AlertInf: emergence predictive model for weed control in maize in Veneto

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Abstract: *Weed control is one of the most important management practices in maize production. Weed time of emergence influences the weed-crop competition, determining the level of damage that the infestation may cause to crop yield. The ability to predict weed emergences can help to optimize control timing, increasing the efficacy of both chemical and mechanical methods and consequently reducing herbicide use. The Department of Environmental Agronomy and Crop Science of the University of Padova has developed the* ***AlertInf*** *model, which provides the percentage of emergence reached by a given weed species in real time using meteorological data, such as soil temperature and rainfall. The Agrobiometeorology Unit of ARPA Veneto has organized an interactive support service using the* ***AlertInf*** *model on their webpage www.arpa.veneto.it/upload_teolo/agrometeo/infestanti.htm to help farmers in planning weed control.*
Keywords: *emergence prediction, weed emergence dynamic, annual weeds, support service*

Riassunto: *La gestione delle infestanti è una delle pratiche più importanti nella coltivazione del mais. Il tempo di comparsa delle malerbe influenza la competizione tra infestante e specie coltivata determinando l'entità del danno che l'infestazione può provocare in termini di resa della coltura. La capacità di prevedere le emergenze delle malerbe può aiutare ad ottimizzare i tempi di controllo, può aumentare l'efficacia dei metodi usati sia chimici che meccanici e di conseguenza può ridurre l'uso degli erbicidi. Il Dipartimento di Agronomia Ambientale e Produzioni Vegetali dell'Università di Padova ha sviluppato il modello* ***AlertInf*** *in grado di fornire la percentuale di emergenza raggiunta da una data specie infestante in tempo reale usando dati meteorologici come temperatura del suolo e pioggia. L'U.O. di Agrobiometeorologia dell'ARPA Veneto utilizzando il modello* ***AlertInf*** *ha organizzato un servizio di assistenza interattivo alla pagina web www.arpa.veneto.it/upload_teolo/agrometeo/infestanti.htm per aiutare gli agricoltori nella programmazione degli interventi di controllo delle infestanti.*
Parole chiave: *previsione delle emergenze, dinamica di emergenza delle infestanti, malerbe annuali, servizio di assistenza*

INTRODUCTION

Maize is one of the most important crops of the Po Valley. It is traditionally rotated with winter wheat and other crops. However, in the last years the evolution in farming techniques has resulted in the increasing abandonment of traditional rotations, with maize being quite often the only crop cultivated over large areas (Giupponi, 2000).

Traditionally, the sowing period is between late April and early May. In recent years, there has been a trend towards anticipating maize sowing in northern Italy from mid-April to mid-March, with many agronomic advantages, but also alterations of weed flora composition, density and time of emergence, which obviously affect weed control (Otto et al., 2009).

In Po Valley, the highest pesticide load comes from herbicide applications, which is estimated to be practiced in 96% of the total maize area. Different strategies are used: only pre-emergence (52% of total maize area treated), only post-emergence (7,5%) or pre and post-emergence (40%) applications (Meissle et al., 2010). Recent studies (Rapparini et al., 2006) and the authors' personal experience suggest that the pre+post-emergence treatment strategies provide the best weed control, but one treatment can often be sufficient and in these cases a post-emergence treatment is better than just one pre-emergence treatment, but only if it is carried out at the proper time. The correct timing of either chemical or mechanical control is indispensable for maximizing its efficacy (Dogan et al., 2004). Knowing the dynamics of weed emergence means being able to estimate how many weeds can be eliminated by a treatment done today and how many will escape by emerging later, thus supporting decision making about the timing of treatments. There have been many studies on emergence dynamics with the aim of creating models that can predict the timing of weed emergence. The first generation of prediction models were based on the

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concept of Growing Degree Days (GDD) or thermal time (Satorre et al., 1985; Bewick et al., 1988; Tan et al., 2000). Emergence dynamics were described considering temperature as the only factor influencing the germination-emergence stages. The more recent models also consider soil water potential as a factor that, along with temperature, can regulate emergence. They are based on the concept of "hydrothermal time" (Gummerson, 1986; Bechini et al., 2004; Larsen et al., 2004; Alvarado and Bradford, 2005; Ekeleme et al., 2005; Leguizamon et al., 2005, Kochy and Tielborger, 2007; Finch-Savage et al., 2008). This latter concept has notably improved the prediction capacity and provided a suitably robust method for understanding how environmental factors interact to determine a given emergence dynamics over time (Bradford, 2002). These models are based on ecophysiological parameters, such as base temperature and base water potential, which depend on the ecotype analyzed, so models created in a given environment require a revaluation of the factors involved and recalibration of the parameters prior to being transferred to another site. Using the existing models as a starting point, a study was initiated to produce a model adapted to environment and management systems in Veneto Region for advising farmers on weed control in maize. The first result of this research is **AlertInf**, a model for predicting emergences of the principal weeds in maize adopted and organized in 2008 as an interactive web service for farmers in the Veneto Region.

Tab. 1 - Parameters used to calculate hydrothermal time and the Gompertz equation.
Tab. 1 - Parametri utilizzati per il calcolo del tempo idrotermico e della funzione Gompertz.

Weed species	Tb (°C)	X (days)	P_{limit} (mm)	a	b
A. retroflexus	12.6	10	5	4.58	0.088
C. album	5.0	10	0.3	7.30	0.016
S. halepense	12.3	10	1.6	4.48	0.081

MODEL DEVELOPMENT

Constructing the model required laboratory tests for calculating the base temperature, the threshold level beneath which germination does not occur. This was estimated according to the method of Masin et al. (2005).
Field experiments were done from 2002 to 2006 to study the emergence dynamics needed to create the model and then field trials were performed in 2007 to validate the model. All experiments were conducted in maize fields of the Veneto Region and consisted of floristic surveys carried out in three plots measuring five rows wide by 5 m long, where weeds were allowed to remain for the whole crop growing season. In these plots, 12 quadrats of 0.75 x 0.10 m, four for each plot, were fixed on the soil perpendicular to the row. Weed seedlings in these areas were

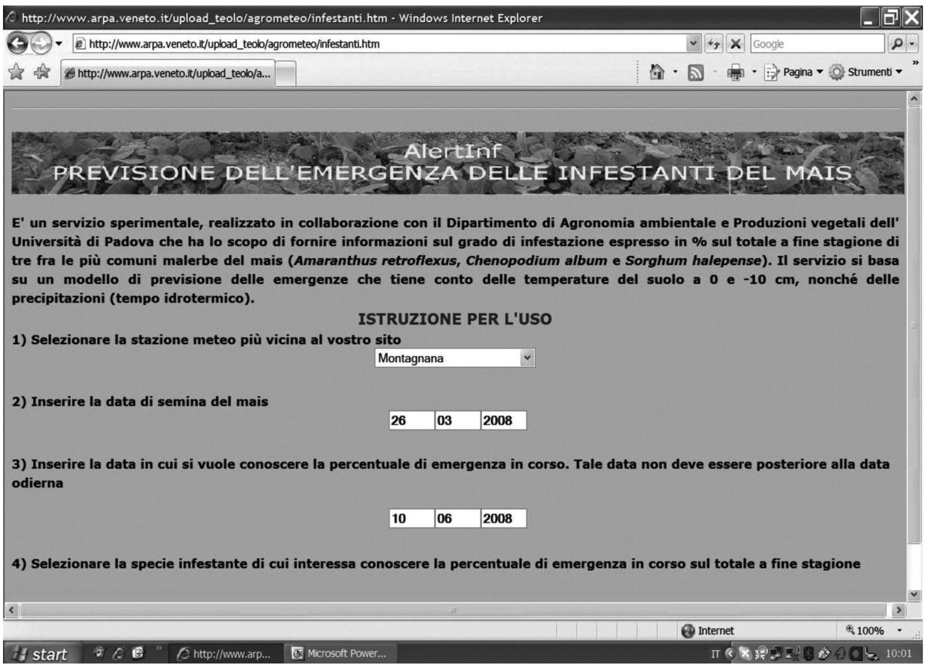

Fig. 1 - Initial screen of the **AlertInf** model in the ARPA Veneto website.
*Fig. 1 - Schermata iniziale del modello **AlertInf** nel sito web dell'ARPA Veneto.*

counted, classified and removed weekly. At the end of the growing season cumulated emergence data were used to create or validate the model.
The formula for calculating hydrothermal time is:

$$GDD = \sum (n \cdot \max(Tsm_i - Tb, 0) + GDD_{i-1} \qquad (1)$$

where Tsm_i (°C) is the soil temperature given by the average of the daily temperatures at 0 and -10 cm, Tb (°C) is the base temperature, x is the number of days to consider for calculating the rainfall limit and P_{limit} (mm) is the minimum total rainfall during x preceding days required to produce emergences. n = 0 if the total rainfall in the past x days is lower than P_{limit} and n = 1 if the it is higher than P_{limit}.
The input data required by the model were obtained from soil temperature and daily rainfall data measured at the ARPAV weather stations. The soil temperature probes used high sensitivity linearity thermoresistors called LTN, due to their higher range of resistance (ohm) than PT100 or NTC. Rainfall was measured by a standard Tipping Bucket Rain Gauge with double switch electric pulse counter.
The accumulation of hydrothermal time starts from the maize sowing date. The base temperature, estimated in a seed germinator, and minimum rainfall amounts required for germination, estimated on the basis of the field trials, are reported in Table 1 for the three weeds currently included in the model: *Amaranthus retroflexus* L., *Chenopodium album* L. and *Sorghum halepense* (L) Pers. When hydrothermal time has been calculated, the cumulated emergence percentage is determined with a Gompertz equation:

$$ET = 100 \cdot \exp[-a \cdot \exp(-b \cdot GDD)] \qquad (2)$$

where *a* represents a GDD lag before emergence starts, and *b* represents the rate of increase of emergence once it is initiated. *a* and *b* depend on the species (Tab. 1).
The program is available on the internet at www.arpa.veneto.it/upload_teolo/agrometeo/infestanti.htm. Java programming language was adopted to implement the script part of the webpage.

