFRW} and GDD_{MSY}. This analysis was followed because the experiments were conducted for different numbers of years in each location (Table 2).

Means were compared with Duncan's multiple range test at $P<0{\cdot}05$. Best-fitted curves and statistical analysis were performed using SPSS software (version 16.0, SPSS Inc., IL, USA).

RESULTS

Thermal and water variables during PGS and AGS

Locations differed significantly regarding thermal and water variables during both PGS and AGS (Tables 1 and 2). Location ranking according to the climatic variables diverged between PGS and AGS. Thus, the southernmost location (Larissa) had the lowest GDD_{PGS} and the highest T_{maxPGS}, ΔT_{PGS} and CT_{25PGS}. The opposite was evident for Xanthi (Table 1). Despite a difference of *c.* 100 mm between the lowest (Larissa) and the highest (Plati) values recorded, $Rain_{PGS}$ did not differ significantly between locations. This was due to the high variation between years, evident mainly in the northern locations (Xanthi and Orestiada) and confirmed by the high coefficients of variation (CVs) (Table 1).

Regarding AGS, Plati showed the lowest GDD_{AGS}. Locations did not differ for $T_{meanAGS}$, while the northern locations (Xanthi and Orestiada) had the lowest T_{maxAGS} and CT_{25AGS}. The highest T_{minAGS} was recorded in Larissa and Orestiada. Larissa and Plati had the highest ΔT_{AGS}, while the lowest was found in Xanthi (Table 2). Locations did not differ significantly for $Rain_{AGS}$ and WI_{AGS} ($Rain_{AGS}$ + $Irrigation_{AGS}$). Based on CVs, Xanthi had the less stable $Rain_{AGS}$ but the most stable $Irrigation_{AGS}$, while Larissa had the less stable inputs. Larissa and Xanthi showed the most variable WI_{AGS} (Table 2).

AGS length, yields (FRW_{LH}, SY_{LH}) and optimal harvest time

The southernmost (Larissa) and the northernmost (Orestiada) locations had longer-lasting DAS_{AGS} (234·0 and 230·1 days, respectively). Plati had the shortest DAS_{AGS} (205·3 days) showing the highest variability (Table 2).

Using combined data over the years, FRW_{LH} and SY_{LH} did not differ significantly between locations (Table 3): FRW_{LH} ranged from 97·4 t/ha in Larissa up to 106·0 t/ha in Orestiada, while SY_{LH} ranged from

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Table 3. *Mean comparisons of time of yield (FRW, SY) maxima achievement in terms of DAS (DAS_{MFRW}, DAS_{MSY}) and GDD (GDD_{MFRW}, GDD_{MSY}), FRW and SY at the last harvest of the season (FRW_{LH}, SY_{LH}) in the five locations. CV% is given in parenthesis. n is the number of years for which experimentation was conducted in each location*

	DAS_{MFRW} (days)	DAS_{MSY} (days)	GDD_{MFRW} (°C)	GDD_{MSY} (°C)	FRW_{LH} (t/ha)	SY_{LH} (t/ha)
Larissa ($n=6$)	193·3 (7)	185·2 (6)	2597·2 (10)	2715·3 (12)	97·4 (17)	14·0 (15)
Plati ($n=8$)	178·1 (10)	181·7 (11)	2671·9 (14)	2724·0 (9)	101·7 (19)	13·3 (24)
Serres ($n=7$)	189·6 (12)	187·3 (11)	2595·2 (13)	2898·8 (12)	101·9 (13)	14·8 (18)
Xanthi ($n=7$)	184·1 (3)	186·0 (6)	2648·8 (15)	2952·4 (12)	101·2 (12)	14·7 (12)
Orestiada ($n=8$)	206·4 (10)	204·5 (6)	2686·5 (15)	2671·9 (5)	106·0 (9)	15·6 (12)
Average	190·4	188·9	2639·9	2792·5	101·6	14·5

13·3 t/ha in Plati up to 15·6 t/ha in Orestiada. Yields were less stable in the southern locations (Larissa, Plati and Serres) compared with the northern (Xanthi and Orestiada).

