

Predicting the energy consumption of heated plastic greenhouses in south-eastern Spain

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Abstract

Measurements of heat consumption in a *parral* type greenhouse, equipped with an air-heating system, were carried out in south-eastern Spain (Almería) during the 1998/99 winter. From the daily values of heat consumption (Q_d , MJ m⁻² d⁻¹) recorded in five identical greenhouses heated to different night temperature set-points (T_c), and data of minimum outside air temperature ($T_{e,min}$), relationships between Q_d and the temperature difference ($\Delta T_{min} = T_c - T_{e,min}$) were established. Linear regressions between Q_d and ΔT_{min} gave satisfactory fits (R^2 ranging from 0.75 to 0.83), considering that $T_{e,min}$ was the only input data for the model. When all data were pooled, the correlation was curvilinear, the best fit to a 2nd order polynomial being $Q_d = 0.049 \Delta T_{min}^2 - 0.001 \Delta T_{min} + 1.107$ ($R^2 = 0.89$). Validation of this model was performed using data obtained during other years, giving a fair agreement at the daily ($R^2 = 0.86$), 10-day ($R^2 = 0.95$) and yearly ($R^2 = 0.99$) time scales. This simple model could be of interest to growers for decision-making related to the choice of set-point temperature and crop planning in heated greenhouses.

Additional key words: air heating, energy use model, *Phaseolus vulgaris*, temperature.

Resumen

Predicción del consumo de energía en invernaderos plásticos calefactados del sureste de España

Se realizaron medidas de consumo de energía de la calefacción por aire caliente en invernaderos tipo *parral* durante la campaña 1998/99 en el sureste de España (Almería). Se determinaron relaciones adecuadas, para cinco invernaderos calentados a diferentes temperaturas nocturnas de consigna (T_c), entre los valores de consumos diarios de energía (Q_d , MJ m⁻² d⁻¹) y la diferencia (ΔT_{min}) entre la temperatura de consigna de calefacción y la temperatura mínima exterior ($T_{e,min}$). La regresión lineal entre Q_d y ΔT_{min} fue satisfactoria (R^2 varió entre 0,75 y 0,83), considerando que $T_{e,min}$ fue la única variable de entrada para el modelo. Cuando se analizaron todos los datos en conjunto, la correlación fue curvilínea, siendo el mejor ajuste para un polinomio de 2º orden, $Q_d = 0,049 \Delta T_{min}^2 - 0,001 \Delta T_{min} + 1,107$ ($R^2 = 0,89$). La validación de este modelo fue realizada utilizando datos de otros años, mostrando un ajuste adecuado para los periodos diarios ($R^2 = 0,86$), 10-días ($R^2 = 0,95$) y anuales ($R^2 = 0,99$). Este sencillo modelo puede ser de interés para los agricultores a la hora de tomar decisiones sobre el mercado, escoger la temperatura de consigna y programar el periodo de calefacción del invernadero.

Palabras clave adicionales: aire caliente, modelo de consumo de energía, *Phaseolus vulgaris*, temperatura.

Introduction

A large area of approximately 38,000 ha of greenhouses, mainly dedicated to vegetable production, is

concentrated in the Mediterranean coastal areas of south-eastern Spain (Castilla and Hernández, 2005). Most greenhouses are *parral* type, consisting of low-cost structures covered with plastic and without heating equipment (Pérez-Parra *et al.*, 2004). This type of greenhouse is considered the archetype of the Mediterranean greenhouse agrosystem, characterised by low technological and energy inputs (Baille, 2002; Pardossi *et al.*,