ILLUSTRATIVE RESULTS

The program available on the internet is simple and intuitive. The user must only select one or more weed species of interest, indicate the location of the farm to automatically download the data from the nearest weather station, and lastly insert the maize sowing date (Fig. 1). After these simple operations the model calculates the percentage of emergence of the selected weed species.
The information provided by **AlertInf** is the percentage of weeds that have already emerged out of the total number of plants that may potentially emerge during the season (Fig. 2). This information is useful for

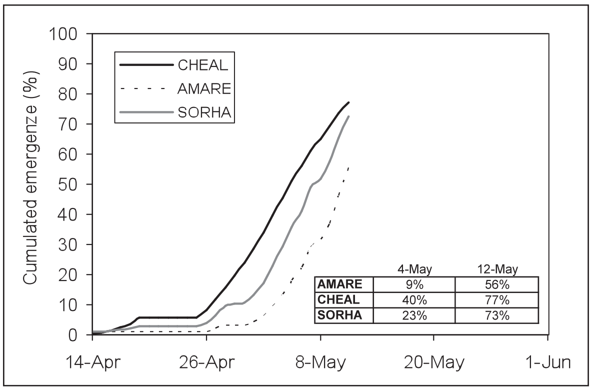

Fig. 2 – The model output is the percentage of emergence reached in the field by the selected species. This information is useful to make a more accurate decision on weed control. Supposing that on May 4th **AlertInf** shows an emergence of 40% or less reached by the three species in the field: on this basis, it can be predicted that many weeds (more than 60%) will emerge over the next few days, so it would be advisable not to treat. Seven days later **AlertInf** indicates an average of 70% of emergence, so the decision can be made to treat. In this case, having waited for a week has meant significantly reducing the number of weeds that would have emerged later and so a second treatment is unnecessary.
*Fig. 2 – L'output del modello è la percentuale di emergenza raggiunta in campo dalla specie selezionata. Tale informazione è utile per decidere più accuratamente il tempo di l'intervento. Supponiamo che il 4 maggio **AlertInf** mostri una percentuale di emergenza raggiunta in campo dalle tre specie uguale o inferiore al 40%. Sulla base di tale dato si prevede che molte infestanti (più del 60%) emergeranno nei giorni successivi, è quindi consigliabile non intervenire. Sette giorni dopo **AlertInf** indica una percentuale di emergenza aumentata mediamente al 70%, quindi si può decidere di intervenire. In questo caso aver atteso una settimana prima di trattare ha significato ridurre notevolmente il numero di infestanti che sarebbero emerse dopo il trattamento e quindi aver evitato un secondo intervento.*

correctly timing the control, either chemical or mechanical, maximizing its efficacy and avoiding a further treatment, with a saving in time and money. For example, if today **AlertInf** displays a low emergence percentage of a given weed, it means that the control treatment will only eliminate these few emerged plants and that the majority of the infestation can be expected to emerge afterwards, so another treatment will be required to avoid a crop yield loss. On the contrary, if the treatment is done when the estimated percentage of emergence is high, for example 70-80% (WeedCast Version 4.0 Documentation), many weeds will be controlled and only a few will emerge later, so no second treatment will be needed.
Unlike decision-support systems (Berti et al., 2003), which identify if a treatment is necessary or not, listing the best solution or solutions, the information provided by **AlertInf** is not advice to be followed, but it has instead to be interpreted by the farmer. **AlertInf**

provides the percentage of emergence of the potential infestation in the field at the end of the season. This means that the model does not display an absolute number of plants per square metre but just a percentage, with the corresponding density depending on the field. Because a given infestation percentage can have a different significance depending on the density a species may reach in the field, it is not possible to give associated advice. It is the farmer who must interpret the information on the basis of what he sees and knows about his own field. Another limitation of the **AlertInf** model is that it does not provide information on the phenological stage (number of true leaves) that the already emerged weeds have reached, whereas each herbicide has a phenological stage limit beyond which its efficacy is much lower. Therefore, once the percentage of emergence has been verified with **AlertInf**, it is important to check the phenological stage reached by the species in the field before deciding whether to wait a few days before treating. **AlertInf** is therefore not a model that gives advice, but just information in support of the farmer's own experience.

FUTURE DEVELOPMENTS

The model has only been made available to farmers by the ARPAV Agrobiometeorology Unit in 2008, so it is not yet possible to make any observations on the responses of the users, who are themselves evaluating the service. The model currently only gives information for three species, but another six important weeds in maize are now being studied, and will soon be added to **AlertInf**: *Abutilon theophrasti* Medik., *Digitaria sanguinalis* (L.) Scop., *Echinochloa crus-galli* L.) Beauv., *Polygonum persicaria* L., *Setaria viridis* (L.) Beauv., *Solanum nigrum* L.. The model only predicts emergence in non-irrigated maize, another improvement to the service will be the possibility of predicting emergence in irrigated maize; indeed it will soon be possible to insert the irrigating calendar, which will be added to the rainfall for the calculation of hydrothermal time.

Weed research is on-going to further our understanding of weed germination, emergence and early growth. Future versions of **AlertInf** will incorporate the results from these studies allowing us to expand and improve the model according to user requests.

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Agro-Hydrological models to schedule irrigation of Mediterranean tree crops

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Abstract: *In this paper a comparison between two agro-hydrological models, used to schedule irrigation of typical Mediterranean tree crops, is assessed. In particular the comparison between the model proposed by FAO, using a black box processes schematization, and the SWAP model based on the numerical analysis of Richards' equation is initially presented for two irrigation seasons, 2005 and 2006, and two Mediterranean tree crops, i.e. grapevine (Vitis vinifera, L.) and olive oil (Olea europea, L.). The comparison mainly focuses on hydrological balance components and on soil water contents.*
After investigating and setting the scheduling parameters ordinarily practiced by the framers in the area (i.e ordinary management), the performance of the two models aimed to evaluate seasonal water requirement and irrigation time, is assessed.
In the validation phase both the models satisfactorily simulated the soil water content, allowing to obtain quite comparable values of evapotraspiration fluxes. On the other hand, when the models are used for scheduling irrigation, the FAO 56 model usually overestimates the irrigation amount, as a result of an overestimation of the transpiration fluxes. On the contrary the SWAP model simulates values of crops water requirements and a number of irrigation corresponding to those evaluated in the ordinary scheduling at the investigated area. Finally, in order to improve the FAO 56 model performance, a modification of the stress function is presented and discussed.
Keywords: *Agrohydrological models, FAO 56, SWAP, Irrigation Scheduling, Vineyard and Olive grove*

Riassunto: *Nel presente lavoro viene presentato un confronto tra due modelli di simulazioni agro-idrologica per la gestione dell'irrigazione in colture arboree mediterranee. Vengono in particolare confrontati il modello proposto dalla FAO che utilizza uno schema a serbatoio ed uno più complesso SWAP basato sulla soluzione dell'equazione di Richards. Il confronto ha riguardato i valori delle componenti del bilancio idrologico ed i contenuti idrici del suolo relativamente alle due stagioni irrigue 2005 e 2006 su colture di Vite ed Olivo. È stata inoltre valutata la performance dei due modelli sulla programmazione dell'irrigazione impostando i parametri di scheduling ordinari della zona. Sebbene nella fase di validazione entrambi i modelli hanno simulato in modo soddisfacente l'andamento temporale del contenuto idrico medio del suolo e stimato valori dei flussi evapotraspirativi del sistema suolo-pianta-bassa atmosfera del tutto confrontabili, nella fase di programmazione dell'irrigazione, il modello semplificato ha sovrastimato i volumi irrigui in conseguenza della sovrastima dei flussi traspirativi. Il modello SWAP ha invece simulato valori del consumo idrico delle colture e del numero di adacquamenti analoghi a quelli ordinari della zona oggetto d'indagine. Ai fini della programmazione dell'irrigazione viene quindi proposta una modifica della funzione di stress utilizzata dal modello FAO, in modo da migliorarne la performance.*
Parole chiave: *Modelli Agroidrologici, FAO 56, SWAP, Programmazione dell'Irrigazione, Vigneto e Oliveto*

INTRODUCTION

The quantification of crop water requirements of irrigated land has a fundamental importance, in particular in the Mediterranean regions characterized by semi-arid conditions. The knowledge of the evapotranspiration fluxes allows to correctly estimate crop water requirements and to dispose of irrigation management strategies able to increase the irrigation systems efficiency. For this purpose, to set out new procedures permitting the correct estimation of crop evapotranspiration on large area, has addressed part of the scientific research towards the development of mathematical models able to provide a detailed description of the processes related to the exchange of mass and energy in the Soil-Plant-Atmosphere system, SPA (Feddes et al., 1978; Bastiaanssen et al., 2007).

The advance of the knowledge related to the energy and mass exchange processes taking part in the SPA system, has carried to the characterization of a unique and dynamic system (continuum) in which the various variables involved in the processes must be considered as mutually dependent. The acquired information will allow to validate the available models aimed to supply a detailed description of the processes

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of mass and energy exchanges in the SPA system (van Dam et al., 1997).
In previous researches, the proposed team, became confident with the models analyzing the dynamics of water in the SPA continuum; such models are also able to describe the water root uptake by means of mathematical functions considering soil matric potential, and therefore are able to reproduce water stress conditions. Other example of model application is represented by WATERUSE (Evaluation of alternatives techniques for determination of water budget components in water-limited, heterogeneous land-use systems, EVK1-CT-2000-079) research program, financed by U.E. The research extended verified the feasibility of such type of approach also to heterogeneous crops characterized by complex root apparatuses, like the olive and grapevine.
Moreover, the boundary conditions that must be used to obtain the numerical solution of Richards equation as well as the functions allowing to estimate the root water uptake were defined. Further studies demonstrated the correspondence of the proposed algorithms not only to fix optimal criteria of irrigation scheduling, but also to identify the crop water stress conditions.
The mentioned research projects, surely representing a scientific starting point, evidence also the lack of information related to some crop biophysical parameters like the root density, the Leaf area index and finally the crop coefficients valid under stress conditions, typical of the Mediterranean environment.
One of most appropriate ways to avoid the irrational water use in agriculture is to supply the exact amount of irrigation water to crops when it is required, so that water use efficiency can be maximized.
Despite the farmer experience, irrigation scheduling established on the basis of simple plants and soils observations, often lead to water overuse, as a consequence of pour effectiveness of the empirical evaluations; otherwise, a precise assessment of irrigation depth and/or irrigation timing, can allow to optimize the water use.
Agro-hydrological models represent the most precise, economic and simple tool to manage water volumes to be supplied with irrigation. Unfortunately, the physically based agro-hydrological models, although very reliable, in relation to the high number of variables and the complex computational analysis, cannot often be used. Therefore, the use of simplified agro-hydrological models may represent an useful and simple tool for irrigation scheduling, even for not skilled operators.
The main objective of the work is to assess the suitability of two different agro-hydrological models for irrigation scheduling. In particular a comparison between the physically based SWAP model (Soil-Water-Plant-Atmosphere, van Dam et al., 1997) and the simplified FAO 56 procedure (Allen et al., 1998) to study the typical management ordinarily practiced by the farmers in the area (i.e. ordinary management) and to estimate the water requirements in two typical Mediterranean tree crops (grapevine and olive) is showed.

Model Description

Agro-hydrological models used for irrigation management, allow to explain the complex relations of water exchange occurring within the Soil-Plant-low Atmosphere (SPA) continuous system. SPA is a very complex system, not only for the high number of variables to be defined, but specially for internal self-regulation phenomena, taking place between the system components.
Whatever the modelling approach used to study the water relations within the SPA system, it is necessary to estimate the evapotranspiration term, which depends on the combination of water evaporation from soil and plant transpiration. According to FAO the reference crop evapotranspiration, ET_{ref} [mm d-1], can be determined on the basis of the following

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

where Δ [kPa °C^{-1}] is the slope of saturation vapour pressure curve, $e_s(T)$ [KPa] is the saturation vapour pressure at air temperature, R_n [MJ m^{-2} giorno^{-1}] is the net radiation, G [MJ m^{-2} giorno^{-1}] is the soil heat flux, $(e_s\text{-}e_a)$ [kPa] is the vapor pressure deficit, γ [kPa °C^{-1}] is the psychometric constant at air temperature T_a [°C] and U_2 [m s^{-1}] is the wind speed measured at 2 m from the soil.
In the FAO 56 procedure the root zone depletion is calculated daily, with a water balance model based on a simple tipping bucket approach:

$$D_i = D_{i-1} - P_i - I_i + ET_{c,i} + DP_i \qquad (2)$$

where $D_{,i}$ [mm] and $D_{,i-1}$ [mm] are the root zone depletions at the end of day *i* and *i-1* respectively, P_i (mm) is the net precipitation, $ET_{c,i}$ [mm] is the actual evapotranspiration and DP_i [mm] is the deep percolation of water moving out of the root zone.
The domain of the depletion function, D_i, is between