The longest DAS_{MFRW} was estimated for Orestiada (206·4 days), while Plati and Xanthi had the lowest values (178·1 and 184·1 days, respectively). The DAS_{MFRW} estimated for Larissa and Serres were 193·3 and 189·6 days, respectively (Table 3). Orestiada had also the highest DAS_{MSY} (204·5 days), while for the remaining locations, DAS_{MSY} ranged from 181·7 to 187·3 days (Table 3).

No significant differences were found among locations regarding GDD_{MFRW} and GDD_{MSY} probably due to the high CVs. Although higher, over location GDD_{MSY} (2792·5 °C) did not differ significantly compared with GDD_{MFRW} (2639·9 °C).

Relationships between FRW_{LH} and SY_{LH} with climatic variables during AGS

Combining data over all locations (CDAL), non-significant or weak relationships were found between climatic variables and yields (FRW_{LH}, SY_{LH}). Setting apart Xanthi, which showed specific thermal features, the remaining four locations (Larissa, Plati, Serres and Orestiada) were grouped together combining data over the four locations (CDFL).

Temperatures (T_{maxAGS}, T_{minAGS}, $T_{meanAGS}$) were significantly related to yields (Fig. 1). Combining data for the four locations gave significant, negative correlations between temperature and FRW_{LH}, with the $T_{meanAGS}$-FRW_{LH} correlation being the strongest ($r=-0·51$, $P<0·01$, $n=29$). In Xanthi, significant correlations were found between FRW_{LH} and T_{minAGS} or $T_{meanAGS}$ (Fig. 1). For CDFL, the T_{maxAGS}-SY_{LH} correlation was significant, whereas in Xanthi, SY_{LH} was correlated significantly with T_{maxAGS} and $T_{meanAGS}$ (Fig. 1). For CDAL, quadratic functions were the best-fitted curves for the T_{maxAGS}-FRW_{LH} ($R^2=0·28$, $P<0·01$, $n=36$) and T_{maxAGS}-SY_{LH} ($R^2=0·18$, $P<0·05$, $n=36$) relationships, whereas a negative correlation associated the $T_{meanAGS}$ and FRW_{LH} ($r=-0·36$, $P<0·05$, $n=36$). The first derivates of the quadratic functions estimated the optimum T_{maxAGS} for FRW_{LH} and SY_{LH} at 25·5 and 25·1 °C, respectively.

In CDFL, significant positive correlations between DAS_{AGS} or GDD_{AGS} and FRW_{LH} or SY_{LH} were found, with the strongest being those between DAS_{AGS} and yield (Fig. 2). In Xanthi, the respective correlations were negative but weak, with only that between DAS_{AGS} and FRW_{LH} found to be significant ($r=-0·81$, $P<0·01$, $n=7$). In CDAL, DAS_{AGS} and yields (FRW_{LH}, SY_{LH}) were positively correlated (FRW_{LH}: $r=0·42$, $P<0·05$, $n=36$ and SY_{LH}: $r=0·43$, $P<0·01$, $n=36$), whereas the best-fitting curves between GDD_{AGS} and yields were curvilinear (FRW_{LH}: $R^2=0·30$, $P<0·01$, $n=36$ and SY_{LH}: $R^2=0·19$, $P<0·05$, $n=36$).

No significant relationship was found between FRW_{LH} and $Rain_{AGS}$, $Irrigation_{AGS}$ or WI_{AGS} in both Xanthi and CDFL. In Xanthi, negative correlations were found between SY_{LH} and $Rain_{AGS}$ or WI_{AGS}, while in CDFL, a positive correlation between SY_{LH} and $Irrigation_{AGS}$ was evident (Fig. 3). In CDAL, significant linear and curvilinear relationships were found between SY_{LH} and $Irrigation_{AGS}$ ($r=0·35$, $P<0·05$, $n=36$) and between FRW_{LH} and WI_{AGS} ($R^2=0·18$, $P<0·05$, $n=36$). The first derivative of the latter function estimated optimum WI_{AGS} for FRW_{LH} at 626·25 mm.