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2004). In these areas, air temperatures tend to be sub-optimal for vegetable production during most of the winter period, especially at night. Monthly mean values of daily minimum outside temperature on the Almería coast vary between 7 and 9°C in winter (Montero *et al.*, 1985) and for more than 8 hours per day, mostly at night, the air temperature is below 12°C (Puerto, 2001). Nocturnal air temperatures in unheated greenhouses are, usually, similar to the outside air (Kittas, 1995; López, 2003) or even lower during cloudless and low wind conditions (Papadakis *et al.*, 2000). Low night temperatures are often associated with conditions of high air humidity during the night due to the proximity of the sea (Montero *et al.*, 1985). These two factors explain, at least partially, the lower productivity and quality of winter vegetable production in unheated low-technology greenhouses in mild winter areas (Tognoni, 1990; Verloot, 1990; Puerto, 2001), and may justify the investment and running costs of a heating system (López *et al.*, 2000). In this context, heating systems have recently been introduced in greenhouses on the Almería coast, mainly to improve winter vegetable production, although their use is still rather limited (Pérez-Parra *et al.*, 2000). In general, pulsed hot-air heating systems are installed in *parral* type greenhouses, mainly due to their lower cost, whereas hot-water heating systems are less frequent and found mostly in climate controlled greenhouses, usually arch-shaped multi-span or multi-tunnel types.

Heating constitutes the major energy requirement for the high-technology greenhouses of north and central Europe. In these greenhouses and for heat-demanding crops, such as rose, tomato or cucumber, Baille (1999) estimated annual greenhouse heating requirements of about 3,000 MJ m⁻² yr⁻¹ in northern European countries, 1,600 MJ m⁻² yr⁻¹ in Southern France and 1,200 MJ m⁻² yr⁻¹ in Israel. Little information is available on the heating requirements of low-technology greenhouses, characterised by relatively poor air tight-

ness (Baille *et al.*, 2006), used in most of the Mediterranean basin. Therefore, in order to assess the feasibility of heating low-technology greenhouses in this area, better knowledge is required of heating inputs and costs, and the optimal heating strategy (Bailey and Chalabi, 1994; López *et al.*, 2002). The main aims of this work were to (i) analyse the heat consumption in the low-cost plastic greenhouses of south-eastern Spain and (ii) propose a simple model for estimating the heating requirements, using as inputs routinely available climate data.

Material and Methods

Site and experiments

All experiments were carried out in a block of five identical multi-span asymmetrical greenhouses *parral* type at *Las Palmerillas-Cajamar* Research Station (36° 48' N, 2° 3' W, 155 m), in the Almería coast, south-eastern Spain. Each E-W oriented greenhouse (Fig. 1), consisted of a low-cost structure covered with 0.2 mm thick thermal polyethylene film (Pérez-Parra *et al.*, 2004) and had two lateral ventilation panels and one continuous roof vent. The ground area of each greenhouse was 432 m² (24 m × 18 m), cladding area was 717 m², and the air volume was about 1,500 m³. A mobile pulsed hot-air heating system of 104 kW (TG-90, Turbocalor, Spain) was located in the eastern part of each greenhouse. The air heating system consisted of an integrated propane burner that discharged the flue gases directly into the greenhouse and was automatically activated when the air temperature was below the established set-point value. To minimise differences in energy consumption between greenhouses due to the surrounding environment, a 4 m wide buffer zone was kept in between and at both ends of the greenhouses.

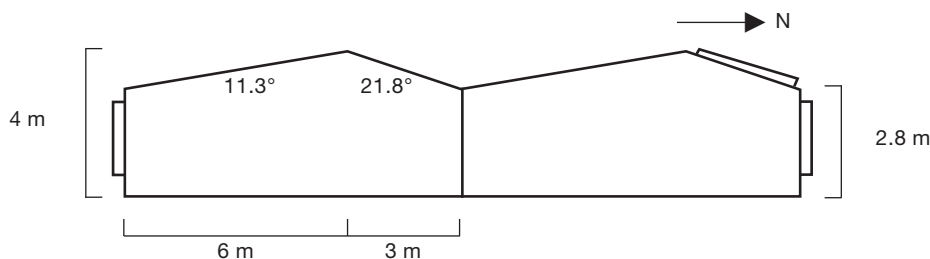


Figure 1. Dimensions and characteristics of the multi-span asymmetric *Parral* greenhouse used in the experiments.

Green bean crops (*Phaseolus vulgaris* L. cv. Donna) were sown in the five greenhouses on 6 November 1998, and the cycles ended on 12 March 1999, 126 days after sowing (DAS). Donna is an indeterminate climbing cultivar widely used in greenhouse autumn-winter cycles. Plants, in rows 2 m apart and 0.5 m within rows, were vertically supported with wires up to a height of 2 m. Crop were managed following common local practices (Villalobos, 2003). The soil was the typical *enarenado* soil, commonly used in the greenhouses of the Almería region (Castilla and Hernández, 2005).