0, which occurs when the soil is at the field capacity, and a maximum value, corresponding to the total available water, *TAW* [mm], for the plant, given by the following equation:

$$TAW = 1000 * (\theta_{fc} - \theta_{wp}) * Z_r \quad (3)$$

where θ_{fc} [cm^3 cm^{-3}] and θ_{wp} [cm^3 cm^{-3}] are the soil water content at field capacity and wilting point respectively and Z_r [m] the depth of the root system. In absence of water stress (potential condition), the crop potential evapotranspiration ET_c is obtained multiplying the dual crop coefficients (K_{cb} + K_e) and the Penman-Monteith reference evapotranspiration rate, ET_{ref}, (Allen et al., 1998). In particular the "dual crop coefficients approach", as explained in FAO 56 paper, splits the single K_c factor in two separate coefficients, a basal crop coefficient, K_{cb}, to consider the plant transpiration, and a soil evaporation coefficient K_e. The crop potential evapotranspiration ET_c can be therefore evaluated as:

$$ET_c = (K_{cb} + K_e) ET_{ref} \quad (4)$$

When water represents a limiting conditions, the coefficients of Eq. (4) have to be multiplied by a reduction factors, K_s, that can be variable between 0 and 1. The reduction factor can be express by:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \quad (5)$$

where *TAW* [mm] is the total available water, D_i [mm] the root zone depletion, and *RAW* [mm] is the readily available water. *RAW* values can be obtained multiplying the *TAW* values by a depletion coefficient, *p*, taking into account the crop water stress resistance. In particular when water storage in the root zone is equal to *RAW*, the reduction coefficient K_s is equal to 1. Values for *p* are listed in tables and differ from one crop to another. A value of 0.50 for *p* is commonly used for many crops. Considered that fraction *p* is a function of the atmospheric evaporative demand, a function for adjusting *p* for ET_c should be used. The following empirical equation can be used to calculate the depletion coefficient (van Diepen *et al.*, 1988):

$$p = \frac{1}{\alpha_p + \beta_p ET_c} - 0.1(5 - No_{cg}) \quad (6)$$

where α_p [-] and β_p [d cm-1] are regression coefficient, respectively equals to 0.76 and 1.5 (van Diepen et al., 1988), *ETc [*cm d^{-1}] is the crop potential evapotranspiration rate and No_{cg} [-] is the Crop Group number, depending on the level of crop resistance to water stress.

The soil evaporation coefficient, K_e, describes the evaporation component of ET_c. Where the topsoil is wet, following rain or irrigation, K_e is maximal. When the soil surface is dry, K_e is small and even zero, in absence of water in the upper layer of the soil surface. When the topsoil dries out, less water is available for evaporation and consequently the soil evaporation reduction occurs in proportion to the amount of water remaining in the soil top layer, or:

$$K_e = MIN \begin{Bmatrix} K_r * (K_{c\_max} - K_{cb}) \\ f_{ew} * K_{c\_max} \end{Bmatrix} \quad (7)$$

where K_e is the soil evaporation coefficient, K_{cb} is the basal crop coefficient, $K_{c\,max}$ is the maximum value of K_c following rain or irrigation, K_r is a dimensionless evaporation reduction coefficient depending on the cumulative depth of water evaporated from the topsoil and f_{ew} is the fraction of the soil that is both exposed and wetted, i.e. the fraction of soil surface from which most evaporation occurs.

The timing of irrigation in the FAO 56 procedure is based on the management allowed depletion, *MAD* [-] (Merriam, 1966) of the available water that can be stored in the root zone, obtained as

$$MAD = \frac{(\theta_{fc} - \theta_{lim})}{(\theta_{fc} - \theta_{wp})} \quad (8)$$

in which θ_{lim} is the average soil water content below which it is necessary to start irrigation. The values for *MAD* are influenced by management and economic factors in addition to the ecophysiological factors influencing *p*. When irrigation is scheduled in absence of crop water stress, the *MAD* parameter can be assumed equal to the *p* coefficient. On the contrary, when irrigation is managed under water deficit conditions the *MAD* parameter is higher than *p*. This last circumstance is typical of the arid Mediterranean environments.

The algorithm proposed in the FAO 56 paper (Appendix 8: Spreadsheet for applying the dual K_c procedure in irrigation scheduling) enables to program only full irrigation technique ($MAD=p$). This assumption cannot be assumed in Mediterranean environment, where frequent conditions of water shortages and consequently crops water stress occur. Therefore, as will be later specified, it was necessary to amend the model FAO 56 in order to allow the scheduling irrigation under deficit conditions ($MAD>p$).

SWAP (Soil-Water-Atmosphere-Plant) is a one-dimensional physically based model for water flow in saturated and unsaturated soil (van Dam at al., 1997) simulating the vertical soil water flow and solute transport in close interaction with crop growth. Richards' equation (Richards, 1931), including root water extraction, is applied to compute transient soil water flow under specified upper and lower boundary conditions.

$$\frac{\partial \theta}{\partial t} = C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right] - S_a(\psi) \quad (9)$$

in which z [cm] is the vertical coordinate, assumed positive upwards, t [d] is the time, C [cm^{-1}] is the differential moisture capacity ($\partial\theta/\partial\psi$), $K(\psi)$ [cm d^{-1}] is the soil hydraulic conductivity function and S_a [d^{-1}] is the root uptake term that, for uniform root distribution, is defined by the following equations:

$$S_a(\psi) = \alpha_w(\psi)\frac{T_p}{z_r} \quad (10)$$

$$T_p = K_c ET_c\left[1-\exp\left(-k_{gr}LAI\right)\right] \quad (11)$$

in which T_p [cm d^{-1}] is the potential transpiration, z_r [cm] the rooting depth and α_w [-] is a ψ-dependant reduction factor accounting for water deficit and oxygen stress (Feddes et al., 1978), K_c [-] is the crop coefficient, ET_c [cm d^{-1}] is the reference evapotranspiration, k_{gr} [-] is an extinction coefficient for global solar radiation and finally LAI [-] is the leaf area index.

The numerical solution of Eqs (9), (10) and (11) is possible after specifying initial, upper and lower boundary conditions and the soil hydraulic properties, i.e. the soil water retention curve, $\theta(\psi)$, and the soil hydraulic conductivity function, $K(\psi)$; detailed field and/or laboratory investigations are therefore necessary.

Different options are available in SWAP to schedule irrigation (i.e. determining irrigation times and specific volumes); for the purpose of this study, only the irrigation time parameter was assessed after

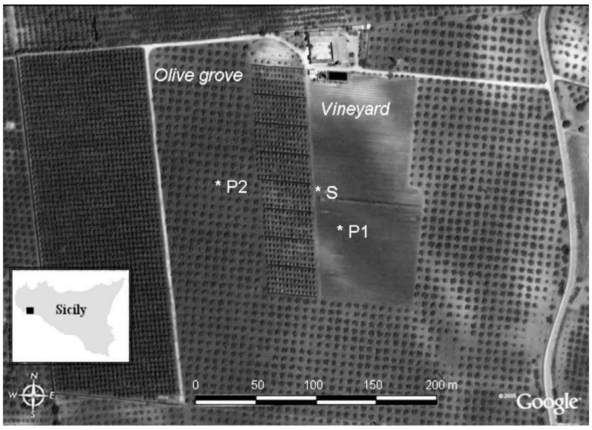


Fig. 1 - Geographic location and Google earth image of test area. The description of land use and the position of installed instruments is showed. S: agrometeorological station; P1, P2: soil moisture measurement.

Fig.1 - Indicazione dell'area test, dell'uso del suolo e degli strumenti istallati. S: stazione agrometeorologica; P1, P2: stazioni per la misura del contenuto idrico del suolo.

defining an allowable depletion fraction, f, of readily available water in the root zone:

$$f = \frac{\sum_{i=1}^{n.s}\left(\theta_{fc} - \theta_{\lim_i}\right)_i}{\sum_{i=1}^{n.s}\left(\theta_{fc} - \theta_{wp}\right)_i} \quad (12)$$

in which θ_{lim} is the soil water content below which it is necessary to provide irrigation water, θ_{fc} and θ_{wp} are the soil water content at field capacity and at wilting point respectively, and n is the number of layers of homogeneous soil, as defined in the model.

MATERIALS AND METHODS

Investigation was carried out during irrigation seasons 2005 and 2006 in an experimental farm (fig. 1) near Castelvetrano (lat.: 37°.6461 N, long.: 12°.8518 E) in which land use is mainly characterized by tree crops (olives, grapes and citrus). During the two years the most important micro–climatic parameters, such us precipitation, wind speed and direction, global radiation, air humidity were monitored. In the same period in two experimental plots (vineyard and olive grove) agro–hydrological and physiological parameters were monitored.

Traditional laboratory methods were used to evaluate the soil hydraulic properties of undisturbed soil cores representative of four different depths of a soil profile. Soil texture, bulk density, hydraulic conductivity of saturated and near saturated conditions, as well as some points of the water retention curve in the potential range between –0.5

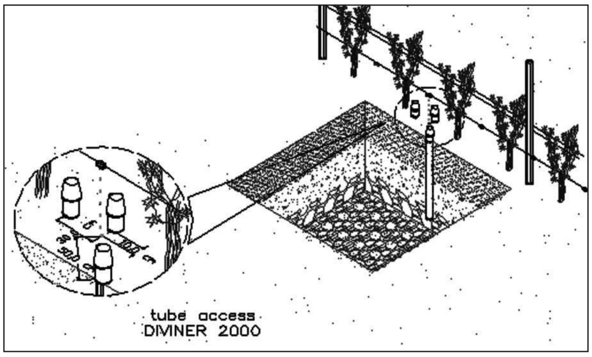


Fig. 2 - Scheme of DIVINER access tubes installation in vineyard.
Fig. 2 - Schema d'istallazione dei pozzetti di accesso DIVINER nel vigneto.

Parameters	Layers			
	I 0-20 cm	II 20-40 cm	III 40-60 cm	IV 60-80 cm
θ_r	0.030	0.139	0.103	0.119
θ_s	0.400	0.444	0.400	0.410
K_s	10.00	3.00	30.00	0.24
α	0.0104	0.0118	0.0159	0.046
n	1.838	2.128	1.548	1.487
λ	0.5	0.5	0.5	0.5

Tab. 1 - Soil parameters used in SWAP simulations.
Tab. 1 - Parametri del suolo utilizzati nelle simulazioni condotte con il modello SWAP.

and -1530 kPa were deduced for each depth. Soil textural class, according USDA classification, is silty clay loam.

The Leaf Area Index (*LAI*) was monitored by means of the optical sensor *Li-Cor LAI 2000*. The root depth distribution has been determined through an indirect methodology based on roots interference on the shape soil moisture profile around the plant, when compared to the shape profile under bare soil condition (Cavazza, 1981).

Temporal variability of soil water contents in the different plots was measured, at several depths, using Diviner 2000 Sentek capacitance probe. The probe containing the sensor can measure the soil water content at different depth, if inserted in an access tube installed in the field. In the vineyard three access tubes were installed at 10, 30 and 50 cm from the point receiving the emitter flow, with an axis-symmetrical scheme, as shown in fig. 2. In the olive grove plot, where irrigation water is supplied with a micro-sprinkler system, a single access tube was installed at the border of wetted zone.

