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ASSESSMENT OF COTTON PHENOLOGICAL STAGES USING AGROCLIMATIC INDICES: AN INNOVATIVE APPROACH.

STIMA DEGLI STADI FENOLOGICI DEL COTONE MEDIANTE INDICI AGROCLIMATICI: UN APPROCCIO INNOVATIVO

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Abstract

Reliable long time-series of phenological observations are not widely available, since recording requires special expertise. In Greece, phenological stations network exists only in fruits trees and for the past 17 years. Thus, crops' phenological data are rare, whereas the few existing data bases are discontinuous. However, cotton (*Gossypium hirsutum*) is the most dynamic extensive cultivation in Greece and a crop of great importance for the national economy. Hence, there is a necessity for assessing cotton phenological stages using alternate methods. In this paper, an innovative approach for assessing phenological stages in cotton cultivation using agroclimatic indices is presented.

Keywords: *Gossypium hirsutum*, phenology, GDD, Cardinal Temperatures.

Riassunto

*Lunghe serie storiche affidabili di dati fenologici non sono facilmente disponibili, poichè la loro registrazione richiede una particolare perizia. In Grecia esiste solo una rete di stazioni fenologiche per i fruttiferi, istituita da 17 anni. Di conseguenza, i dati fenologici sulle colture sono rari, mentre le poche basi di dati esistenti sono discontinue. In Grecia, il cotone (*Gossypium hirsutum*) è la più dinamica coltivazione estensiva, di grande importanza per l'economia nazionale. Perciò c'è la necessità di stimare con metodi alternativi gli stadi fenologici del cotone. In questo lavoro, viene presentato un approccio innovativo alla stima delle fasi fenologiche nella coltivazione del cotone mediante indici agroclimatici*

Parole chiave: *Gossypium hirsutum*, fenologia, gradi giorno, temperature cardinali

Introduction

Complete and reliable meteorological long-series data-bases are difficult to be found. Data loggers contribute to automatic recording of meteorological data, but still temporal gaps and discontinuities exist due to sensor failures or human errors (delayed upload of data, pure maintenance etc.) Meteorological data come usually from a very sparse meteorological network, sometimes incomplete and/or not always available. Furthermore, phenological growth stages data are even more difficult to be found, since they require the presence of an expert in order to identify the onset and end of the phenophase. Phenological observations in Greece started in 1950 by agricultural research Institutes and the Ministry of Agriculture, focused on research programmes and thus, not on a systematic basis. The recording of observations of phenological stages started in the early 90's. Government organizations named Centers of Plant Protection and Quality Control (CPPQC) started collecting phenological data for fruit trees. For example, CPPQC of Volos has one of the largest phenophases data base for fruit trees, for 17 consecutive years (from 1991 until today). Other CPPQCs, in other Prefectures of Greece have also phenological observations data bases for fruit trees (Tsiros *et al.*, 2008). But the lack of available personnel for the supervision of the phenological-agrometeorological stations (most of the stations operate automatically) in

combination with disastrous extreme weather events has resulted to discontinuous data bases.

Besides the existence of "recent" time-series, the discontinuity and the uneven spatial distribution of phenological stations in Greece, another problem is that only in fruit trees there is a phenological network favouring and receiving data for plant phenology (Tsiros *et al.*, 2008). This is one of the main reasons for the scarcity of crops' phenological stages and the discontinuity in any existing data base. For example, Domenikiotis *et al.* (2003 and 2004) used cotton phenological stages for production estimation and Mygdakos and Gemtos (1998) for relating Growing Degree Days (GDD) with cotton phenophases and final yield. Other than these records, no other information for crops' phenological data is found. Therefore, many researchers and practitioners use the phenological stages for crops provided by F.A.O. (Food and Agriculture Organization) for Mediterranean.

Summarizing, phenological observations have a short history in Greece, whereas no literature is related to phenophases. Thus, there is a need to assess crop phenological stages using alternate methods. This paper presents an innovative approach for assessing phenological stages in cotton cultivation using agroclimatic indices. Specifically, GDD along with temperature range, cardinal temperatures and rainfall anomaly are used for

Tab. 1 - Cotton (*Gossypium hirsutum* L.) phenophases monitored in Greece. BBCH-code by Meier (1997).