The green bean crop was subjected to the following thermal treatments (one per greenhouse): without heating or reference crop (T_R); heated to a night air temperature near 12°C (T_{12}); heated to a night air temperature of 14°C during the vegetative stage, and 12°C afterwards ($T_{14}T_{12}$); heated with a split night temperature regime, i.e. 14°C during the first half of the night and 12°C thereafter ($T_{14,12}$); and heated at a night air temperature of 14°C (T_{14}).

Measurements

Dry and wet bulb air temperatures were measured inside each greenhouse (2 m above the ground) and outside (1.5 m above the ground) by ventilated psychrometers (mod. 1.1130, Thies Clima, Germany), located in the centres of the greenhouses. Data were recorded every 2 s, averaged every 10 min and recorded with a data logger system (mod. 3497 A, Hewlett Packard, USA). The heating system and the lateral and roof vents were controlled by a climate-control system which maintained the established set-point values of temperature.

Daily gas volumetric consumption ($\text{m}^3 \text{d}^{-1}$) in each greenhouse was recorded at the beginning of each day from the register of a volumetric meter (G4 S6.20M, Magnol, France), and converted into mass units (kg d^{-1}) using pressure measurements from a gas manometer. The calorific value of propane gas was taken as 11,450 kcal kg^{-1} of propane.

A simulation model using the minimum daily outside temperature as input data was developed in order to predict the energy consumed for heating a greenhouse. Energy consumption data from the four heated green bean cycles grown during the 1998/99 season were used for the model parameterisation, and data from three additional crop cycles were used for model validation (Table 1).

Table 1. Characteristics of the validation heating treatments

	1997/98 season	1999/00 season
Greenhouse	Asymmetrical <i>parral</i>	Asymmetrical <i>parral</i>
Heating system	Air heated	Air heated
Crop	Cucumber	Green bean
Cycle	13/11/97- 06/03/98	29/10/99-29/02/00
Heating treatments	T_{15} : Minimum night temperature of 15°C T_{12} : Minimum night temperature of 12°C	$T_{15}T_{12}$: Minimum night temperature of 15°C until onset of harvesting and 12°C afterwards

Results and Discussion

Analysis of heating energy consumption

The total energy consumption over the whole heating period (Q_t , MJ m^{-2}) ranged from 250 MJ m^{-2} for the highest heating level (T_{14}) to 120 MJ m^{-2} for the lowest one (T_{12}). These values were highly and linearly related to the mean daily greenhouse air temperature averaged over the heating period ($T_{i,t}$), as shown in Figure 2. The slope of this linear relationship indicated that an energy amount of 104 MJ m^{-2} (2.2 kg m^{-2} of propane gas) was required to increase the mean greenhouse air temperature by 1°C for the whole heating period.

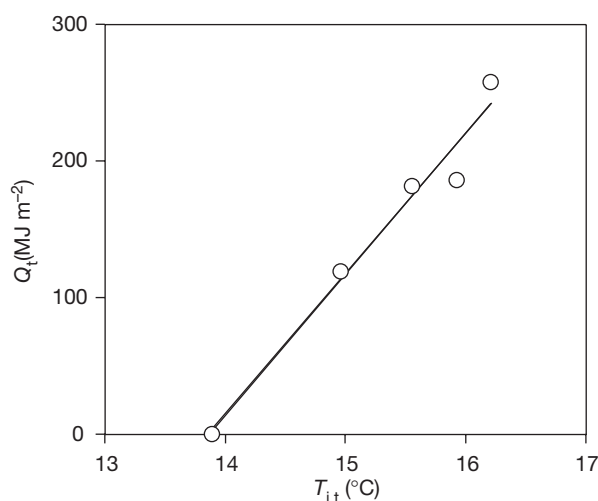


Figure 2. Total energy consumption (Q_t , MJ m^{-2}) versus daily mean air greenhouse air temperature ($T_{i,t}$) averaged over the heating period. Data of the 1998/99 heating treatments (T_R , T_{12} , $T_{12}T_{14}$, $T_{14}T_{12}$ and T_{14}). The line is the best fit regression to the data: $Q_t = 103.6 T_{i,t} - 1437$, $R^2 = 0.97$.