Setting models

The van Genuchten-Mualem parameters of soil hydraulic characteristics, showed in tab. 1, were

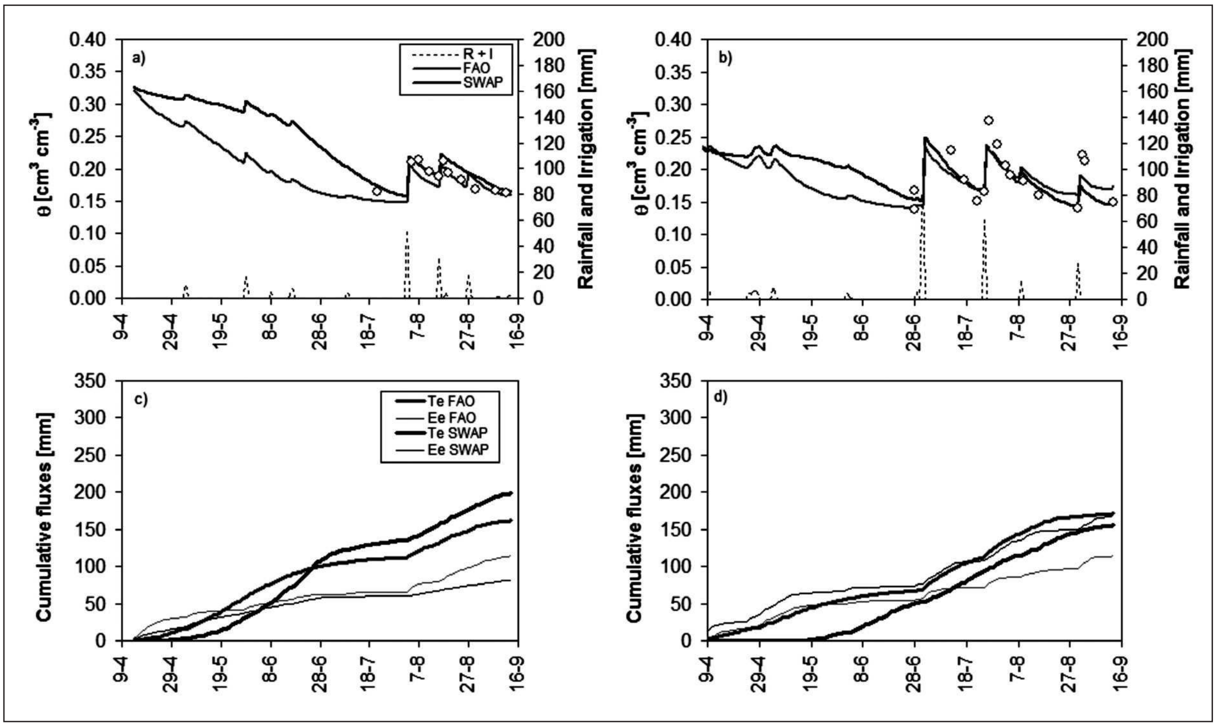
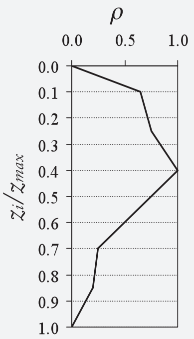
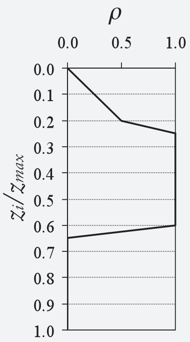


Fig. 3a-d - Average soil water content simulated by the two models for the 2005 (a) and 2006 (b) season in vineyard; the cumulated soil evaporation and tree transpiration fluxes are showed below (c-d).
Fig. 3a-d - Vigneto. Udogrammi simulati dai due modelli per la stagione irrigua 2005 (a) e 2006 (b) e corrispondenti flussi cumulati di evaporazione dal suolo e di traspirazione dalla pianta (c-d).

VARIABLES		Vineyard	Olive grove
Length of the crop cycle [d]		153	153
Extinction coeff. for diffuse visible light, κ_{df} [-]		0.45	0.5
Extinction coeff. for directvisible light, κ_{dir} [-]		1.0	1.0
Minimum canopy resistance [s/m]		70.0	70.0
Precipitation interception coefficient		0.25	0.35
Critical soil water pressure head [cm.c.a] (Taylor e Ashcroft, 1972)	ψ_{sat}:	-10	-10
	ψ_{fc}:	-25	-25
	ψ_{p_high}:	-750	-1500
	ψ_{p_low}:	-1000	-1500
	ψ_{wp}:	-10000	-16000
Threshold level high atm. demand [cm]		0.5	0.5
Threshold level low atm. demand [cm]		0.2	0.2
Crop Factor Bare Soil, K_{soil}		1	1
Max. rooting depth [cm], Z_r		100	65
Root density, ρ			
Leaf Area Index, *LAI* Crop coefficient, *Kc*		**DVS** / **LAI** / **Kc** **0.00** / 0.5 / 0.50 **0.65** / 2.0 / 0.75 **1.88** / 2.0 / 0.75 **2.00** / 2.0 / 0.63	**DVS** / **LAI** / **Kc** **0.00** / 1.5 / 0.75 **1.00** / 1.5 / 0.75 **2.00** / 1.5 / 0.75
Irrigation Timing, *f*		0.48	0.51

Tab. 2 - Input parameters used in SWAP simulations.
Tab. 2 - Parametri di input utilizzati nelle simulazioni condotte con il modello SWAP.

VARIABLES		Vineyard	Olive grove
θ_{fc} [cm³/cm³]		0.32	0.32
θ_{wp} [cm³/cm³]		0.13	0.13
Available Water [mm/m]		187.6	187.6
TEW [mm]		32.2	32.2
REW [mm]		9	9
f_w		0.53	0.23
Development stage [J]	J_{plant}	105 (116)	105 (95)
	J_{dev}	110 (120)	105 (95)
	J_{mid}	160 (162)	105 (95)
	J_{late}	247 (249)	258 (258)
	J_{harv}	258 (258)	258 (258)
Basal crop coefficients	$K_{cb\ ini}$	0.15	0.55
	$K_{cb\ mii}$	0.65	0.65
	$K_{cb\ end}$	0.40	0.65
Maximum crop height, *H* [m]		1.5	3.0
Minimum rooting depth [cm]		80.0	65.0
Midseas, Av, Wind Speed [m/s]		1.1 (1.2)	1.2 (1.3)
Midseas, Av, RH_{min} [%]		47.7 (55.9)	48.9 (59.0)
Management Allowed Depletion, *MAD*		0.83	0.96

Tab. 3 - Input parameters used in FAO 56 simulations. Value between brackets were used for the 2006 irrigation season.
Tab. 3 - Parametri utilizzati nelle simulazioni condotte con il modello FAO 56. I dati tra parentesi sono relativi alla stagione irrigua 2006.

determined with the $\theta_i(\psi_i)$ and $K_i(\psi_i)$ experimentally obtained, by using the RETC code (van Genuchten et al., 1991).
The values of different soil-crop-atmosphere parameters used as input for the simulations with the SWAP and the FAO 56 models, are showed in tab. 2 and 3 respectively. The values of θ_{fc} and θ_{wp} used to run the FAO 56 simulations are obtained averaging the correspondent values measured in four different soil layers, as considered for the SWAP simulations. For both the irrigation seasons, the initial soil water contents assumed along the soil profile were fixed according to the measured values.
In order to evaluate the values of the irrigation scheduling parameters (*MAD* and *f*) a preliminary simulation was carried out on both vineyard and olive grove, considering the irrigation timing and the water volumes derived from the observed data.
The performance of the models was evaluated by

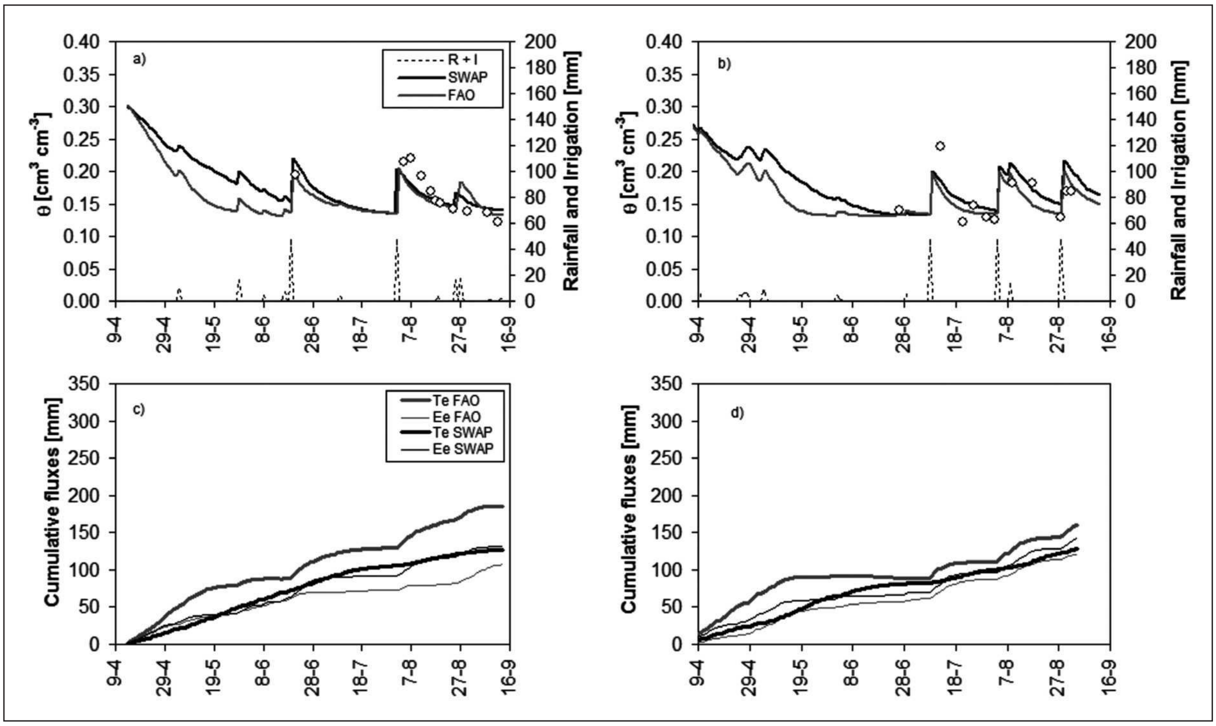


Fig. 4a-d - Average soil water content simulated by the two models for the 2005 (a) and 2006 (b) season for olive grove; the cumulated soil evaporation and tree transpiration fluxes are showed below (c-d).
Fig. 4a-d - Oliveto. Udogrammi simulati dai due modelli per la stagione irrigua 2005 (a) e 2006 (b) e corrispondenti flussi cumulati di evaporazione dal suolo e di traspirazione dalla pianta (c-d).

calculating the root mean square error (RMSE), the mean bias error (MBE), defined as:

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} d_i^2\right)} \quad (13)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \quad (14)$$

Statistic	SWAP		FAO 56	
	Vineyard	Olive grove	Vineyard	Olive grove
R^2	0.69	0.48	0.74	0.46
RMSE [% vol.]	2.09	2.77	2.06	2.67
MBE [% vol.]	-0.41	0.65	-0.83	-0.18
t value	1.04	1.13	2.18	0.32
$t_{crit}(\alpha=0.05)$	2.05	2.05	2.05	2.05

Tab. 4 - Statistical comparison between measured and simulated soil water content.
Tab. 4 - Statistici ottenuti dal confronto tra i contenuti idrici stimati e misurati.

where N is the number of data, d_i is the difference between the predicted and the measured values (Kennedy and Neville, 1986).
Because, the use of only RMSE and MBE combined is not adequate to evaluate the model performance, additional statistical tests was used. In particular, the analysis involved also the t-statistic, defined through the MBE and RMSE errors (Kennedy and Neville, 1986), as:

$$t = \sqrt{\frac{(N-1)MBE^2}{RMSE^2 - MBE^2}} \quad (15)$$

To determine if the difference between measured and simulated soil water content are statistically significant, the absolute value of the calculated t must be less than the critical t value (t_{crit}), obtained from the statistical tables. In this study, a significance level a=0.05 has been taken and, for N-1 degrees of freedom, the value of t_{crit} is equal to 2.05.