Tab. 1 – Fenofasi del cotone (*Gossypium hirsutum* L.) monitorate in Grecia. Codice BBCH (Meier, 1997).

| Phenological Growth Stage | BBCH code |
|-----------------------------------|-----------|
| Planting | 00 |
| Emergence | 09 |
| Cotyledon | 10 |
| First leaf – 7 th leaf | 11-17 |
| Square | 51-52 |
| Blooming | 61-67 |
| First bolls | 71 |
| Bolls open | 80-89 |
| First picking - Third picking | 99 |

Sources: Domenikiotis *et al.*, 2006; Mygdakos and Gemtos, 1998.

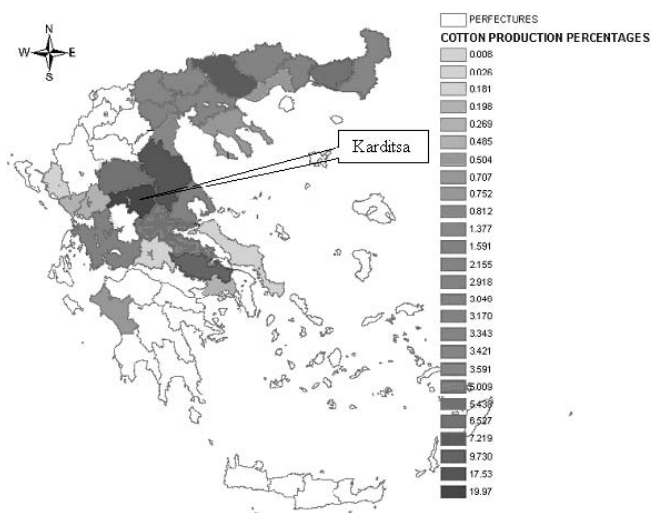


Fig. 1- Location of the study area, Prefectures of Greece and cotton production percentage contribution (Domenikiotis *et al.*, 2003).

Fig. 1 – Localizzazione dell'area di studio, prefetture greche e contributo percentuale alla produzione nazionale di cotone (Domenikiotis *et al.*, 2003).

assessing cotton phenophases. Finally, the use of NOAA/AVHRR Land Surface Temperature (LST) in GDD computations is examined.

Cotton Phenology in Greece

Greece is the primary cotton productive country in European Union (EU). Cotton is the most dynamic extensive cultivation in Greece. It's a crop of great importance for the agricultural and national economy. But beside cotton's great importance as a field crop, there is no systematic recording of phenological observations or even of the development stages of cotton. The only records that exist start in 1991, for certain years (1991-1996 and 2005-2008) and for specific regions (Mygdakos and

Gemtos, 1998; Domenikiotis *et al.*, 2006), and were obtained for research reasons. The principal growth stages of cotton being monitored along with their corresponding BBCH Code (Meier, 1997) are illustrated in Table 1.

In Greece, the varieties of cotton that are cultivated belong to the *Gossypium hirsutum* L. specie. Cotton in Greece is mainly cultivated between 35°N and 41°N latitude, and only about 0.5% is grown in areas lower than the 38°N parallel. Generally, cotton is cultivated in Central and Northern Greece. The most significant cotton production areas are depicted in figure 1. During spring and autumn in these areas, the climate is usually not stable, having a major influence on cotton, as both seasons are very critical for the crop (planting-harvesting periods) (Domenikiotis *et al.*, 2003).

In Greece, cotton needs 170 to 210 days in order to fulfil its biological cycle, according to the variety and the climatic conditions. The biological cycle of the cotton plant can be divided into five stages (Danalatos, 2007):

1. Germination: the period from sowing to emergence, where the hypocotyl with cotyledons is breaking through the soil surface (Meier, 1997). Germination usually lasts eight to ten days but in years with unfavourable weather conditions it can reach up to two to four weeks.
2. First Development: the period from leaf development, where the cotyledons are completely unfolded, to the detection of first square. This stage lasts from 35 to 50 days according to the variety and the weather conditions.
3. Inflorescence Emergence: the period from the formation of the first square to the detection of the first flowers. The duration of the stage is 20 to 25 days.
4. Flowering and development of fruits. This stage starts with the first flowers opening and ends when almost all bolls have attained their final size. The duration of the stage is 45 to 50 days.
5. Ripening of fruits: the period from the first open bolls on the first fruiting branches until about 90% of bolls are open (Meier, 1997), lasting from 45 to 70 days according to the variety and the weather conditions.

