Effects of Meteorological Parameters and Irrigation on Cotton Phenology in Greece

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ABSTRACT

The influence of temperature, relative humidity, rainfall and irrigation on the duration of cotton phenological stages was studied in the cotton producing zone of Greece during a 10 year period (1986-1994). Influence was found to be parameter and stage dependent. Temperature was the most time affecting parameter. More specifically, the minimum temperature in the early stages and the maximum temperature in the late stages played the most significant (negative) role. Within the temperature range encountered, the variability between temperature (T_a) and time to a certain phenological stage (N) was explained only slightly better by an exponential than a linear function. By fitting a linear regression between 1/N and T_a, the thermal time required above a threshold temperature (T_o) was estimated for each developmental stage between sowing and harvesting and for the whole cotton cultivation zone. Rain lengthened cotton developmental stages, particularly when falling between sowing and anthesis or boll opening and harvest. Addition of irrigation water to rainfall, weakened regressions. The role of the relative humidity in regulating cotton phenology was insignificant, except occasionally after squaring. Multiple regression analysis, taking into account together all parameters studied, was justified as the coefficient of variation was usually increased. However, in many cases one or more parameters, apart from temperature, could be omitted as non-significant. Predictability of the relations established is discussed.

Introduction

Crop development is regulated mainly by the external environmental factors of temperature, photoperiod and in certain cases water stress and nutrients availability. Extension of cotton cultivation to low temperature areas dramatically influenced the crop biological cycle especially at the beginning and end. Low-temperature-restriction of the growing period may not be counterbalanced by higher radiation and calls for early maturing (low-producing) varieties.

Low temperatures (< 11^{o}C according to Constabe *et al.*, 1976) at the beginning of the plants life have an effect on post- emergence developmental rates as well as on cotton yield and quality (Christiansen and Tomas, 1969; Sabinina, 1971; Gibson, 1972). Temperatures 5-10^{o}C following a warm period - a case rather frequent in Greece especially the north - are even more harmful (Christiansen, 1963, 1964). Also high temperatures especially when combined with water stress may also affect cotton cultivation (Bhardwaj *et al.*, 1968; Bhatt, 1977; Bhatt and Nathan, 1977). Fiber length varies with date of flowering and this was attributed to moisture by Balls as early as 1915. Untimely or lack of rainfall is a severe problem in cotton producing Greece. Position of the first flowering node- an index of earliness- is affected by the daily temperature range (e.g. Low *et al.*, 1969; Incramov and Mirdaev, 1970; Gipson, 1974), implying possible different effects of day and night temperatures. Generally, rising temperature promotes developmental rates (Bilbro and Ray, 1973).

Therefore cotton growers need information on rates of crop development both for planning the dates of sowing and for determining the weather effect on the time of crop maturation. Since the time between phenological stages depends on weather, there is a need for a biometerological time scale (having the same, value independent of time and space of cultivation) against which the progress of plants towards maturity could be noticed.

Determination of the qualitative and quantitative effects of meteorological parameters and irrigation on all phenological stages of cotton grown in Greece will be attempted here.

Methods and Data

Development towards maturity (M) depends on daily rate of development (R), a function of the prevailing weather (F(w)) between developmental stages S1, and S2

$$M = \int_{S1}^{S2} R dt = \int_{S1}^{S2} F(w) dt = 1 \qquad (1)$$

When only daily mean temperature (T_m) is linearly affecting development

$$R = a + bT_m = b(T_m + a/b) \qquad (2)$$

providing to eq. 1 the form

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$$\sum_{S1}^{S2} [R] = \sum_{S1}^{S2} [b(T_m + a/b)] = M = 1 \quad (3)$$

Dividing by b (and omitting limits), eq. 3 becomes

$$S[T_m + a/b] = 1/b = k \quad \text{or} \quad S[T_m - T_o] = k \quad (4)$$

Eq. 4 provides the thermal time k (in d $_o$C) used for estimating the time to a certain phenological stage under a specified thermal regime. T_o = -a/b is the "apparent" base temperature where development commences and may be different from the physiological temperature. Constants a and b may be determined by regression analysis. Although the relation between temperature (T_a) averaged for the time to a stage (N) is a curvilinear (hyperbolic) function the relation between the inverse of N (1/N=R_a=average rate of development) and T_a is linear.