In order to analyse the seasonal trend of heating energy consumption, the heating period was divided in six consecutive growth phases of 15 to 20 days duration (P1: 13 to 30 November; P2: 1 to 20 December; P3: 21 December to 10 January; P4: 11 to 31 January; P5: 1 to 20 February; and P6: 21 February to 10 March). For each phase (Fig. 3), a tight linear relationship was obtained between the average daily energy consumption (Q_p , MJ m⁻² d⁻¹) and the mean daily greenhouse air temperature ($T_{i,p}$). The slope of these relationships is about 1.0 MJ m⁻² d⁻¹ °C⁻¹ for all the crop phases, with no significant differences between phases ($P < 0.05$). These results suggested that increasing the greenhouse air temperature by 1°C led to relatively steady energy consumption throughout the crop cycle, irrespective of the outside meteorological conditions. This simple relationship could be used for predicting the energy consumption in air-heated greenhouses of southern Spain and other Mediterranean coastal areas. However, this approach would require the knowledge of the mean daily greenhouse air temperature during the heating period, data which is not commonly available in low-cost greenhouses.

In a following step, heat consumption was analysed in relation to the minimum outside air temperature ($T_{e,min}$). This approach has a greater potential for pre-

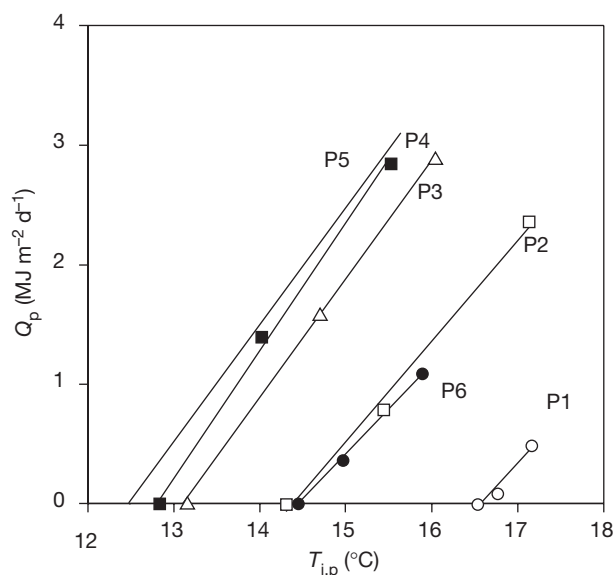


Figure 3. Daily mean energy consumption (Q_p , MJ m⁻² d⁻¹) versus daily mean air temperature ($T_{i,p}$), both averaged over growth periods of 15-20 days (P1, P2, P3, P4, P5 and P6). Data correspond to three treatments of the 1998/99 season (T_{12} , T_{14} and T_{14}). The lines are the best fit regressions to the data. All slope values are close to 1 MJ m⁻² d⁻¹ per °C.

diction purposes as this variable is currently measured in all meteorological stations. As illustrated in Figure 4, for each heating treatment a linear correlation was found between the daily values of heating energy consumption (Q_d , MJ m⁻² d⁻¹) and the temperature difference between the night set-point temperature (T_c) and the $T_{e,min}$, i.e. $\Delta T_{min} = T_c - T_{e,min}$ (°C). The slope of the linear regression between Q_d and ΔT_{min} for each heating treatment can be considered as a global greenhouse energy losses coefficient. The slope values ranged from 0.49 to 0.56 MJ m⁻² d⁻¹ °C⁻¹ and did not differ significantly between treatments. The slight differences observed could be due to differences in the daily heating duration or in the cover heat loss, the latter being dependent on the cover temperature (Kittas, 1986; Papadakis *et al.*, 1992; Baille *et al.*, 2006), and therefore on the heating level. Leakage losses of a greenhouse are an important parameter to evaluate its exchange of heat. Most greenhouses in Almería are *parral* type where the film is punctured and tied to the main wires, making this type of greenhouse not very air tight. Baille *et al.* (2006) found for *parral* greenhouse heat leakage losses about 20% of the total greenhouse air heat losses.