Environmental Temperature and Crop Growth

Environmental temperature (soil and air temperature) has a primary role in plant growth since it governs the physical and chemical processes that control biological reactions within plants such as solubility of plant nutrient substances and diffusion rate of gases and liquids (Mavi and Tupper, 2004). Soil temperature is an environmental factor that influences the germination of seeds, the functional activity of the root system, the rate of plant growth and the appearance of plant diseases (Singh *et al.*, 1998). Air temperature is the most important climatic variable that affects plant growth. Temperature delimits the areas of successful production of most agricultural crops (Pereira, 1982).

Crops vary in their sensitivity to temperature. Annual plants do not need a cold period during their development, except for plants that germinate in autumn and flower in spring or summer after a cold winter. In gen-

eral, there is a certain temperature range beyond which crop growth and development is affected. Cotton is a crop grown in tropical and subtropical regions and thus, temperature is a very important environmental factor, especially when the crop is cultivated into colder regions. Extreme temperatures are associated with low and variable cotton yields (Oosterhuis, 1997). Yield and fiber characteristics respond to variations of daily mean temperature and temperature range (Roussopoulos *et al.*, 1998).

GDD, also called heat units or thermal time, is a simple index for relating plant growth, development and maturity to air temperature. The concept is widely accepted as a basis for building phenology and population dynamic models (Mavi and Tupper, 2004). Degree-day units (°C-d) are often used in agriculture in order to estimate or predict the lengths of the different phases of the development in crop plants. Indicatively, Table 2 presents the phenology of two cotton varieties and depicts calendar days and DD needed for each growth stage.

GDD represents the accumulation of temperature above a critical threshold throughout the growing season, usually calculated on a daily basis. Thus, for a summation based on daily mean air temperature using the standard degree-day method the following equation is used:

$$GDD = \sum_{i=1}^n \delta_i (T_{mean} - T_c) \quad (1)$$

where $\delta_i=1$ for $T_{mean} > T_c$, $\delta_i=0$ for $T_{mean} \leq T_c$, T_{mean} is the mean daily air temperature (°C), T_c is the threshold or base temperature (°C) and n is the number of days according to the period under consideration.

It is widely recognized that different crops have different temperature thresholds to initiate development. The basis temperature for cotton (*Gossypium hirsutum* L.) according to the international literature ranges from 10°C to 15°C, whereas the thermal time needed for cotton phenological development is about 1450-1800 °C-d (Danalatos, 2007). In Greece, the most commonly used T_c are 10°C and 12°C, whereas above normal crop production occurs when GDD is higher than 1800 °C-d. Table 3 presents the phenology of Zeta 2 cotton variety in Karditsa prefecture for the period 1991-1995 and depicts average number of calendar days, GDD and accumulated GDD (Acc.GDD) needed for each growth stage. Other methods for estimating GDD such as maximum instead of means method or the reduced ceiling method are available by Perry *et al.* (1997).

Even though degree-days (DD) is a simple and useful index, it has a number of weaknesses. A number of factors affecting the predictive capability of DD have been identified. Also, it is essential that regardless of the calculation method, DD are never more than estimates of

Tab. 2 - Phenology of cotton (*Gossypium hirsutum*) cultivars (Acala SJ-2 and SJ-5) (Fageria *et al.*, 1997).

Tab. 2 – Fenologia delle cultivar del cotone (*Gossypium hirsutum* L.) Acala SJ-2 e SJ-5 (Fageria *et al.*, 1997).

| Growth Stage | Calendar Days | | Degree Days (base 15.6°C) |
|------------------------|---------------|---------|---------------------------|
| | Range | Average | |
| Sowing to Emergence | 5-20 | 10 | 50 |
| Emergence to Square | 40-60 | 50 | 450 |
| Square to Bloom | 20-27 | 23 | 330 |
| Bloom to Open bolls | 45-80 | 58 | 950 |
| Normal crop production | 190-210 | 200 | >2800 |

Sources: Adapted by El-Zik and Sevacherian, 1979.