RESULTS AND DISCUSSION

Model validation and assessment of scheduling parameters

Fig. 3a,b shows the daily average soil water content in the root zone simulated by SWAP (continous

Date	Irrig.	Date	DOY	*f*	*MAD*
Vvineyard	1	03-08-05	215	0.48	0.90
	2	16-08-05	228	0.34	0.72
	3	02-07-06	183	0.50	0.92
	4	29-07-06	207	0.47	0.79
	5	31-08-06	243	0.59	0.85
		average		**0.48**	**0.83**
Olive grove	1	20-06-05	171	0.45	0.96
	2	02-08-05	213	0.54	0.96
	3	26-08-05	237	0.50	0.92
	4	09-07-06	190	0.55	0.98
	5	04-08-06	216	0.53	0.98
	6	29-08-06	241	0.50	0.97
		average		**0.51**	**0.96**

Tab. 5 - Values of MAD and f obtained for both vineyard and olive grove for each irrigation practised by the farmer.
Tab. 5 - Valori dei parametri di programmazione irrigua, MAD ed f, ottenuti per entrambe le colture e per ciascun adacquamento praticato dall'agricoltore.

Cell	Original Algorithm Test, Value or Formula	Modifcated Algorithm Test, Value or Formula
AE2	**empty**	Nocg
AF2	empty	value
AO2	empty	MAD*
AP2	empty	value
AH3	**MAD during Initial Stage**	empty
AK3	value	empty
AH4	**MAD after Initial Stage**	empty
AK4	value	empty
AM13	empty	**Fraction depletion, p**
AM14	empty	=((1/(0,76+(1,5*H14/10)))-(0,1*(5-AF2)))*100
AF14	=MAX(SE(D14<Q$4;AK$3;AK$4)/100*AE14*$AF$5;AF13)	=AM14/100*AF5*AF3
AH14	=SE(D14>=Q$3;SE(D14<(Q$6+Q$7)/2;SE(AG14>AF14;AG14;0);0);0)	=SE(D14>=Q$3;SE(D14<(Q$6+Q£7)/2;SE(AG14>AP2;AG14;0);0);0)

Tab. 6 - Amendment of the FAO 56 algorithm.
Tab. 6 - Modifica dell'algoritmo proposto nel quaderno FAO 56.

lines) and FAO 56 model (shaded lines) in the vineyard, for the two considered irrigation seasons. The average water contents measured in the soil profile (white dots) as well as the rainfalls and the irrigation amounts (dashed lines) are also showed . As can be observed in the fig. 3a,b both the models are able to predict quite well the average soil water contents during the considered irrigation seasons. Differences between the two models are mainly observed at the begin of the first irrigation season (2005), during which the simulated values of soil water content obtained with the FAO 56 model are

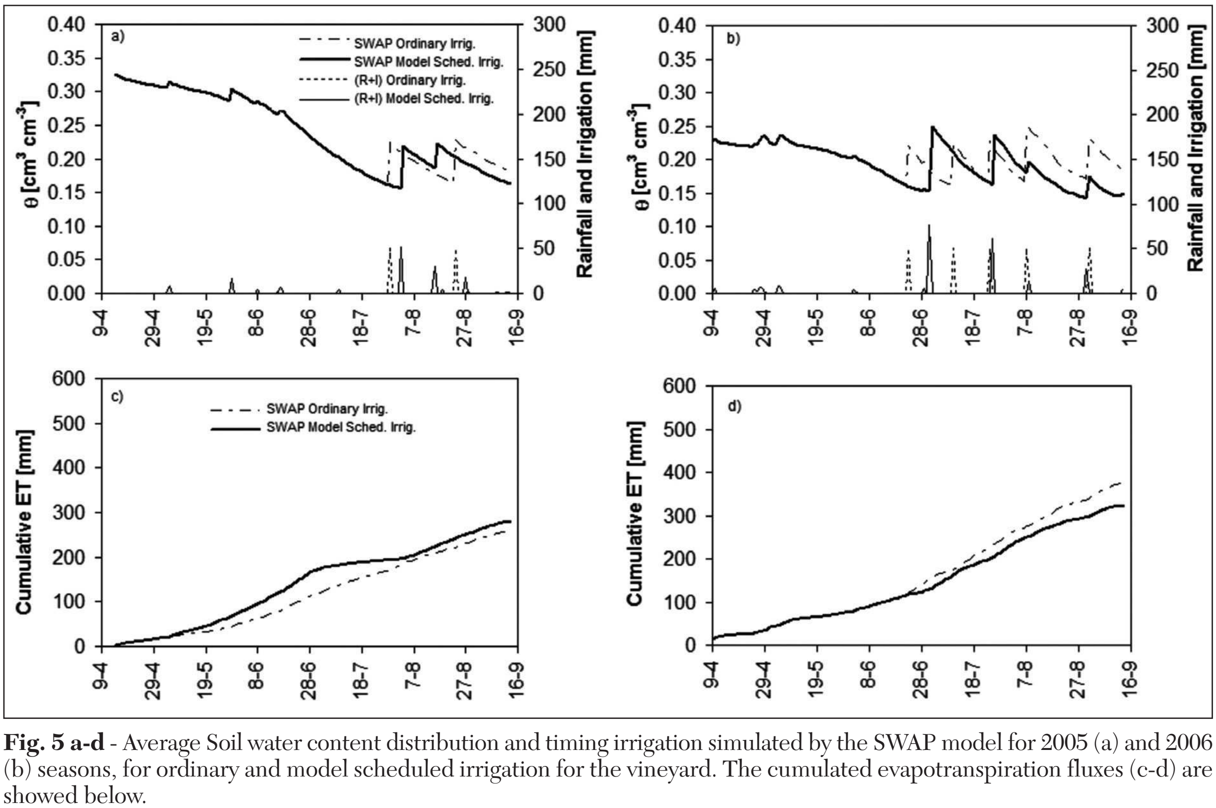


Fig. 5 a-d - Average Soil water content distribution and timing irrigation simulated by the SWAP model for 2005 (a) and 2006 (b) seasons, for ordinary and model scheduled irrigation for the vineyard. The cumulated evapotranspiration fluxes (c-d) are showed below.
Fig. 5 a-d - Vigneto. Udogrammi e distribuzione degli adacquamenti simulati da SWAP per le stagioni irrigue 2005 (a) e 2006 (b) nel caso di programmazione irrigua ordinaria o programmata dal modello. Sono riportati in basso i corrispondenti flussi cumulati di evaporazione dal suolo e di traspirazione dalla pianta (c-d).

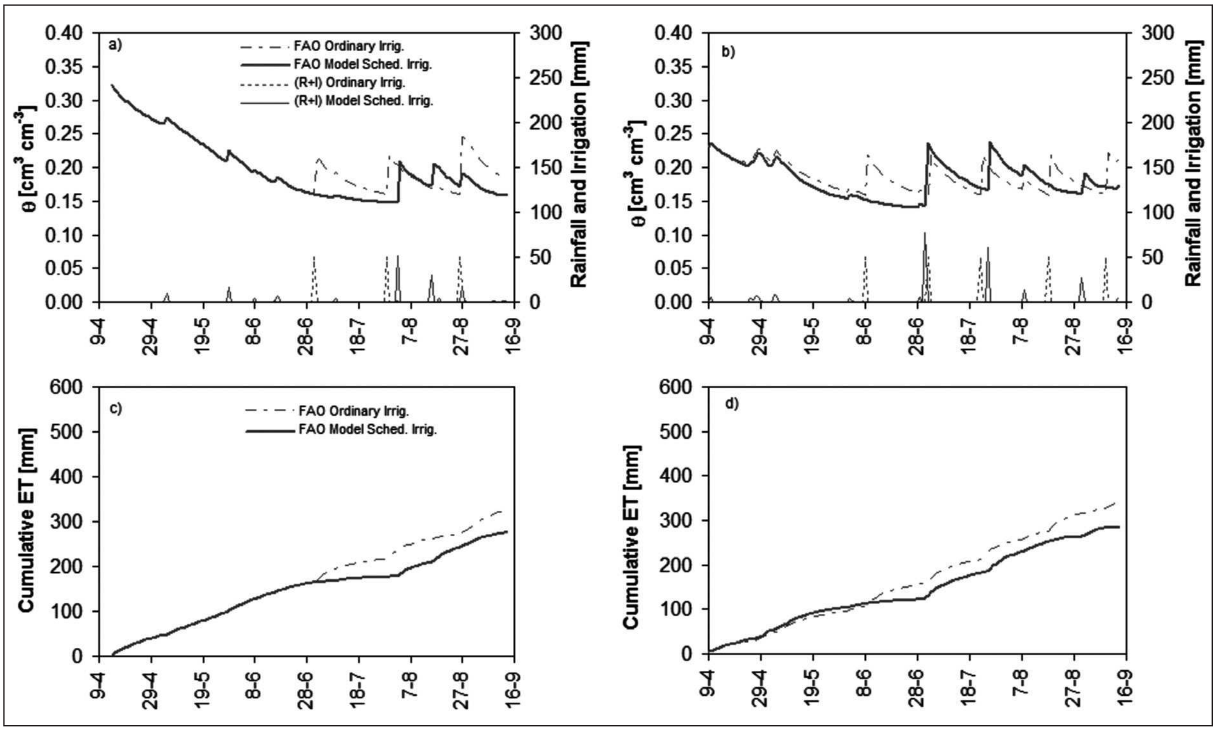


Fig. 6a-d - Average Soil water content distribution and timing irrigation simulated by the modified FAO 56 model for 2005 (a) and 2006 (b) seasons, for ordinary and model scheduled irrigation for the vineyard. The cumulated evapotranspiration fluxes (c-d) are showed below.

Fig. 6a-d - Vigneto. Udogrammi e distribuzione degli adacquamenti simulati dal modello FAO 56 modificato per le stagioni irrigue 2005 (a) e 2006 (b) nel caso di programmazione irrigua ordinaria o programmata dal modello. Sono riportati in basso i corrispondenti flussi cumulati di evaporazione dal suolo e di traspirazione dalla pianta (c-d).

lower than those obtained with the SWAP model, due to the higher simulated evapotraspiration rates, as showed in fig. 3c,d. Unfortunately, the absence of measured water contents during the initial phase of the irrigation seasons, does not allow to verify which of the two models performs better.

Similar results are obtained for the olive grove, as illustrated in fig. 4a,d, for both the considered irrigation seasons.

Tab. 4 shows the values of the coefficient of determination (R^2), root mean square error (*RMSE*), mean bias error (M*BE*) and *t*-statistic, for the examined crops by considering measured and simulated soil water contents.

In the vineyard, SWAP model performed slightly better than the FAO-56 model according to the *t*-statistic. The opposite occurs in the olive grove. For practical purposes therefore, the distinction between the SWAP and FAO-56 models is negligible because both the models produced different between simulated and estimated soil water content not statistically different ($t<t_{crit.}$).

The outputs of the two models allowed to examine the farmer strategy for irrigation. Ordinary scheduling parameters *f* and *MAD* were therefore calculated as the average of the values obtained in the two years of observations. In particular the values of *MAD* and *f*, corresponding to each irrigation practised by the farmer, were evaluated according to equations (8) and (12) respectively, as results of the simulations carried out by means of SWAP and FAO 56 models respectively. Then the average values MAD_{av} and f_{av} were considered as ordinary scheduling parameters for the study area. Tab. 5 shows the values of *MAD* and *f* obtained for both the considered crops during the investigated irrigation seasons, as well as their average values. These parameters were used to run the following simulations, in order to determine the irrigation timing.