Linear regression may also be applied when relating other meteorological parameters (rainfall, relative humidity) and irrigation to stage duration. Finally, analysis of variance (ANOVA) was applied to multivariable models to determine the combined effect of the parameters studied in each phenological stage of a cotton crop.

Standard meteorological data of the Hellenic Cotton Board stations network spread all over the cotton producing country was used. Area balanced averages of daily maximum, minimum and mean temperature, rainfall and relative humidity were calculated. Region average data of irrigation water applied were also used.

The phenological data used refer to observations on the 15%, 50% and 85% of completion for the stages of sowing, emergence, squaring, flowering, beginning of boll opening, boll opening and harvesting throughout the cotton cultivation zone of the country, similarly balanced. The period 1986-1994 was studied.

Results

One-variable models

a. Temperature. At first, the time (N) required between phenological stages was related to the corresponding average temperature (T_a) via an exponential equation ($N = a\, e^{-bTa}$).

In Thessaly, N is related better to the extreme values of temperature, mainly the minimum temperature, for which the coefficient of variation R_2 is generally high and particularly for the period between emergence and harvesting it is higher than 0, 95 (Fig. 1). Considering the entire cotton producing zone of Greece (Fig. 2), the only difference with the region of Thessaly is the slightly higher significance of the daily mean temperature.

Plotting the inverse of time (1/N) against T_a (Figs 3 and 4) a straight line would fit to the data, providing the thermal time as the inverse of slope and the threshold temperature (T_o) as the intercept (Table 1). Even one-degree difference in T_a may significantly affect N. For example, considering the thermal time requirements above T_o for the stage, 60 days after sowing, squaring has not started yet at 19 $_o$C, it has just started at 20 $_o$C and it had started already a week ago at 21 $_o$C.

Calculated values of T_o vary among phenological stages, although for certain stages T_o is close to 10$_o$C proposed earlier for cotton (e.g. Constable *et al.*, 1976; Liakatas and Roussopoulos, 1991). 80 d $_o$C are required for emergence above T_o=12.2$_o$C and 1400 d $_o$C for anthesis above T_o = 6.6 $_o$C. A lower number of degree days until anthesis was estimated, presumably above a higher T_o by McMahon and Low (1972).

The significance of the minimum, mean and maximum temperatures in all developmental stages is expressed by the corresponding R_2 values (Fig. 5). In Thessaly, maximum temperature is more important for stages from sowing until flowering, but when considering longer periods (up to boll opening or harvesting) it is the minimum temperature that plays the most significant role. For stages starting around anthesis, maximum is again the most determining temperature. This interchange of significance of extreme temperatures must be related to the degree of deviation (stress) of the corresponding parameter from its optimum value. Over the whole country, apart from the late stages (after about anthesis), the minimum temperature affects stage duration more than the maximum temperature, probably due to the higher stress (thermal deficit) imposed by the contribution of cooler districts (Macedonia and Thrace) in determining T_a. This could also explain the weaker correlations of the mid - (in comparison with the early - or late) season stages that are completed under reduced thermal stress(higher T_a values).

b. Rainfall and irrigation. Rainfall significantly affects the time required for cotton development (Fig. 6). Cotton life cycle is linearly influenced (R_2=0.91) by rainfall, causing a two-week delay of harvest for a total rainfall increase of 100mm in Thessaly. For the usual rainfall range (70-330 mm) the harvest time ranges longer than a month, with the earliest harvest (in the driest year) 160 days after sowing. During specific stages of crop development, rainfall is most significant (R_2=0.87) between sowing and flowering. Rain falling between squaring and beginning of boll opening does not differentiate significantly the time required for the completion of these stages. After boll opening, however, rainfall regains its significance (Fig. 7). Similar is the effect of rainfall on a country scale (Figs 8,9).