Tab. 3- Cotton phenological stages and average number of calendar days and GDD (base 15°C) for the period 1991-1995 for Palama region (Mygdakos and Gemtos, 1998).

Tab. 3 – Fasi fenologiche del cotone e numero medio di giorni e di gradi giorno (soglia 15°C) per il periodo 1991-95, per la regione di Palama (Mygdakos e Gemtos, 1998).

| Phenological Stages | Days | Acc. days | GDD | Acc.GDD |
|--|------|-----------|-----|---------|
| Planting to Emergence | 9 | 9 | 17 | 17 |
| Emergence to 1 st leaf | 10 | 19 | 17 | 34 |
| 1 st leaf to 2 nd leaf | 10 | 29 | 24 | 58 |
| 2 nd leaf to 3 rd leaf | 10 | 39 | 47 | 105 |
| 3 rd leaf to squaring | 13 | 52 | 121 | 226 |
| Squaring to blooming | 24 | 76 | 231 | 457 |
| Blooming to bolls open | 53 | 129 | 522 | 979 |
| Bolls open to 1 st picking | 40 | 169 | 205 | 1184 |
| 1 st picking to 2 nd picking | 14 | 183 | 47 | 1231 |
| 2 nd picking to 3 rd picking | 8 | 191 | 14 | 1245 |

the development time (Perry *et al.*, 1997; Bonhomme, 2000). Specific limitations according to the use of DD are (Mavi and Tupper, 2004):

- While using DD, the physiological and mathematical bases upon which they are founded are sometimes forgotten, resulting in questionable interpretations (McMaster and Wilhelm, 1997).
- A lot of weight is given to high temperature (except from the ceiling methods).
- There are no differentiations regarding to the seasons.
- The daily range of temperature is not taken into consideration, and often this variable is more important than the mean daily temperature.
- No assumption/allowance is made for threshold tem-

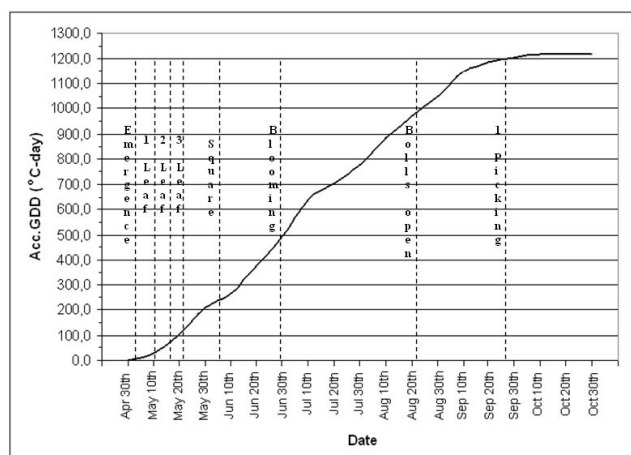


Fig. 2 - Acc.GDD values for 1996 and estimated phenological stages based on the 1991-1995 average Acc.GDD values.

Fig. 2 – Valori cumulati dei gradi giorno nel 1996 e fasi fenologiche stimate sulla media 1991-95 dei valori cumulati di gradi giorno.

perature changes with the advancing stage of crop development.

- Net responses of plant growth and development are due to the temperature of the plant parts, and they may be quite different from the measured air temperature. The cumulative effect of this difference through the entire growing can be very large.
- Soil fertility that may affect crop maturity is not taken under consideration.
- Topography, altitude and latitude and their effects to crop growth are not taken into account.

In spite of these limitations, DD is always useful in answering a number of questions in plant phenology and growth (Mavi and Tupper, 2004). In order to eliminate the weaknesses of GDD, the latter can be combined with other agroclimatic indices. Agroclimatic indices that can be used to reduce the limitations derived by GDD are described below.

Daily Temperature Range (DTR). During the growing season cotton crops experience temperature variations ranging from 5°C to 45°C (Reddy, 1994). Daily amplitudes of soil and near soil air temperatures have a vast influence on the growth and development of cotton. Roussopoulos *et al.* (1998) studied the growth and development of cotton plants grown in pots in growth rooms under constant day/night temperature and varying temperature regimes throughout the day and/or night with common mean temperature (22°C), using heat units calculated with a basis temperature of 12°C (except from the initial stage, when it was lower). They found that vegetative growth was almost exclusively time and temperature dependent, whereas varietal differences were insignificant. Also, they remarked that temperature variation affected vegetative growth to a greater extent in the early than in the later stages of development.