Model application to schedule irrigation

The models were then applicated in order to obtain the irrigation timing, whereas the water supply was fixed up to 50 mm, corresponding approximately to the average irrigation depth provided by the farmer (scheduled irrigation). The scheduling MAD_{av} and f_{av} parameters were assumed equal to the average values indicated in tab. 5. Figg. 5a,d shows the outputs of the SWAP model in the cases of scheduled and ordinary irrigation for vineyard in 2005 and 2006. In particular figg. 5 a,b shows the evolution of soil water content during the two irrigation seasons, whereas figg. 5c,d illustrates the cumulated evapotraspiration fluxes obtained under ordinary and model scheduled irrigation. The analysis shows, for both the considered seasons, a satisfactory performance of SWAP model allowing to identify, the time of the first water supply as well as the watering distribution during the crop seasons. The actual evapotraspiration fluxes, showed in figg. 5c,d, obtained when irrigation is scheduled by the model, are very similar to those estimated by considering the ordinary management. Furthermore, SWAP model suggests the first irrigation before the plant slow down its transpiration consumption. This is particularly evident in the 2005 season, during the critical stage of growth (June-July).

Before running the FAO 56 model to schedule irrigation for the examined cases, it was necessary to modify the original algorithm, in order to take into account the crop water stress conditions recognized in the field. In particular in the *MAD* factor, hereafter indicated by the acronym *MAD**, the ecophysiological component, *p,* was separated from the one related to economic management factors. This amendment was carried out in the spreadsheet suggested in the FAO 56 paper (Annex 8; BOX 8.1: Spreadsheet formulas and corresponding equations for Excel spreadsheet programs). Tab. 6 shows the suggested amendments of the FAO 56 algorithm.

Fig. 6a,d shows the outputs of the modified FAO 56 model in the case of ordinary and model scheduled irrigation obtained for the vineyard.

The modified model allows to evaluate three and four irrigation supplies in 2005 and 2006 respectively, distributed throughout the irrigation seasons in an appropriate manner within the crop cycle. The total evapotranspiration fluxes for both the examined conditions (ordinary and model scheduled irrigation), evaluated with the FAO 56 model resulted comparable to those estimated with the SWAP model (fig. 6c-d). As for SWAP even FAO 56 model suggests the first irrigation before the reduction of crop transpiration. However the performance analysis showed, that the FAO 56 model for both the seasons anticipates of some days the first irrigation timing if compared to the ordinary management, and suggesting a slightly higher seasonal water requirement.

Similar results were obtained for the Olive grove, for which the FAO 56 model suggests to anticipate the irrigation timing and higher seasonal water requirements compared to the SWAP model.

CONCLUSIONS

Both the models well simulated the measured values of average soil water content in the root zone. In general, the two considered models, produced estimates that are not statistically different from the measured values (α=0.05) with *RMSE* lower than 3%.

Both the models provided similar estimation of the actual evapotranspiration fluxes.

The models were then compared in order to verify their suitability for irrigation scheduling. Firstly, considering irrigation timing and volumes observed in the field, the ordinary scheduling parameters, f_{av} and MAD_{av}, were obtained. Secondly the FAO 56 and SWAP models' outputs (irrigation scheduled volumes and timing irrigation) were compared. FAO 56 model simulates reliable values of average water content of soil profile when a modification of stress function K_s is used, even if, compared with the SWAP model, a certain overestimation of evapotranspiration fluxes is observed. For both the examined crops FAO 56 model suggests to anticipate the first soil watering and to supply a slightly higher seasonal water requirements, if compared to the ordinary management.

AKNOWLEDGEMENTS

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Systems to evaluate the effects of atmospheric CO_2 concentration on field crops: a review of open top chambers

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Abstract: *The increase in atmospheric carbon dioxide concentration [CO_2] during the last century has been one of the causes of climatic global changes. In general, crops react to a greater availability of CO_2 with an increase in leaf photosynthesis, biomass and yield. In order to evaluate the effect of CO_2 on crops, experimental trials need to be carried out using different approaches: closed (greenhouses, growth chambers, tunnels, closed top chambers), semi-open (open top chambers= OTCs) and open systems (Free-Air Carbon dioxide Enrichment facilities=FACEs). In this paper, a review of Open Top Chamber (OTCs) systems is presented as well as their uses, construction and operational details. OTCs are suitable tools for this type of experiment: they have the advantages of providing the crop with conditions that closely correspond to reality, can be placed in open field for several seasons and are easy to transport. However, the disadvantages are that inside the OTC, CO_2 is lower than in the normal concentration of air and temperatures are higher than those found externally. Nevertheless, these systems are useful for this type of research, principally for crops with short growth cycles.*
Keywords: *climatic global change, OTC shapes and materials, measurement instruments, atmospheric CO_2 concentration*

Riassunto: *Una delle cause dei cambiamenti climatici globali è l'aumento della concentrazione di anidride carbonica nell'atmosfera, costantemente in ascesa nel corso dell'ultimo secolo. In generale, ad una maggiore disponibilità di CO_2, le colture agrarie rispondono con un aumento della fotosintesi e, di conseguenza, della biomassa e della resa. Per osservare e valutare l'effetto della [CO_2] sulle colture, occorre impostare prove sperimentali utilizzando varie strumentazioni: sistemi chiusi (serre, camere di crescita, tunnel, camere chiuse in alto), semi-aperti (camere a cielo aperto= OTCs) e aperti (sistemi in cui l'aria libera è arricchita da diossido di carbonio=FACEs). Questa nota è una review sui sistemi delle camere a cielo aperto (Open Top Chambers = OTC), delle quali si riportano le esperienze, i dettagli costruttivi ed operativi. Le OTC sono sistemi idonei per questo tipo di sperimentazione: hanno il vantaggio di porre la coltura in condizioni molto vicine alla realtà, sono poste in campo per diverse stagioni e sono facilmente trasportabili; hanno degli svantaggi poiché al loro interno la [CO_2] risulta un po' più bassa della concentrazione normale dell'aria e la temperatura un po' più alta di quella esterna. Sono comunque utili sistemi per questo tipo di ricerche specie per colture con cicli colturali non eccessivamente lunghi.*
Parole chiave: *cambiamenti climatici globali, forme e materiali delle OTC, strumenti di misurazione, concentrazione atmosferica di CO_2*

INTRODUCTION

CO_2 concentration in the Earth's atmosphere has increased from approximately 280 to 370 ppm since 1750 (Fig. 1) and it is expected to reach 600-1000 ppm by the end of this century (IPCC, 2007). Along with atmospheric CO_2, the air-temperature at the Earth's surface has also increased during the past 200 years and mathematical climate models predict that rising CO_2 will cause additional warming (Tubiello and Ewert, 2002).

Elevated atmospheric CO_2 concentration induces an initial stimulation of plant growth, as demonstrated by many studies (among others, Cure and Acock, 1986; Drake *et al.*, 1997; Drake and Rasse, 2003; Kimball, 1983; Norby *et al.*, 1999). When CO_2 concentration is approximately doubled (from 350 to 700 ppm), crops react to elevated CO_2 with an increase in biomass (32% on average), yield (43%) and leaf photosynthesis (54%) (Gifford, 1977); in general the increase in biomass is higher in C_3 plants (58%) than in C_4 (22%) and CAM plants (15%) (Poorter, 1993). Several studies carried out on wheat (a C_3 plant) show grain yield increases of 15% (Mitchell *et al.*, 1993), 24% and 33% (Weigel *et al.*, 1994, in two different cultivars) and of 35% (Cure and Acock, 1986) with doubled CO_2 concentration. The effects of elevated CO_2 are beneficial on plant

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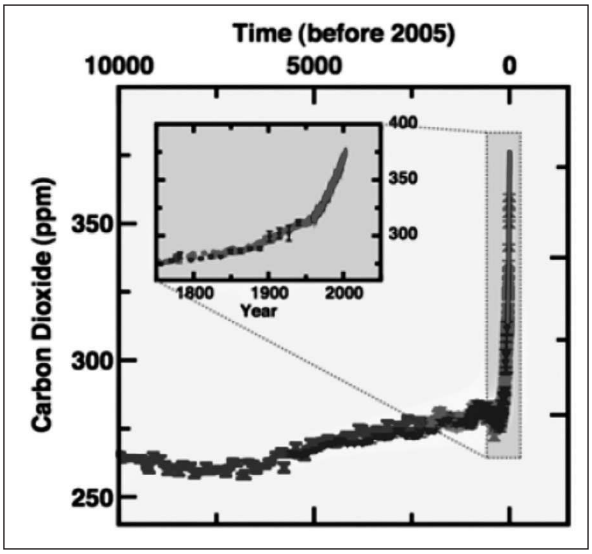

Fig. 1 - Atmospheric concentrations of CO_2 over the last 10,000 years (large panel) and since 1750 (inset panel) (from IPCC, 2007).
Fig. 1. Concentrazione atmosferica della CO_2 per gli ultimi 10,000 anni (riquadro grande) e dal 1750 (riquadro piccolo) (da IPCC, 2007).

photosynthesis (Fig. 2) (Bacon, 2006; Morison and Lawlor, 1999), but reduce stomatal conductance and increase water-use efficiency in C_3 plants (Lawlor and Mitchell, 1991), so the beneficial effects of elevated CO_2 on yield may in fact be due to changes in photosynthesis, water-use or water-use efficiency or even all these three factors.
The wide range of responses to elevated CO_2 concentration, among and within species and the effects of environmental variables on these responses, make it difficult to define a general model

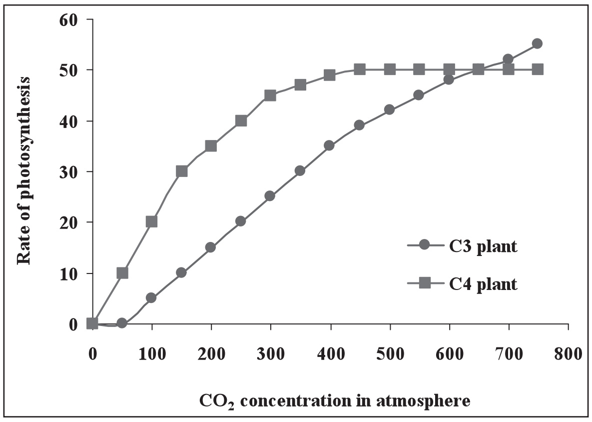

Fig. 2 - Relationship between CO_2 concentration in atmosphere and rate of photosynthesis (modified from Bacon, 2006).
Fig. 2 - Relazione tra la concentrazione di CO_2 in atmosfera e il rapporto di fotosintesi (modificato da Bacon, 2006).

of plant response to rising CO_2 concentration. Other recent results from long-term studies suggest that the stimulation of plant photosynthesis and growth is sustained in time, especially in nutrient-rich systems (Ainsworth *et al.*, 2003a; 2003b; Idso and Kimball, 2001; Temperton *et al.*, 2003), but also in other native ecosystems (Ainsworth *et al.*, 2002).
Lawlor and Mitchell (1991) reported that in comparison with the very large number of controlled-environment studies, there are few experiments conducted in the field. Almost all of these studies were done in the United States and were heavily biased in favour of few crops (wheat, maize, cotton, rice, cowpea, sweet potato, carrot, radish etc.) and particularly soybeans. The reasons for this are due to the fact that controlled-environment experiments provide long-term, stable conditions with clear differences between treatments and allow combinations of changes in conditions (e.g. temperature and CO_2). The obtained values of productivity are very general and may not be true in open field due to the conditions which may be substantially different between the two environments (light, radiation, nutrients, water, pests etc.). On the other hand, field studies provide results from highly variable conditions and consequently depend on the season and site. Therefore, it is important that the main environmental factors are monitored during a field experiment.
Hence, long term field experiments are necessary in order improve our understanding of the ecological effects of elevated CO_2 concentration.
In order to study the effects of elevated CO_2 on crop plants, many different experiments were performed, according to Amthor (2001), Morison and Lawlor (1999), Tubiello and Ewert (2002), using closed systems (controlled environment chambers, greenhouses and glasshouses, inside temperature gradient tunnels, closed-top field-chambers and solar domes) and open systems like Open-top chambers (OTCs) and Free-Air Carbon Dioxide Enrichment Facilities (FACE).
OTCs have been used since the early 1970s to evaluate the effects of trace gases on vegetation (Heagle *et al.*, 1973; Mandle *et al.*, 1973) for field studies about the effects of air pollution (Bou Jaoudé *et al.*, 2008; Maggio *et al.*, 2009) and were also adapted for elevated CO_2 research (Heagle *et al.*, 1979; Rogers *et al.*, 1983).
They are highly suitable for studying the effects of elevated CO_2 on natural and agricultural ecosystems and are also appropriate for the study of temporal atmospheric CO_2 concentration variations in plant canopies (Ziska *et al.*, 2001). These experiments

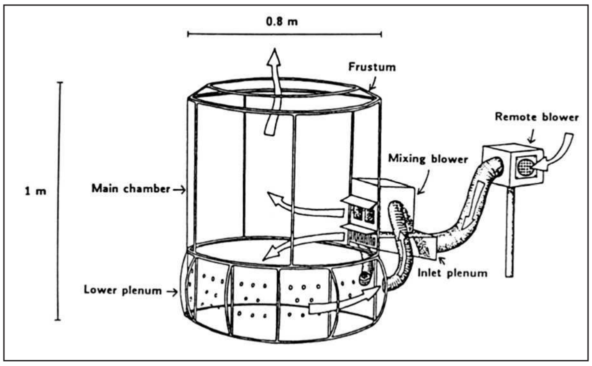

Fig. 3 - The cylindrical shape of an OTC (from Strain *et al.*, 1991).
Fig. 3 - La forma cilindrica di una OTC (da Strain et al., 1991).