Adding irrigation water to rainfall reduces the number of stages in which water plays an important role and weakens correlelations (Rmax = 0.89 compared with 0.95).

c. Relative humidity: In Thessaly, the period that seems (Fig. 10) to be affected more (R_2=0.61) by relative humidity (RH) is that between sowing and emergence, followed by the stages sowing-squaring and sowing-flowering, although with much lower R^2 values (<0.31). Lengthening of the period due to RH increase is not very obvious on a country scale. In this case, the stages starting at squaring are the most sensitive to RH variations (R^2 = 0.4). It is possible that the relatively high dependence of mainly early stage duration on RH in Thessaly may be indirect via the effect of temperature and rainfall. The rainfall effect in the entire cotton producing country is drastically reduced after squaring due to moisture uniformity in the plants environment, as a result of the generally applied irrigation. However, the significant decrease of the temperature effect is only minor, analogous to thermal stress due to relatively high temperatures in the same time.

Multi-variable models

As meteorological parameters and irrigation may be interrelated or act in combination to affect stage duration, a multiple correlation analysis was attempted for one district (Thessaly).

Analysis of variance indicated the stages mostly affected by the combination of the minimum, mean and maximum temperatures, the relative humidity and the sum of rainfall plus irrigation.

The model fitted in the period between sowing and harvesting is:

period duration=222.06+2.2Tmean - 8.33 Tmin+0.16 Tmax+0.51 RH-0.02 (Rain+Irrig.)

This relation is statistically significant approximately at the 99% (P=0.016) level. R^2 shows that the model may explain 97.1% of variation in duration where its adjusted (for degrees of freedom) value (Ra^2) is 92.3%. The standard error of estimate (S.E. of Est.) is 2.13 and the mean absolute error (MAE) is 1.05. As the Durbin-Watson parameter (DW) is 3.02 (higher than 1.4), there must be no important autocorrelation in residuals. Plotting observed against predicted duration (Fig. 11), it may be observed that scattering around the straight line of slope 1:1 is negligible.

To make the model as simple as possible, all variables with P>0.1 were then excluded, namely Tmax (P=0.95), Tmean (P=0.32) and the sum Rain+Irrig.(P=0.2). The stepwise regression led to a two-variable model where only the minimum temperature and the relative humidity in combination would significantly (P=0.0005) affect this period duration:

period duration: 246.95-6.31Tmin+0.41 RH

In this case R^2=0.92, Ra^2=0.9 and still very small scattering around the time of absolute fitting (slope 1:1).

In the other stages of development, a varying number of variables could not be obliterated from the model. The equations of the simplified models are given below:

sowing - flowering
stage duration =96.61- 3.72Tmax +3.85 Tmin+0.47 RH+0.05(Rain+Irrig.)

sowing - squaring
stage duration = 134.24-4.25 Tmean +0.28RH

emergence - harvesting
stage duration = 304.8-9.27 Tmin

emergence - flowering
stage duration= 175.05-4.26 Tmean

emergence - squaring
stage duration= -70.76+7.1 Tmin+0.12(Rain +Irrig.)

emergence - boll opening
stage duration= 271.37-6.99 Tmin - 0.04(Rain+Irrig.)

squaring - boll opening
stage duration = 211.56 - 3.16 Tmax - 0.04 (Rain+Irrig.)

squaring - harvesting
stage duration = 256.4 - 4.16 Tmax - 0.04 (Rain+Irrig.)

and the statistics from the ANOVA are provided in Table 2.

Conclusions

The role of the daily extreme temperatures (especially of the minimum) is more important than that of the mean temperature. Their significance is stage dependent. Stage shortening due to temperature increase follows an exponential function, with R^2 values surprisingly high for the extensive areas of data collection. Greater amounts of rain water or (less often) higher relative humidity slow down crop development, resulting in higher thermal time requirements.