Daily heating requirements were also analysed by multiple regression analysing using other external meteorological variables (e.g. daily wind speed and solar radiation). No significant correlations were found, probably for the low regimen of wind at night period (< 2 m s⁻¹) where the heating is necessary, indicating that the minimum outside temperature was the main variable explaining the variability of Q_d in the conditions of our experiments.

Model construction and validation

A simple model to predict the Q_d was developed using the daily minimum outside temperature and the heating night set-point temperature as input data. Based on the similarity found in the slopes between Q_d and ΔT_{min} in Figure 4, a second order polynomial curve (Fig. 5; Eq. 1) was adjusted to the pooled data of the four heating treatments:

$$Q_d = 0.0497 \Delta T_{min}^2 - 0.001 \Delta T_{min} + 1.107 \quad \text{with } R^2 = 0.89 \quad [1]$$

Equation [1] predicted realistically measured daily and cumulative values of heating energy consumption as shown by Fig. 6 for the T_{12} and T_{14} treatments during the 1998/99 season. Cumulative values were obtained

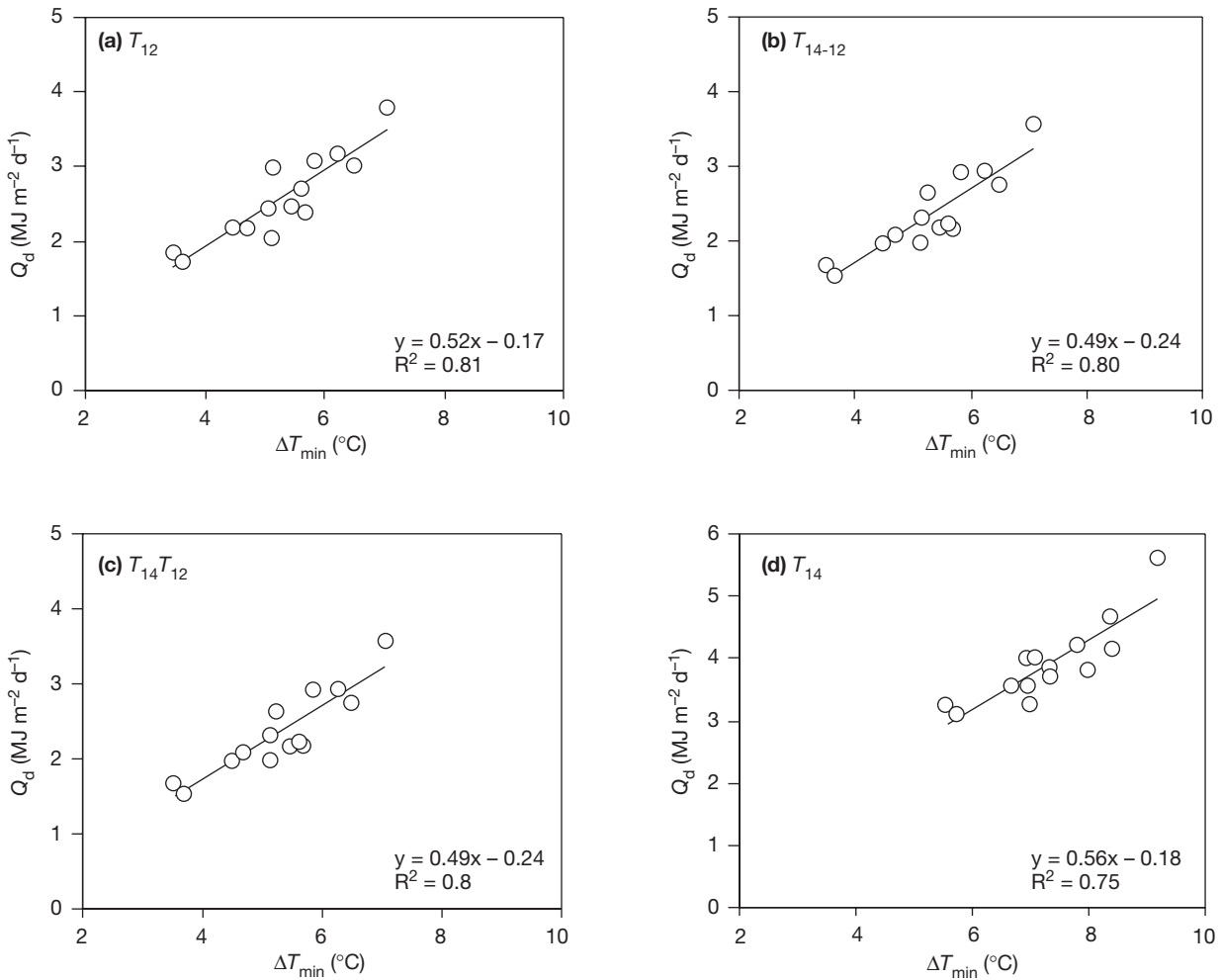


Figure 4. Daily heat consumption (Q_d , $\text{MJ m}^{-2} \text{d}^{-1}$) vs daily temperature difference (ΔT_{\min}) between the heating set-point temperature and the minimum outside air temperature under treatments (a) T_{12} , (b) T_{14-12} , (c) $T_{14}T_{12}$ and (d) T_{14} .