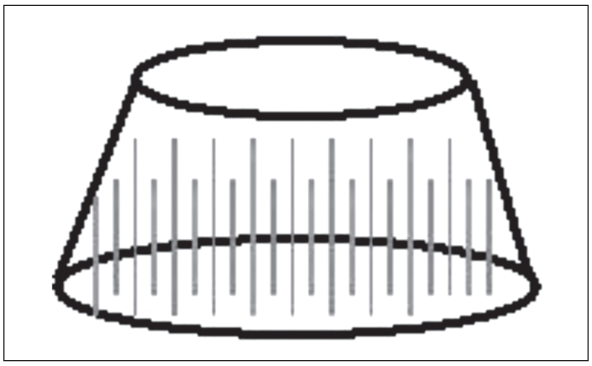

Fig. 4 - The cone design of an OTC (modified from Molau and Mølgaard, 1996).
Fig. 4 - La forma a cono di una OTC (modificato da Molau and Mølgaard, 1996).

often require long-term CO_2 enrichment as plants grow in their native soil and experience normal fluctuations in climate (Drake and Leadley, 1991; Owensby *et al.*, 1993; Rogers *et al.*, 1984). In recent years, OTCs have received increasing levels of attention (Marion *et al.*, 1997).
Nevertheless, Open Top Chambers can be considered semi-open systems, since they more or less modify the microclimatic conditions (Fagnano *et al.*, 2004), even if the degree of the modifications depends on construction and operational details of the chambers (Norris and Bailey, 1996).
The advantages and disadvantages of OTC as a tool for research on the effects of ozone pollution on crops are discussed by Fagnano *et al.* (2009).
A study was carried out on soybean plants in OTCs in the Mediterranean region at three levels of ozone (Bou Jaoudé *et al.*, 2008), which shows a significant relationship between ozone exposure-gas exchanges and the ozone exposure-daily evapotranspiration of soybean crops grown in different watering conditions. This type of chamber helps to verify the effect of ozone (or CO_2) on plant growth, yield and other characteristics.
The aim of this paper is to focus on the description of the construction and operational details of different Open-Top Chambers and the effects of atmospheric CO_2 levels, used in some experiments listed in table 1.

DESCRIPTION

Different kind of OTC have been developed and used in the experiments listed in table 1.
Hereafter the OTCs shapes, dimension, constructive characteristics , CO_2 feeding systems, and measurement systems adopted are described.

A - Shapes, dimensions and materials

Open-Top Chambers consists of three parts (Fig. 3) (Allen *et al.*, 1992; Drake *et al.*, 1989; Strain *et al.*, 1991): the bottom half, the top half and the top opening. In the bottom panel, a door can be built on the side opposite the fan, to allow for a convenient access to the inside of the chamber (Bhattacharya *et al.,* 1990). In the top the chambers have a large opening of 50 to 100 % of the chamber's basal area (Ham *et al.*, 1993), so they have inwardly inclined sides (40°-60° with respect to the horizontal). When the crops are very short (20-30 cm in height), the OTCs are formed only by the top of chamber and therefore the cone (Fig. 4) and hexagon (Fig. 5) designs are used (Marion *et al.*, 1997; Molau and Mølgaard, 1996).
The materials used included fabric, Plexiglas, fibreglass, and plastic (Molau and Mølgaard, 1996). Fibreglass material, is commonly used in horticulture, especially for greenhouse applications. Polycarbonate material is used all year round at several European sites. Schapendonk *et al.* (2000)

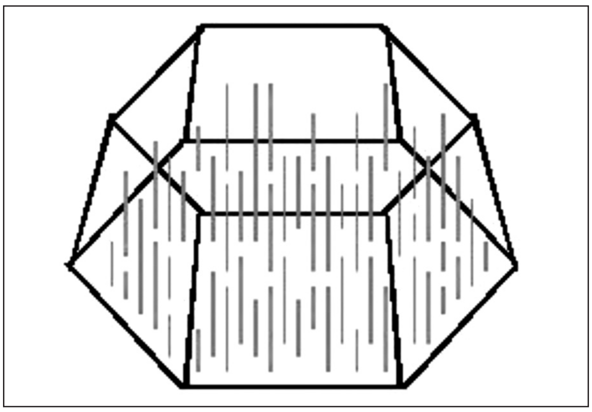

Fig. 5 - The hexagon design of an OTC (modified from Molau and Mølgaard, 1996).
Fig. 5 - La forma esagonale di una OTC (modificato da Molau and Mølgaard, 1996).

Shape	Crop	Experiment site	Density or number of plants	References
Cylindrical	Cereal	Braunschweig (Germany)	140 plants m^{-2}	Weigel *et al.,* 1994
	Winter wheat and corn	Beltsville, Maryland (USA)	60 plants m^{-2}	Rudorff *et al.*, 1996
	Spring wheat	Braunschweig (Germany)	140 plants m^{-2}	Weigel *et al.,* 1992
	Spring wheat	Braunschweig (Germany)	140 plants m^{-2}	Manderscheid and Weigel, 1997
	Spring wheat	Giessen (Germany)	Pots	Fangmeier *et al.,* 1996
	Winter wheat	Gödöllő (Hungary)	52 plants m^{-2}	Harnos *et al.,* 2006
	Scirpus olneyi and *Spartina patens*	Edgewater, Maryland (USA)	many	Rasse *et al.*, 2002
	Scirpus olneyi and *Spartina patens*	Edgewater, Maryland (USA)	many	Drake *et al.*, 1989
	Tallgrass prairie	Manhattan, Kansas (USA)	many	Ham *et al.*, 1993
	Soybean	Jamnu (India)	pots	Srivastava and Khanna, 2003
	Soybean	Rutigliano (Italy)	many	Bou Jaoudé, 2006
	Grassland	Gödöllő (Hungary)	many	Harnos *et al.,* 2006
	Sweet potato	North Carolina (USA)	pots	Bhattacharya *et al.,* 1990
	Grapevine	Washington (USA)	1 plant/OTC	Perez Peña *, 2004*
	Citrus aurantium L.	Phoenix, Arizona (USA)	1 plant/OTC	Idso and Kimball, 2001
	Betu la pendula	Suonenjoki, (Finland)	1 plant/OTC	Vapaavuor*i et al.,* 2002
Squared	Cotton	Phoenix, Arizona (USA)	10 plants m^{-2}	Radin *et al.*, 1988
	Forage crops	Norway	116 plants m^{-2}	Saebø and Mortensen, 1995
	Wheat, barley and oats	Norway	83 plants m^{-2}	Saebø and Mortensen, 1996
Rectangular	*Agave vilmoriniana* Berger	Phoenix, Arizona (USA)	2 plants m^{-2}	Idso and Kimball, 1995
Hexagonal	Potato	Wageningen (Netherlands)	20 plants m^{-2}	Schapendonk *et al.*, 2000
	Winter wheat	Wageningen (Netherl ands)	360 plants m^{-2}	Dijkstra *et al.*, 1999
	Grassland	Switzerland	many	Leadley *et al.*, 1997
	Cryptogam communities	Northern Maritime Antarctic, Orkney Islands	many	Bokhorst *et al.,* 2007
Octagonal	*Quercus* ssp.	Florida (USA)	1 plant/OTC	Dore *et al.*, 2003
	Quercus ssp.	Florida (USA)	1 plant/OTC	Hall *et al.*, 2005

Tab. 1 - Synoptic table of main OTC references.
Tab. 1 - Tabella sinottica dei principali riferimenti bibliografici sulle OTC.

used chambers made of 3-mm polycarbonate without chamber supports. Plexiglas material is recommended and most commonly used with a thickness of 2-3 mm.

Different OTC shapes have been adopted:
– Cylindrical, the most common shape of OTC (Allen *et al.*, 1992; Drake *et al.*, 1989; Rudorff *et al.*, 1996) (Fig. 6 and 7). Chambers (with a diameter usually

Fig. 6 - The cylindrical form of an OTC [from CRA – SCA (Agricultural Research Council – Research Unit for Cropping Systems in Dry Environments), 2006].
Fig. 6 - La forma cilindrica di una OTC [da CRA – SCA (Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di Ricerca per i Sistemi Colturali degli Ambienti caldo-aridi), 2006].

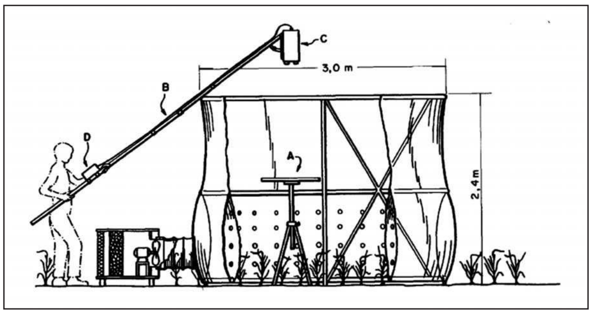

Fig. 7 - The cylindrical form of an OTC, from Rudorff et al., 1996.
Fig. 7 - La forma cilindrica di una OTC, da Rudorff et al., 1996.

ranging from 1.5 to 4.5 m and a height ranging from 2.0 to 2.4 m) are composed by metal frame covered with a transparent plastic film. This chamber was used for cotton (Fangmeier *et al.*, 1996), for wheat (Manderscheid and Weigel, 1997; Weigel *et al.*, 1992) and for sweet potato (Bhattacharya *et al.*, 1990).

– Squared, with a basal area of 9 m² (3.0 m x 3.0 m) and 1.8 - 2 m high, surrounded by a transparent plastic film (0.2 mm polyethylene) mounted on wooden frames. This chamber was used for cotton (Radin *et al.*, 1988), for forage crops (Saebø and Mortensen, 1995), and for wheat, barley and oats (Saebø and Mortensen, 1996).
– Rectangular, with a basal area of 3.2 m wide by 6.5 m long. In each chamber, 160 plantlets of *Agave vilmoriniana* Berger were grown (Idso and Kimball, 1995).
– Hexagonal (Fig. 8), is constructed as equilateral hexagons with side width and length of 0.87 m, a height of 1.95 m, and a volume of 3.8 m³. The ground area inside the chamber is 1.95 m². A frustum of 0.25 m at an angle of 45° is added on top. This chamber type was used for potato (Schapendonk *et al.*, 2000), for winter wheat (Dijkstra *et al.*, 1999) and for grassland (Leadley *et al.*, 1997).
– Octagonal, is 3.6 m in diameter and from 1.76 m to 3.4 m in height, with each chamber enclosed in a clear polyester film (Dore *et al.*, 2003; Hall *et al.*, 2005).