The combined effect of all parameters studied is characterized by the prevailing role of temperature, the parameter that cannot be obliterated during model simplification. The significance of the other parameters in a multi-variable model is stage dependent. For a high level of statistical significance (>99%) the combination of mostly two variables, i.e. temperature (minimum, mean or maximum) and usually available water (rainfall plus irrigation) determines the length of cotton phenological stages.

Models based simply on temperature may be of reduced reliability but are useful for local application where other influencing parameters are rather uniform. When development models are to be used in areas covering more than one climatic zones, simply a water factor (taking into account that most cotton varieties are photo-neutral) would provide a desirable improvement. On the other hand, since maximum and minimum temperature vary space-wise and the development response to day and night temperatures may be different, models including both should be preferred.

Meteorological variables should be measured in the physical micro-environment of a cotton crop. Such measurements are not taken on a routine basis. They are available, however, for a number of years and cotton fields all over Greece and will be correlated with data from standard meteorological stations, so that estimation of in-canopy weather conditions could be based on routine observations.

Acknowledgements

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Table 1. Thermal time (1/a), threshold temperature (T_o) and time (N) to 50% of a stage completion at an average temperature (T_a).

Stages	WHOLE COUNTRY				THESSALY			
	R_2	1/b (dC_o)	-a/b=T_o ($_oC$)	N(d) / $\bar{T}$	R_2	1/b (dC_o)	-a/b=T_o ($_oC$)	N(d) / $\bar{T}$
Sowing – emergence	0.26				0.65	80	12.2	14/18
- squaring	0.02				0.55	904	6.3	60/21.5
- flowering	0.78	1587	-1.8	83/21	0.83	1404	6.6	86/23

- start of boll opening	0.70	3378	1.4	141/22.5	0.64	3921	-2.6	142/25
- boll opening	0.63	4032	3.4	169/22.5	0.36			
- harvesting	0.72	4292	2.7	174/22	0.58	4739	-3.0	176/24
Emergence – squaring	0.27				0.71	645	8.9	49/22
- flowering	0.78	1297	-3.5	70/22	0.90	1188	7.6	78/24
- start of boll opening	0.62	2849	-0.9	129/23	0.59	3247	0.5	130/25.5
- boll opening	0.58	3401	0.9	145/22.5	0.40	3663	-0.3	145/25
- harvesting	0.66	3745	0.8	157/23	0.54	4065	-0.6	159/25
Squaring – flowering	0.24				0.42	467	9.3	26/27
- start of boll opening	0.49	3077	11.9	83/25	0.32			
- boll opening	0.53	3425	10.4	100/24	0.23			
- harvesting	0.71	3215	4.3	118/23	0.45	3745	6.8	200/25.5
- flowering - boll opening	0.29				0.04			
- harvesting	0.50	2512	4.6	91/23	0.13			
start of boll opening - harvesting	0.84	709	1.3	33/20	0.37			
boll opening – harvesting	0.56	269	-3.6	19/18	0.63	270	5.4	17/21

Table 2. Analysis of variance of the simplified model for various stages cotton development.

Development Stages	P	R2	Ra2	S.E of Est	MAE	DW
Sowing – flowering	0.003	0.97	0.93	1.17	0.64	2.99
Sowing – squaring	0.01	0.77	0.70	1.87	1.22	2.82
Emergence – squaring	0.004	0.85	0.80	1.57	1.07	2.02
Emergence – flowering	0.001	0.89	0.87	1.65	1.18	2.17
Emergence - boll opening	0.001	0.90	0.86	2.80	1.98	1.40
Emergence – harvesting	0.0001	0.89	0.87	3.11	2.30	2.88
Squaring - boll opening	0.003	0.85	0.80	2.70	1.53	2.59
Squaring - harvesting	0.009	0.79	0.72	3.59	2.53	2.90

Figure 1. Effect of stage min temperature on time required, Thessaly (Emergence 50% - Harvesting 50%).