DISCUSSION

Yields and time of yield maxima

Sugar beet is grown as an irrigated spring crop in central and northern Greece on medium- to

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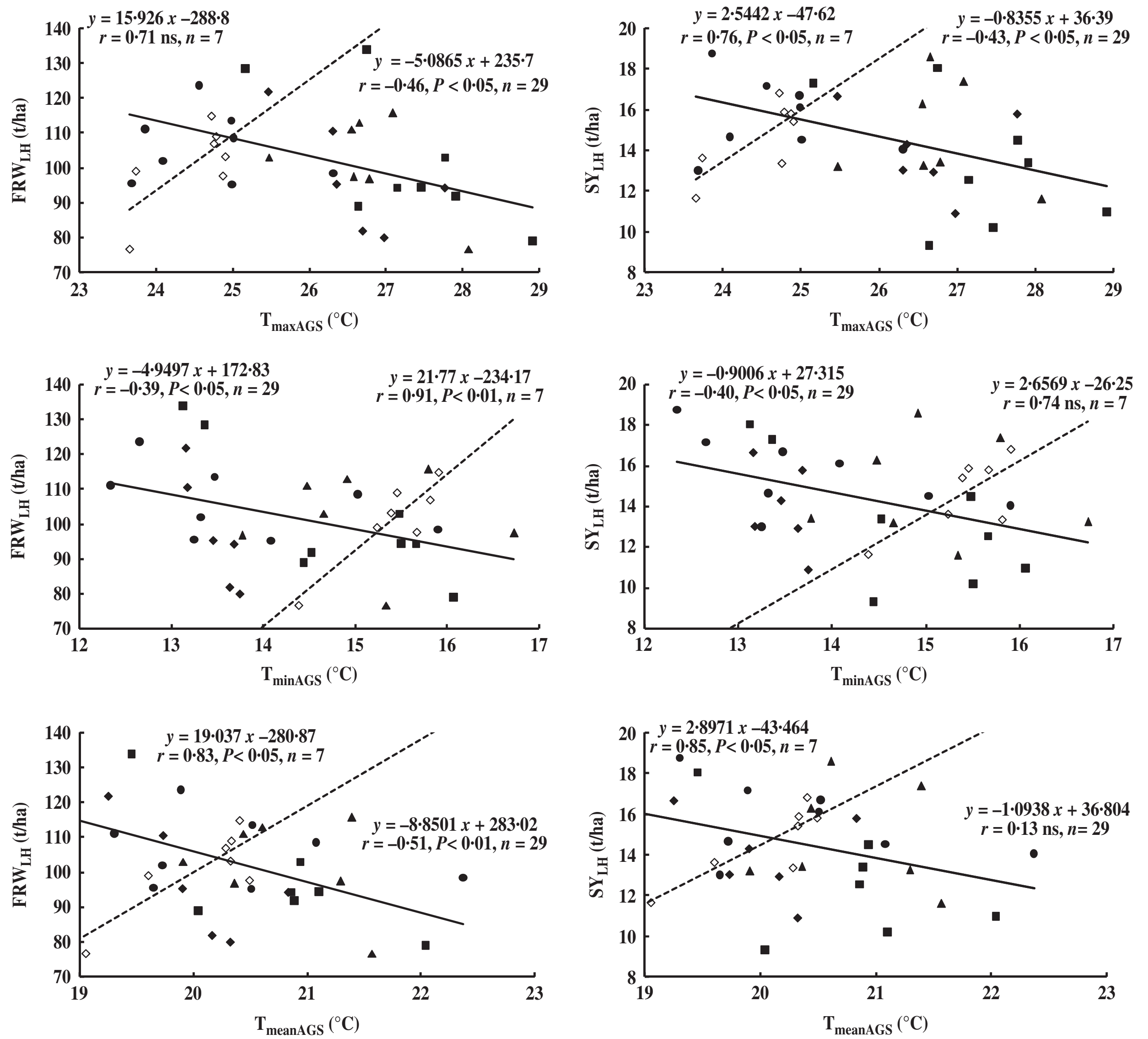