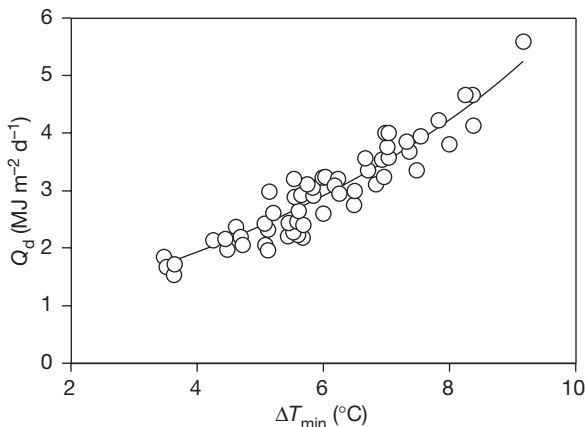


Figure 5. Daily heat consumption (Q_d , $\text{MJ m}^{-2} \text{d}^{-1}$) vs daily temperature difference (ΔT_{\min}) between the heating set-point temperature and the minimum outside air temperature. Pooled data of heating treatments: T_{12} , T_{12-14} , $T_{12}T_{14}$ and T_{14} .

by summation of Q_d values estimated by Eq. [1] throughout the whole heating period. Measured and estimated values of total energy consumption were 119 and 122 MJ m^{-2} respectively for T_{12} , and 257 and 256 MJ m^{-2} for T_{14} , indicating a fairly good agreement.

The model was applied to the three additional crop cycles used for validation (Table 1), using the corresponding input data of $T_{e,\min}$ and T_c . Summation of values estimated by Eq. [1] provided an accurate simulation of the evolution of the cumulative heat consumption (Q_{cum}) throughout the two heated cucumber cycles (T_{12} and T_{15} treatments) during the 1997/98 season (Fig. 7). Total measured and estimated heat consumption (Q_t) was 51 and 59 MJ m^{-2} , respectively, for T_{12} , and 204 and 209 MJ m^{-2} for T_{15} . Eq. [1] also gave fairly good estimates of cumulative heat consumption for the heated green bean crop during the 1999/00 season

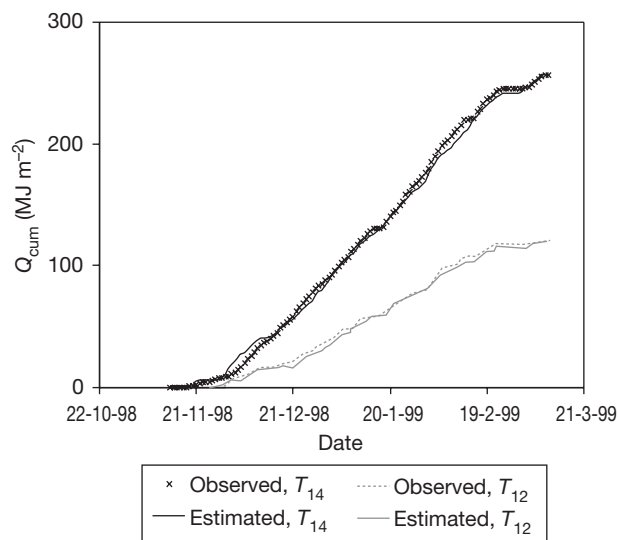


Figure 6. Measured and estimated evolution of cumulative heat consumption (Q_{cum}) in T_{12} and T_{14} heating treatments during the 1998/99 season.