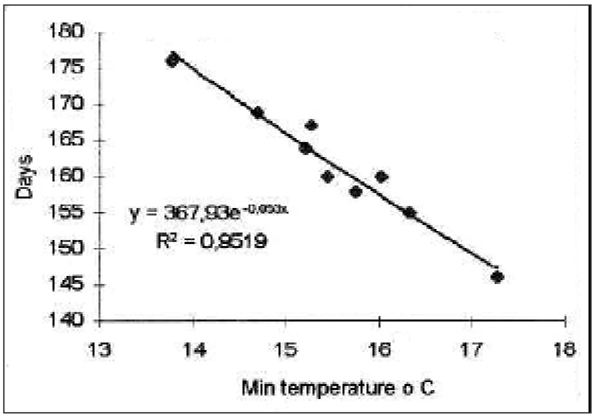


Figure 2. Effect of stage average mean temperature on time required. Total whole country (Sowing 50% - Flowering 50%).

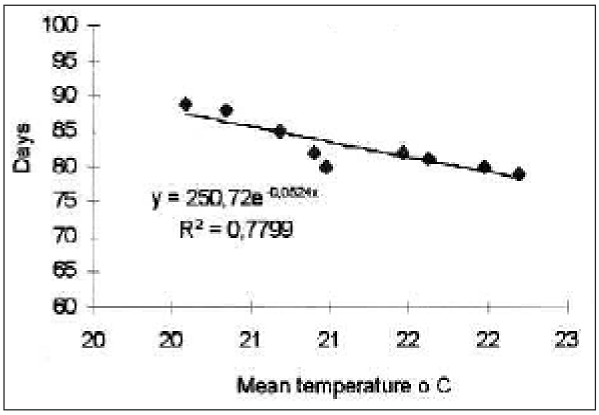


Figure 3. Effects of stage average mean temperature on the inverse of time (1/days) Thessaly (Sowing 50% - Flowering 50%).

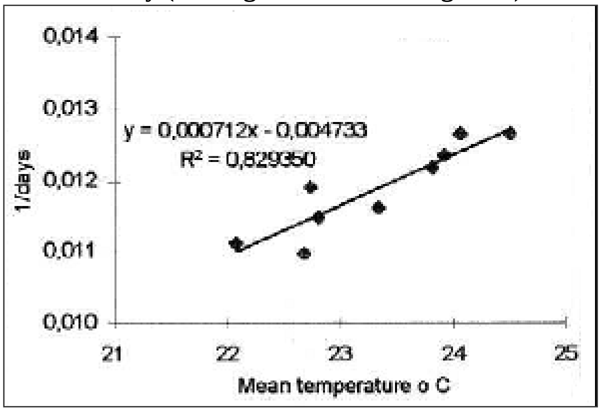


Figure 4. Effect of stage averae mean temperature on the inverse of tim (1/day) Total whole country (Sowing 50% - Flowering 50%).

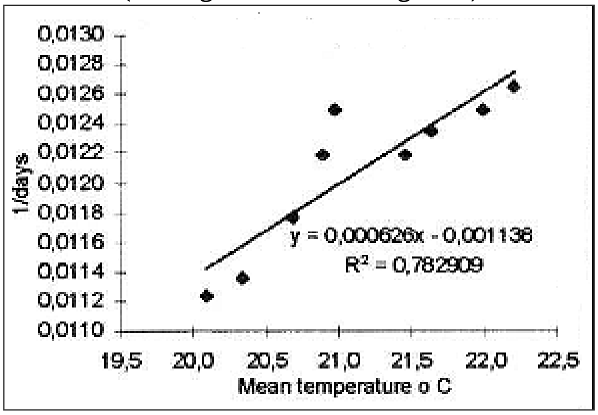


Figure 5a. Effect of stage average temperature (mean, max, min) on 1/days, expressed by R_2 coefficient values for all stages in Thessaly (50% of completion stage).