Fig. 1. Correlations between yields (FRW_{LH}, SY_{LH}) and average temperatures during the AGS (T_{maxAGS}, T_{minAGS}, $T_{meanAGS}$) in Xanthi (dashed line, $n=7$, ◊) and combined data over the four locations (solid line, $n=29$, Larissa: ◆, Plati: ■, Serres: ▲, Orestiada: ●). ns: non-significant.

heavy-textured soils and under Mediterranean to mild continental conditions. Xanthi, on a sandy loam, showed the most favourable and stable temperatures for sugar beet, recording the highest GDD and the lowest CT_{25} among locations for both PGS and AGS. Temperature and water availability were most limiting in the southernmost Larissa.

Sugar beet yield is significantly affected by location and year (Märländer *et al.* 2003; Hoffmann *et al.* 2009) showing high variability (Chloupek *et al.* 2004). Over years, yield was not affected by location but, using CVs as a yield stability index (Peltonen-Sainio *et al.* 2009), southern locations (Larissa, Plati, and Serres) showed higher variation. The highest variation was found in Plati and was ascribed to the highly variable DAS_{AGS}, which was negatively correlated with temperatures (data not shown). Previously, Richter *et al.* (2006) reported a negative relationship between sugar beet yield stability and soil water availability.

It is important to harvest sugar beet at the appropriate time in order to maximize sugar extraction and meet daily factory demands. Usually, factories monitor yield trends during the course of the growing season by conducting successive samplings in commercial fields. This process is time-, labour- and consequently, money-intensive. Models evolved to predict yield

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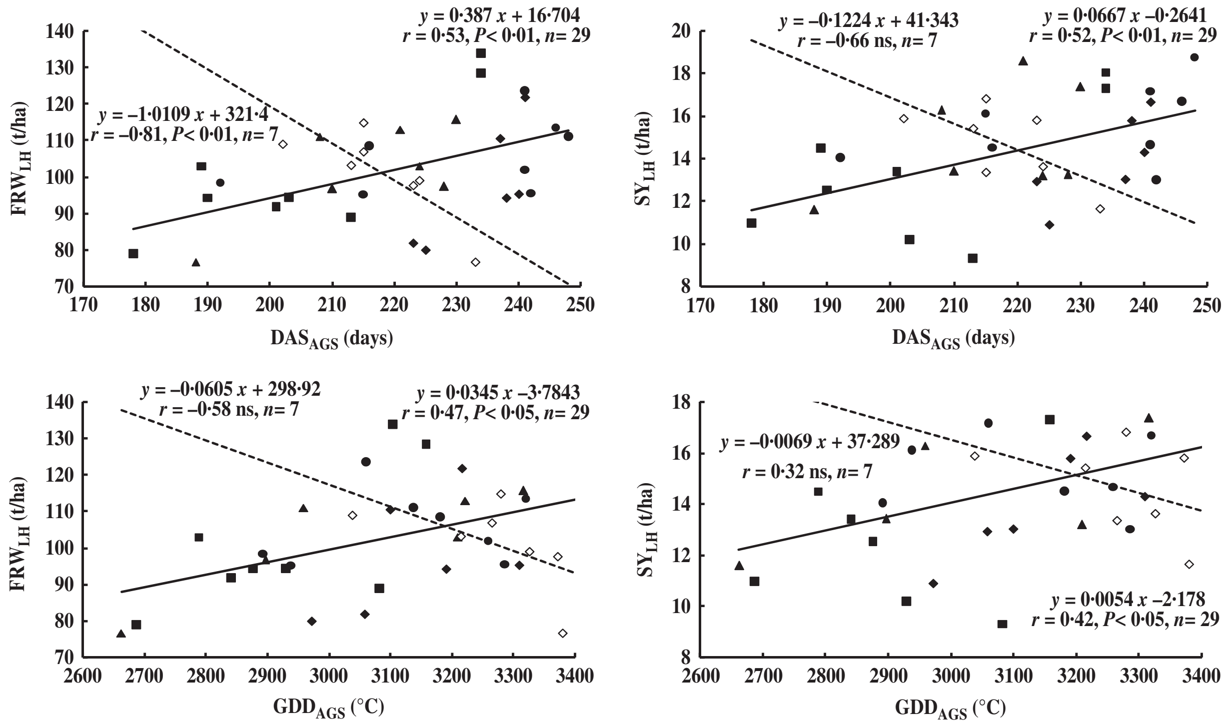