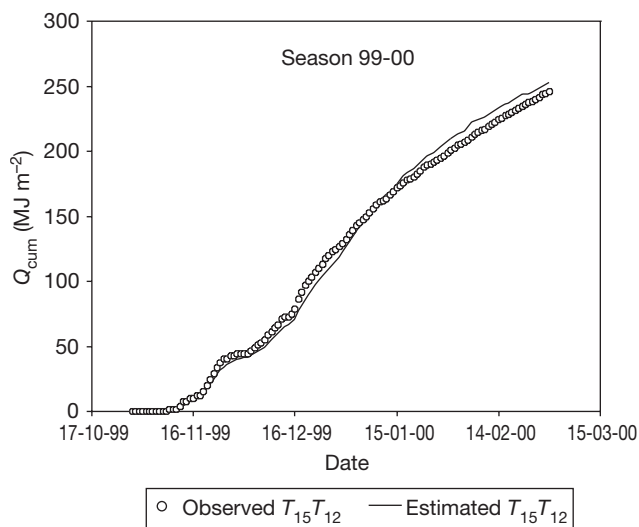


Figure 8. Measured and estimated cumulative values of heat consumption (Q_{cum}) of a green bean crop heated to $T_{15}T_{12}$: minimum night temperature of 15°C until onset of harvesting and 12°C afterwards during the 1999/00 season.

(Fig. 8), both during the period from sowing to first harvest ($T_c = 15^{\circ}\text{C}$) and during the harvest period ($T_c = 12^{\circ}\text{C}$).

Figure 9 presents estimated *versus* measured values of heat consumption for the three validation cycles at the daily, 10-day, and seasonal scales. Data are closely distributed around the 1:1 line for the three scales and the values of the intercept and the slope of the regression line were not significantly different from zero and unity, respectively ($P < 0.05$). The model's accuracy improved when the integration time increased from the

daily to the seasonal scale. The mean absolute error (Wilmott, 1981) was 0.47 MJ m^{-2} on the daily scale, 1.63 MJ m^{-2} on the 10-day scale, and 1.97 MJ m^{-2} on the seasonal scale. Therefore, the heating energy consumption of heated low-technology greenhouses in Spanish Mediterranean coastal areas can be fairly well predicted at the 10-day and seasonal scales with a simple model based on daily minimum outside air temperature data, a variable commonly measured at meteorological stations. The model realistically reproduces the time-evolution of greenhouse heating requirements throughout the heating season.

A priori, the north-European heating strategy does not appear to be advisable for Mediterranean greenhouse growers, where heating is not absolutely necessary. In the high-technology greenhouses located in north and central Europe, the heating season is longer (September to June), the climatic conditions are harsher (low or negative temperatures) and the heating set-points, generally based on applying optimum crop growth temperatures and close control of temperature and humidity, are usually higher (16°C to 18°C). Furthermore, heating is often required during diurnal winter periods due to low solar radiation levels and growers usually apply dehumidification —by heating and ventilating at the same time— in order to control better the inside air humidity and hence, fungal diseases. All these practices increase substantially the greenhouse energy requirements, leading to energy consumption of up to