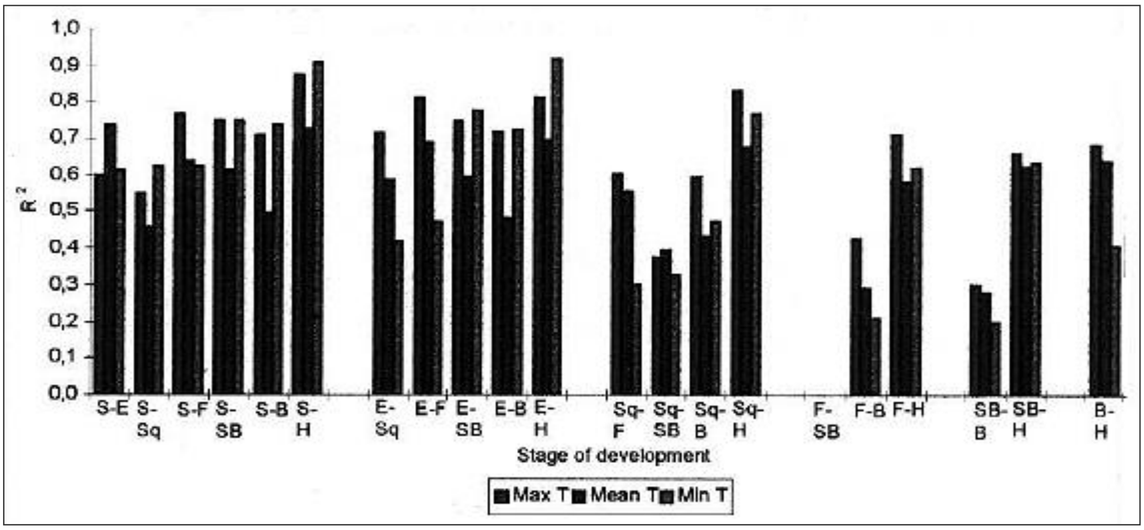


Figure 5b. Effect of stage average temperature (mean, max, min) on 1/days, expressed by R_2 coefficient values for all stages in total country (50% of completion stage).

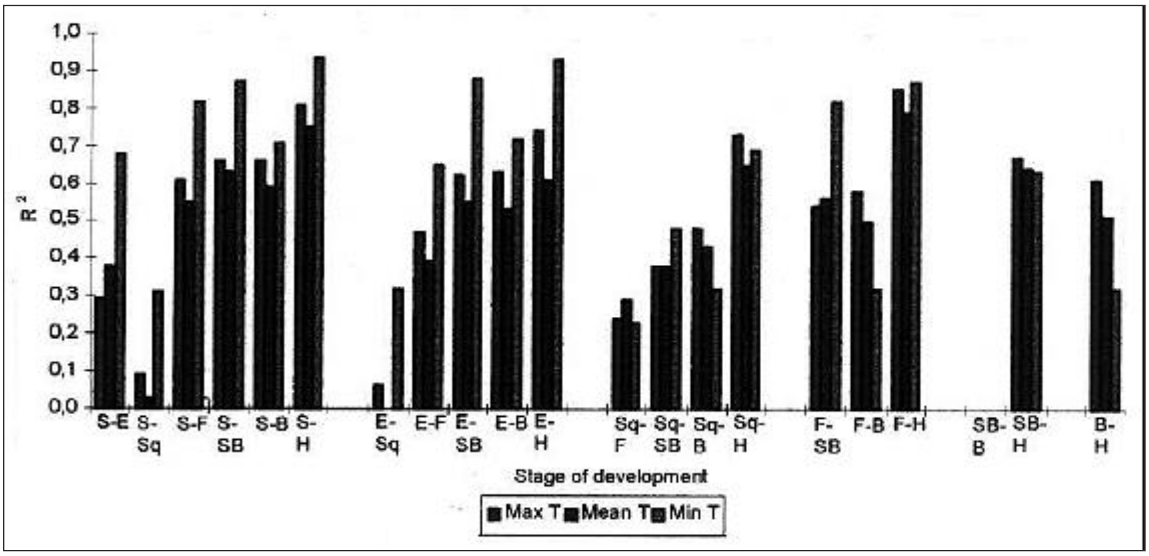
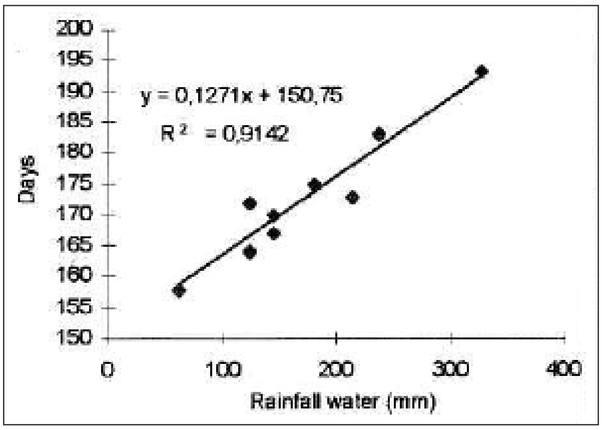