Fig. 2. Plotting yields (FRW_{LH}, SY_{LH}) against DAS_{AGS} and GDD_{AGS} in Xanthi (dashed line, $n=7$, ◊) and combined data over the four locations (solid line, $n=29$, Larissa: ◆, Plati: ■, Serres: ▲, Orestiada: ●). ns: non-significant.

trends during growing season are based on climatic and soil variables (Spitters *et al.* 1990; Qi *et al.* 2005; Richter *et al.* 2006; Jaggard *et al.* 2007), but their accuracy is acceptable only under specific preconditions.

The present paper attempts to define the optimum time for sugar beet harvest in each location in terms of DAS and GDD. Based on GDD, optimum harvest time did not differ between locations. Over locations, average GDD_{MFRW} and GDD_{MSY} were estimated at 2639·9 and 2792·5 °C, respectively, being lower than 2900 °C, defined as a limit for spring crops to complete their growth cycle (Matzarakis *et al.* 2007). The five locations differed significantly for DAS necessary for maximum yields, with the northernmost Orestiada requiring the longest period (DAS_{MFRW}: 206·4 days, DAS_{MSY}: 204·5 days). The means over locations were estimated at *c.* 190·0 days for both DAS_{MFRW} and DAS_{MSY}. Elongation of the growing season (early sowing, late harvest) has been proposed as a means for increasing yield in climates where water availability is a limiting factor (Richter *et al.* 2006). Early sowing is considered to be more effective for growing-season elongation because of the earlier canopy closure and thus, the better radiation interception during early crop growth (Richter *et al.* 2006; Malnou *et al.* 2008). Delayed harvest has a lower impact on yield due to the small yield increment in late autumn as a result of low solar radiation (Tsialtas & Maslaris 2008). Moreover, the use of heavy machinery, such as harvesters, late in the season is restricted by wet conditions, especially on clay soils, which causes soil compaction and increases losses (Richter *et al.* 2006). Early sowing could be an effective means of increasing yields in Plati where a wide gap between PGS and AGS climatic variables was evident.

Effects of thermal and water variables on yields (FRW_{LH}, SY_{LH})

According to Qi *et al.* (2005), the most important variables affecting sugar beet performance are temperature, solar radiation, rainfall, evapotranspiration and soil water availability. Radiation interception is the major limiting factor in northern Europe and for this reason, yield prediction models are based on this variable (Richter *et al.* 2001; Qi *et al.* 2005). In the Mediterranean basin, high temperatures and water availability during summer determine yield (Jaggard & Qi 2006; Rinaldi & Vonella 2006). Optimum mean daily air temperature for sugar beet root growth