Cardinal Temperatures (CT). Three cardinal temperatures, also called cardinal points, are recognized and used

(Mavi and Tupper, 2004): a minimum temperature below which no growth occurs, an optimum temperature at which maximum plant growth occurs and a maximum temperature above which the plant growth stops. These soil temperatures are of vital importance in plant life and activity. The cardinal points for the germination of cotton plant varieties cultivated in Greece are 10-12°C, 34°C and 39-41°C (Danalatos, 2007), corresponding to the minimum, optimum and maximum temperatures, respectively. In general, cardinal temperatures and especially optimum temperatures vary with stage of plant development and the physiological process of concern.

Discrete and cumulative rainfall anomalies (DRA and CRA). Available moisture is another important factor affecting growth and yield of cotton. Although cotton is mostly an irrigated crop, proper rainfall distribution during the growing season is also important (Fageria *et al.*, 1997). The rainfall anomaly directly measures the shortage of rainfall, and is expressed by the difference between the observation and the long-term climatological mean. Also, it is possible to consider a cumulative precipitation anomaly. These anomalies are primitive indices of drought, and are not especially informative, since the importance of the anomaly depends on climate and the magnitude of the anomaly is related to normal conditions. Nevertheless, these indices are simple and easy to use, and quite efficient in depicting amount and duration of water deficit or surplus when calculated using departures of monthly measurements from long-term monthly averages.

Case Study

A case study is conducted in order to evaluate the capability of GDD for assessing cotton phenological stages. The study area is the area of Palama in Karditsa Prefecture, located in Central Greece (figure 1). Karditsa is one of the most important cotton productive prefectures, having the highest cotton production percentage contribution (figure 1).

Average values of Acc.GDD (base 15°C) for the period 1991-1995 (Table 3) are used as basis for the estimation of the phenological stages of Zeta 2 cotton variety. Applying equation (1), GDD per ten-day and Acc.GDD are computed for the year 1996 using NOAA/AVHRR LST over Palama region and based on the average Acc.GDD values needed per phenophase, the phenological stages for 1996 are estimated. GDD is computed using a base temperature of 15°C. For avoiding mixed pixel effects, the area where LST is obtained is double-checked with Corine 2001 database. The estimated phenological stages for 1996 are validated using field observations from the area of Palama. Finally, the agroclimatic indices are used to describe "abnormalities" in the phenological development of cotton cultivar.

Results and Discussion

The main factors affecting growth of cotton are environment (climate and soil), pests, the cultivated varieties, and cultural practices. Temperature is the most important climatic factor affecting cotton phenological development. If all conditions are favorable, including cultural

practices and pest management, the development of cotton follows a specific phenological pattern. In this study, GDD values for five consecutive years (1991-1995) are used in order to define the connection of this pattern of Zeta 2 variety with GDD, for Palama region. GDD computed for the year 1996 using LST is used to test the predictive capability of the method. Furthermore, the pattern in which simple agroclimatic indices are reducing the limitations of GDD is examined.

The Acc.GDD values for 1996 along with the estimated phenological stages based on the 1991-1995 average values are presented in figure 2. In Table 4 are illustrated the observed versus the predicted dates of cotton phenological stages using the GDD method in Palama for 1996. The late emergence (usually emergence occurs around 22nd of April) is due to delayed planting caused by the relatively low temperatures that prevailed during the first two ten-days of April. CTs were in acceptable range after the 20th of April, giving optimum values (T_{mean} around 18°C) after the 1st of May. DTR's were also favorable and this way no limitations are induced due to this parameter.