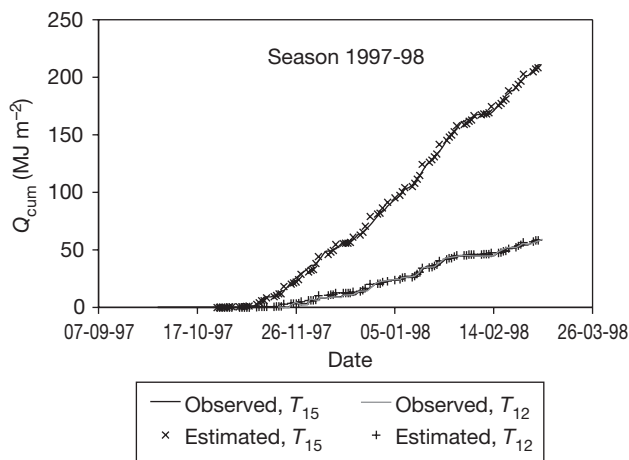


Figure 7. Measured and estimated cumulative values of heat consumption (Q_{cum}) for two cucumber crops heated at 12°C (T_{12}) and 15°C (T_{15}) during the 1997/98 season.

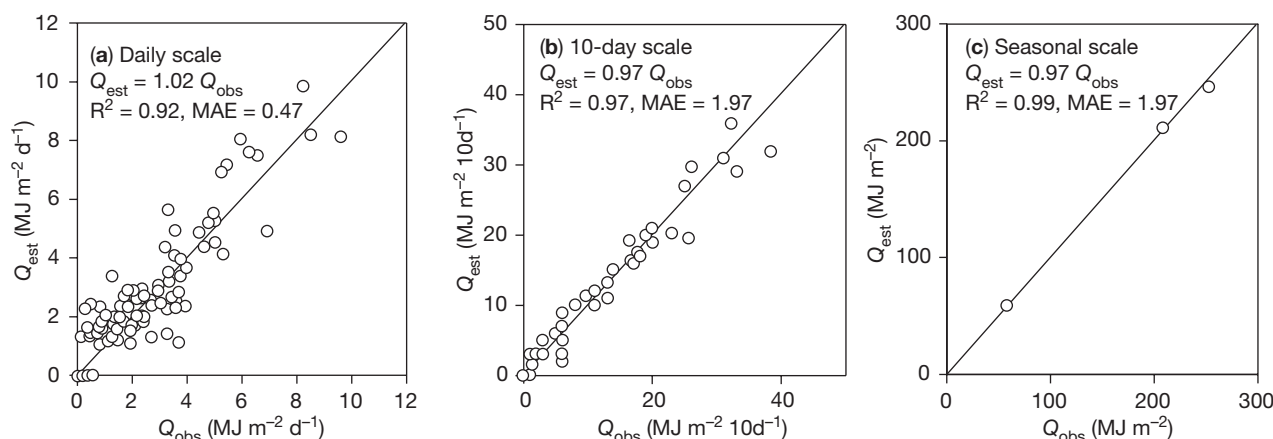


Figure 9. Estimated (Q_{est}) versus observed (Q_{obs}) values of heat consumption at (a) daily, (b) ten-day, and (c) seasonal scales. MAE: mean absolute error. Pooled data of the three validation treatments.

3,000 MJ m⁻² (Baille, 1999), which is 10 to 20 times more than the order of magnitude reported in this study. The heating strategy studied in this work can be considered as a low-cost rather than a crop-optimum strategy. The use of low to moderate heating strategies (12°C to 15°C) together with the mild winter climate in the coastal areas of southern Spain explain the much lower greenhouse energy consumption over the heating season (December to early March) compared to those reported for greenhouses located in north and central Europe. Additionally, there appears to be scope for improving the heating efficiency and lowering the energy consumption in low-cost Mediterranean greenhouses. The heating energy efficiency could be improved by using high performance heating systems (e.g., heated pipes located near the crop; Baille and von Elsner, 1988) or by energy-saving measures (double cover, thermal screen, improved greenhouse air-tightness, etc.). These energy-saving methods associated with technological improvements should first be assessed both agronomically and economically.

The results presented in this work provide better knowledge of heating requirements in low-technology greenhouses commonly found in southern Spain under low to moderate heating regimes and using air-heating systems. However, further studies are required to identify the best heating strategies adapted to such greenhouses (López *et al.*, 2002; López, 2003). In these studies, the heating energy consumption model proposed in this work could be a valuable tool for assessing of heating energy consumption under different heating strategies in Mediterranean climatic conditions, and, therefore, for taking decisions about heating installation feasibility.

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