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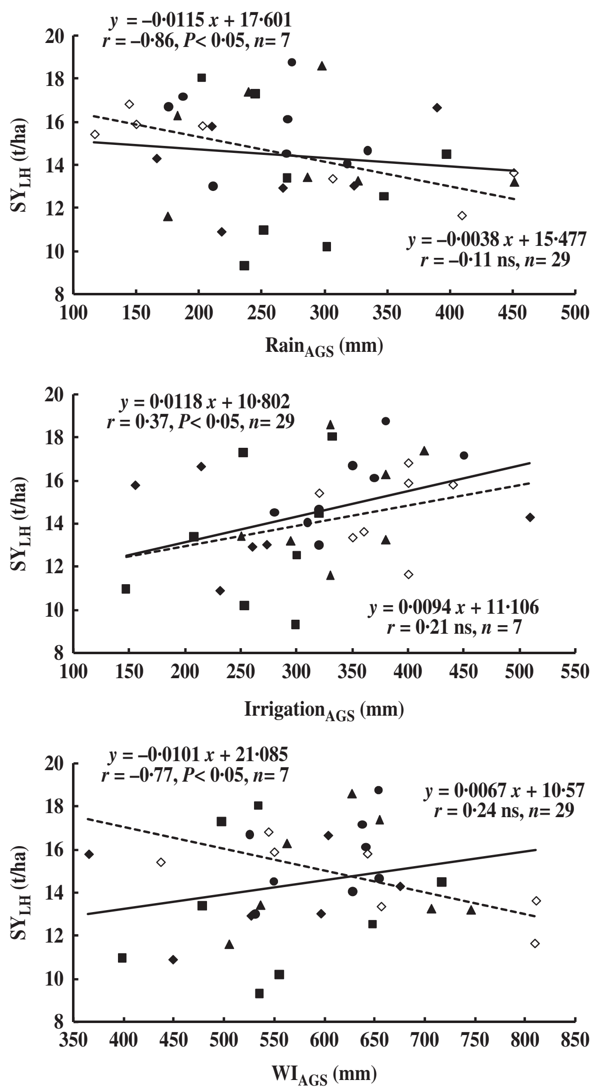

Fig. 3. Correlations between SY_{LH} and water variables during the AGS ($Rain_{AGS}$, $Irrigation_{AGS}$ and WI_{AGS}: rain + irrigation) in Xanthi (dashed line, $n=7$, ◊) and combined data over the four locations (solid line, $n=29$, Larissa: ◆, Plati: ■, Serres: ▲, Orestiada: ●). ns: non-significant.

was defined at 18 °C, corresponding to maximum temperatures of 22–26 °C (Kenter *et al.* 2006), coinciding with the optimum temperature (25 °C) for sugar beet photosynthesis (D'Ambrosio *et al.* 2006). In accordance, over locations, optimum T_{maxAGS} for FRW_{LH} and SY_{LH} were estimated at 25·5 and 25·1 °C, respectively. These optima were derived from the conjunction of the positive correlations found for the cooler, sub-optimal temperatures of Xanthi and the negative ones of the warmer, above-optimal temperatures of the remaining locations.

In southern locations and particularly in Larissa, sugar beet is grown under temperatures higher than optimum from as early as May, thereby accumulating higher and more harmful temperatures (CT_{25AGS}). During July and August, maximum daily temperatures higher than 35 °C are common, leading to foliage senescence and thus, diminishing radiation interception. Irrigation is proposed as a means for cooling heat-stressed crops (Mahan *et al.* 1995; Qi & Jaggard 2006) but, in Larissa, irrigation water is supplied at sub-optimal rates (Analogides 1993) because of its shortage and/or the priority given to the irrigation of cotton. Lower yields under higher T_{minAGS}, and actually under higher night-time temperatures, could be ascribed to increased respiration of sugar beet resulting in higher consumption of carbohydrates composed under the stressful daytime conditions. Low night temperatures increase SC in roots (Ulrich 1955; Yadollahi & Asadiyeh 2009), thus compensating for root weight losses and keeping SY unaffected. The findings of the present paper contrast with those of Milford & Thorne (1973), who reported that under UK conditions, sugar beet subjected to low night temperatures contained less water and had lower FRW.