Table 4 shows that the highest error occurred in predicting the appearance of the second and third leaf. This is probably due to the irregularly low rainfall that exhibited the first three ten-days of the growing season. Indicatively, whereas in 1994 rainfall values for these ten-days (April 3rd – May 2nd) were 70mm, 98mm and 14mm, respectively, in 1996 the exact values were 22mm, zero and 11mm. The other predicted dates were accurate with the difference between the observed and the predicted date ranging from zero to two days. No predicted values were obtained for October due to low temperatures. That's also accurate, since in 1996 due to unfavorable weather the second and third pickings of cotton were very low, giving minimum contribution to the final yield. The year 1996 was the worst year for cotton cultivar. The yield data presented in Table 5 confirm this fact.

The agroclimatic indices described earlier can deal with some of the limitations of DD and are selected due to their simplicity. CT's can be used in order to identify and limit the problem derived by unfavorable temperatures, whereas the use of GDD by definition delineates the season. In addition, using the DTR, daily amplitudes of temperature are taken into consideration, whereas water stresses affecting growth can be identified using DRA or even better CRA. Other limitations such as soil fertility, topography and altitude, and their effect to crop growth are constrained by the fact that the methodology is applied to the same region resulting to minimum variations of these parameters.

Regarding to the problem deriving from the use of a constant base temperature throughout the entire growing season, the validation of the results showed that there is no need for using different threshold values according to the growth stage. However, in order to determine the base temperature per variety, records of developmental rates obtained for different daily temperature ranges and in absence of possible limitations (non-optimal photoperiod, water stress etc.) are required (Bonhomme, 2000). For Zeta 2 cotton variety, the results justify the use of

Tab. 4 - Observed* and predicted dates using the GDD method (based on LST) of cotton phenological stages for the area of Karditsa for 1996.

Tab. 4 – *Date osservate* e previste usando il metodo dei gradi giorno (basato sulla Land Surface Temperature) delle fasi fenologiche del cotone per il 1996 nell'area di Karditsa.*

| Phenological Stages | Observed Date | Predicted Date |
|---------------------|---------------|----------------|
| Planting | 24/4 | ---- |
| Emergence | 5/5 | 6/5 |
| First leaf | 11/5 | 11/5 |
| Second leaf | 20/5 | 15/5 |
| Third leaf | 29/5 | 22/5 |
| Square | 5/6 | 5/6 |
| Blooming | 1/7 | 29/6 |
| Bolls open | 22/8 | 22/8 |
| First picking | 28/9 | 28/9 |
| Second picking | 28/10 | ---- |
| Third picking | 10/11 | ---- |

*Observed dates adapted by Dalezios et al., 2001.

Table 5: Percentage departure of average cotton yield for the area of Karditsa (data provided from the National Statistical Service of Greece).

Tab. 5 – *Scarti percentuali delle rese medie di cotone per l'area di Karditsa (dati forniti dal Servizio Statistico Nazionale greco).*

| Year | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
|-----------------------------|--------|-------|-------|-------|-------|--------|
| Yield (kg/ha) | 2,494 | 2,805 | 3,198 | 3,381 | 3,098 | 1,863 |
| Percentage Departure | -11.1% | 0.0% | 14.0% | 20.5% | 10.4% | -33.6% |

15°C as base temperature. Nevertheless, it is of great importance not to forget that every variety has its own unique characteristics.

Conclusions

The knowledge of cotton growth and development pattern is essential to improve management practices and maximize yield. GDD can be used alone (favorable conditions needed) or along with other agroclimatic indicators in order to model cotton phenology and growth. Furthermore, it is of great importance to take into account the daily temperature range, especially when below optimal temperatures prevail during nighttime. This way accurate estimation of principal growth stages can be accomplished.

The GDD as estimated by the satellite data identifies in a similar way the cotton phenology. Using satellite derived LST for extracting GDD seem to work well for homoge-

neous areas where cotton is the dominant cultivation. Further work will examine mixed pixel cases.

GDD has a number of limitations, but despite its constraints is a useful and well adjusted index. The great value of GDD in modeling cotton phenology lies in its simplicity. Thus, the use of many and sophisticated agrometeorological indices will increase the complexity of the procedure and ruin this advantage. Nevertheless, the physiological and mathematical bases upon which the index was founded must always be considered in order to avoid misinterpretations.

Lastly, DD are never more than estimates of the development time and the growth stage and must always be validated using phenological observations. Thus, it is preferable not to use GDD if there are no recorded phenophases in order to calibrate the correspondence between thermal time and principal growth stages.

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