Figure 6. Effect of stage of rainfall water on time required Thessaly (Sowing 15% - Harvesting 15%).



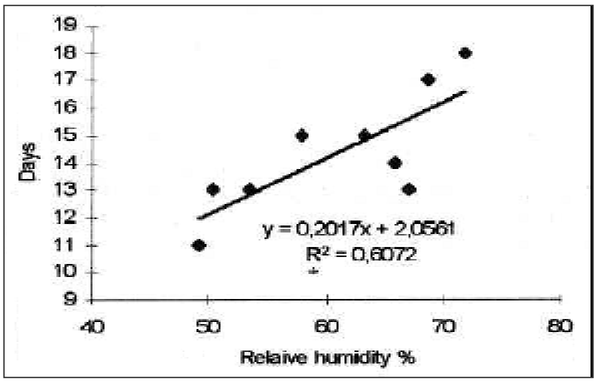
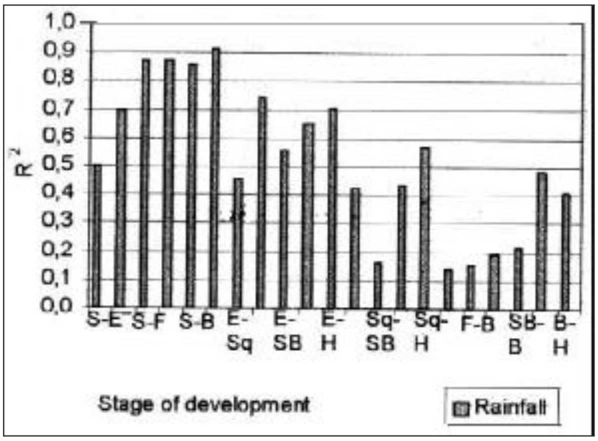


Figure 7. Effect of stage of rainfall on days expressed as R2 coefficient values for all stages, Thessaly (15% completion all stages).



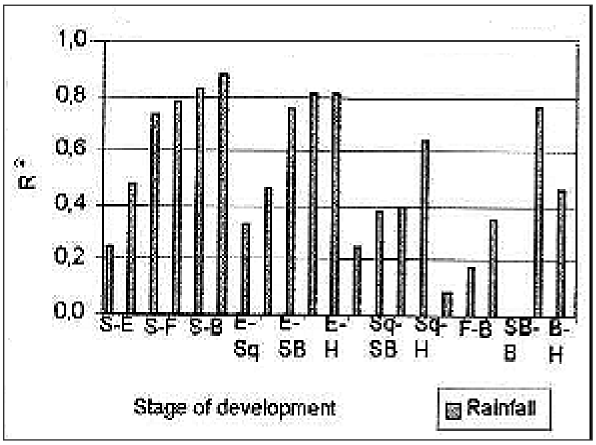


Figure 10. Effect of stage relative humidity on time required Thessaly (Sowing 50% - Emergence 50%).

Figure 8. Effect of stage of rainfall water on time required whole country (Sowing 15% - Harvesting 15%).

Figure 9. Effect of stage of rainfall on days expressed as R2 coefficient values for all stages , whole country (15% completion all stages).

Figure 11. Predicted against observed stage duration for Thessaly (Sowing 50% - Harvesting 50%).