Xanthi, a location with different soil type and climatic variables than the other locations, resembles the temperate regions. Average temperatures (T_{min}, T_{max}, T_{mean}), ΔT and CT_{25} during both PGS and AGS were the lowest, while the average T_{max} did not exceed the optimum of 25 °C. Thus, the positive correlations found between temperatures and yields are completely rational. The positive correlation between FRW_{LH} and T_{minAGS} could be ascribed to the higher water content and consequently higher FRW of sugar beet grown under higher night temperatures as reported by Milford & Thorne (1973). SY increased with increasing T_{maxAGS} and $T_{meanAGS}$, which were averaged at 24·5 and 20·0 °C, respectively. The restrictive effect of sub-optimal air temperatures on yield was intensified by higher rainfall during the cooler growing seasons since a negative correlation between the variables was evident (data not shown). In Xanthi, supplemental irrigation (381 mm) exceeded optimum (200 mm) for this location (Analogides 1993), resulting in further cooling of the sugar beet canopy and intensifying the negative effects of the sub-optimal temperatures on productivity (Kincaid *et al.* 1993). The light-textured soil and consequently low soil water-holding capacity, along with the high $Rain_{AGS}$ variation, led growers to over-irrigate in order to secure ample water supply. Thus, they further lowered sub-optimal temperatures for sugar beet, with detrimental effects on yields. Leaching was not considered as a case

https://doi.org/10.1017/S0021859612000998 Published online by Cambridge University Press

relating high WI with low yield because N fertilization was within the recommended range (or even higher) and despite the fact that water was excessively supplied at Xanthi, WI did not exceed the amount (650 mm) necessary for maximum yield (FAO 2012). Moreover, sugar beet is a deep-rooted species pumping up water and nutrients from depth down to 1·8–2·0 m, thereby helping to minimize N losses due to leaching.

Contrary to other locations in Greece, the projected climate change with the projected temperature increase during summer is likely to affect yield positively in Xanthi (Jaggard *et al.* 2007). This confirms Donatelli *et al.* (2002), who reported climate change to have both negative and positive impacts on sugar beet productivity in different regions in the Mediterranean basin.

Regarding thermal variables, it is noteworthy that no significant correlation was found between yields (FRW_{LH}, SY_{LH}) and ΔT_{AGS} ($T_{maxAGS} - T_{minAGS}$). High day/night temperature amplitude has been reported to increase yield and improve quality since it leads to a highly positive net photosynthate budget (Bakker & van Uffelen 1988).

Elongation of AGS (DAS_{AGS}) by early sowing and the subsequent increase of GDD_{AGS} would be beneficial for sugar beet grown in warmer locations, but not in Xanthi with its sub-optimal temperatures. Previously, Niwa *et al.* (2008) reported a relationship between GDD and SY in Japan. Actually, elongation of the growing season in warmer locations would affect yield positively through a decrease of average temperatures (T_{maxAGS}, $T_{meanAGS}$). Adversely, in Xanthi, AGS elongation sub-optimizes growing season temperatures by growing sugar beet under even sub-optimal temperatures and increasing WI_{AGS} (mainly $Rain_{AGS}$).

In conclusion, over the study period, locations differed mainly in thermal variables but they had similar yields (FRW_{LH}, SY_{LH}) and GDD_{MFRW}. However, locations showed significant differences in DAS_{MFRW} and DAS_{MSY}, with the northernmost Orestiada showing the longest periods (>200 days). Over locations, DAS_{MFRW} and DAS_{MSY} were estimated at *c.* 190 days. Temperatures had contrasting effects on yields. Combining data over the four locations (Larissa, Plati, Serres and Orestiada), FRW_{LH} and SY_{LH} were negatively correlated to average temperatures over the AGS (T_{maxAGS}, T_{minAGS}, $T_{meanAGS}$). In Xanthi, sugar beet was grown under sub-optimal temperatures and yield was increased by higher temperature. Elongation of AGS could eliminate the adverse effects of temperature on yield only in the warmer locations. In Xanthi, projected temperature increase, due to climate change, would be beneficial for sugar beet.

We would like to thank the staff of Hellenic Sugar Industry SA engaged in experimentation and Hellenic National Meteorological Service for providing meteorological data. We are grateful to Dr A. A. Gagianas, Professor Emeritus, Faculty of Agriculture, Aristotle University of Thessaloniki, for his critical reading of the paper.

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https://doi.org/10.1017/S0021859612000998 Published online by Cambridge University Press