B - Soil and plants management

In open top field chambers, plants can be grown in both natural soil and pots. Usually experiments are carried out in soil: for example Harnos *et al.* (2006) used OTCs (130 cm in diameter and 100 cm in height) to grow winter wheat and grassland (*Festuca rupicola* Heuff., *Filipendula vulgaris* Monch and *F. rupicola*).

Sometimes pots are preferred (Fig. 9): Manderscheid and Weigel (1997) and Weigel *et al.* (1992) studied varieties of spring wheat using pots (42 cm height, 10.5 cm diameter) placed in open top chambers. The pots were placed close together in a cylindrical

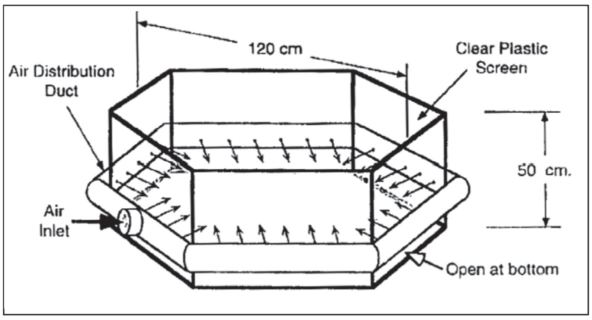

Fig. 8 - The hexagonal form of an OTC, from Leadley *et al.*, 1997.
Fig. 8 - La forma esagonale di una OTC, da Leadley et al., 1997.

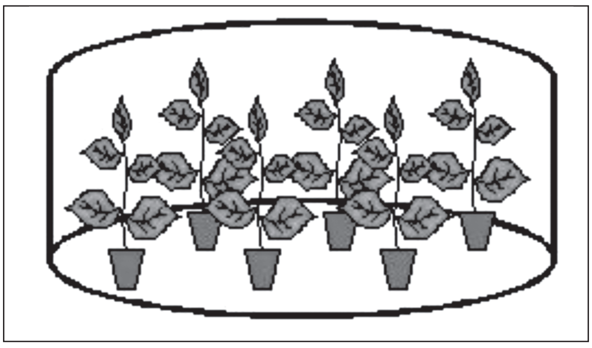

Fig. 9 - Potted plants in an OTC (design of Laura D'Andrea).
Fig. 9 - Piante in vasi in una OTC (disegno di Laura D'Andrea).

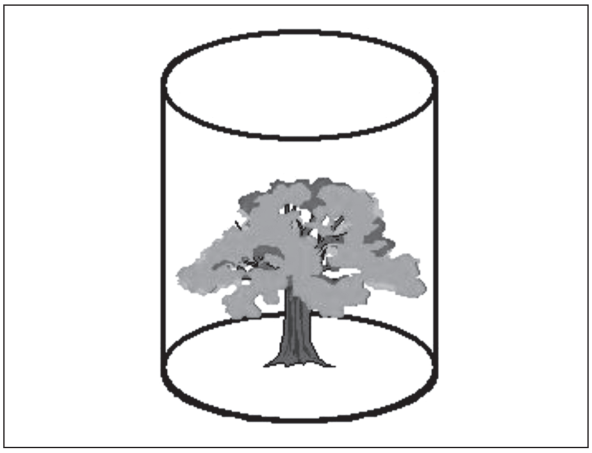

Fig. 10 - Single plant in an OTC (design of Laura D'Andrea).
Fig. 10 - Pianta singola in una OTC (disegno di Laura D'Andrea).

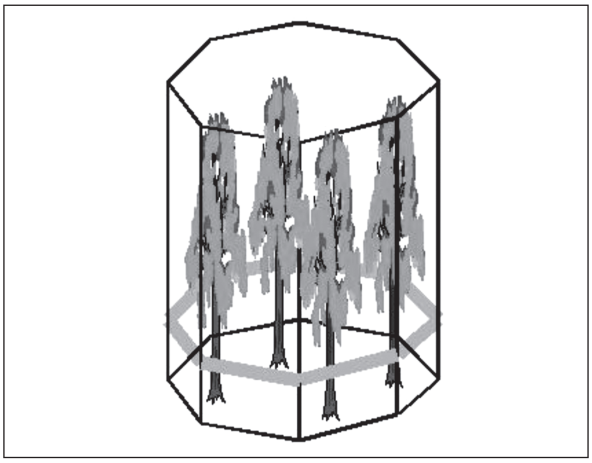

Fig. 11 - Multiple plants in an OTC (design of Laura D'Andrea).
Fig. 11 - Molte piante in una OTC (disegno di Laura D'Andrea).

excavation (0.45 m depth, 1 m diameter) at the bottom of each OTC to simulate a canopy with a density of 140 plants m^{-2}. Similarly, Srivastava and Khanna (2003), used pots to study soybean response to different CO_2 levels, but in this case, the pots were placed on the ground in OTC chambers.
Experiments, using the same instruments, were also carried out on wheat by Fangmeier *et al.* (1996) and on sweet potato by Bhattacharya *et al.* (1990).
In open top field chambers, the number of individual plants can be one or many (Fig. 10 and 11). There is one plant for each OTC for tree plants, such as grapevine (Perez Peña, 2004), sour orange tree (*Citrus aurantium* L.) (Idso and Kimball, 2001), and forest plants such as *Quercus* ssp. (Dore *et al.*, 2003) and *Betula pendula* (Vapaavuori *et al.*, 2002). There is a number of plants for each OTC for herbaceous plants (the most frequent examples), soybeans (Bou Jaoudé, 2006) (Fig. 12), grassland (Harnos *et al.*, 2006), cryptogam communities (Bokhorst *et al.*, 2007), wheat (Fangmeier *et al.*, 1996; Harnos *et al.*, 2006; Manderscheid and Weigel, 1997; Rudorff *et al.*, 1996; Weigel *et al.*, 1992; Weigel *et al.*, 1994;) and also in other cases.

C - Management of OTC
Open top chambers are usually placed in the field after crop emergence (3 weeks in the case of wheat and corn plants) and are removed at physiological maturity (Rudorff *et al.* 1996). In perennial species the chambers are normally removed from plots after plant senescence and returned at the onset of the growth period.
Air is usually forced into an OTC by means of an axial fan positioned outside the chamber and a pipe

Fig. 12 - A number of soybean plants for an OTC [from CRA – SCA (Agricultural Research Council – Research Unit for Cropping Systems in Dry Environments), 2006].
Fig. 12 - Molte piante di soia per OTC [da CRA – SCA (Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di Ricerca per i Sistemi Colturali degli Ambienti caldo-aridi), 2006].

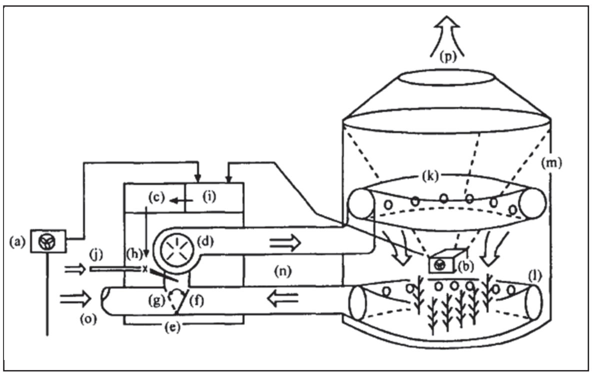

Fig. 13 - *Flow systems in an OTC, from Norris et al., 1996.*
Fig. 13 - Sistemi di flussi in una OTC, da Norris et al., 1996.

moves the air from the fan into the OTC (Fig. 13) (Norris *et al.*, 1996), where it is distributed within the chamber by means of a double-walled compartment: the inside wall has hundreds of circular holes in order to uniformly distribute air toward the vegetation (Allen *et al.*, 1992; Drake *et al.*, 1989; Rudorff *et al.*, 1996) (Fig. 3 and 7).
In field chambers, Saebø and Mortensen (1996) used perforated (1 mm holes) pipes (4 mm diameter) placed on the ground (13 holes m^{-2}). Pure CO_2 gas from a container was supplied through the tubes at a flow rate of 150 L CO_2 m^{-2} (field chamber area) h^{-1}, day and night.
Schapendonk *et al.* (2000) blew air into the chamber with a blower through a series of manifolds and pipes placed in the soil before planting. Air entered the chamber through small straight upward pipes. A windbreaker, mounted over the pipes, reduced the wind speed from 30 m s^{-1} in the pipes to less than 2 m s^{-1} at soil level. A second air-inlet system was a circular flexible transparent PVC tube, placed at about 2/3 of the OTC height, well over the canopy. Chamber air was replaced 3.6 times min^{-1}. Temperature and CO_2 concentration were measured in all chambers every 6 min. Pure CO_2 was added at the ventilator inlet and thoroughly mixed inside the OTC. CO_2 concentration was measured and adjusted when needed.
For winter wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) Rudorff *et al.* (1996) blew in carbon dioxide from Monday to Friday for 12 h per day^{-1} (7a.m. – 7p.m.), from emergence to physiological maturity.
Rasse *et al.* (2002) used chambers, 0.8 m in diameter and 1.1 m tall, that were ventilated at a rate of three–four air changes per minute with air drawn from 2.5 m above soil level. During the periods of gas exchange measurements, the chambers were fitted with a lid equipped with an exit chimney to help prevent back flow of local environment air.
Hymus *et al.* (2003) blew air through the OTCs at a rate of approx. 27 m^3 min^{-1}, entering through four circular ducts each 20.3 cm in diameter, with a total surface area of 0.123 m^2, and exiting through exhaust ports in the lids with a total exit surface area of 0.096 m^2. The difference in the entrance and exit area increased the chamber air pressure. The net ecosystem CO_2 exchange (NEE) was measured for 5–10 days per month.

D - Measurement instruments

In OTCs, different equipment can be used in order to check environmental conditions and to measure specific physiological variables.
The difference in CO_2 concentration between air entering the chamber and air inside the chamber is measured with an Infra-Red Gas Analyzer (IRGA) operating in differential mode. The effect of elevated CO_2 is often quantified by comparing growth dynamics inside CO_2-enriched chambers with those in chambers with local environment air (non-enriched). Although biomass measurements provide an integrated assessment of treatment effects, more explicit measurements of CO_2 exchange are needed to evaluate the effect of elevated CO_2 on photosynthesis, respiration, and the ecosystem C budget. Researchers often measure single-leaf photosynthesis inside OTCs using a portable gas exchange system (Wullschleger *et al.*, 1992).
Air temperature (Ta), soil temperature (Ts), soil water content (SWC), wind velocity, net radiation and photosynthetic photon flux density (PPFD) are measured simultaneously inside and outside the chambers and recorded with a data logger (Dore *et al.*, 2003; Hymus *et al.*, 2003). Ta (°C) is recorded at different heights (2.5-2.0-1.5-1.0-0.5 m), both in the centre of the chamber and outside, using shielded, cross-calibrated copper/constant thermocouples. Ts (°C) is measured at a depth of 0.01-0.1 and 0.5 m. SWC (% vol) is measured in each chamber using water content reflectometers integrating over the first 15 cm. Wind velocity (m s^{-1}) is measured with a three-dimensional sonic-anemometer, positioned 3.5 m above the soil. Net radiation is measured above the vegetation with a net radiometer. PPFD (µmol m^{-2} s^{-1}) is recorded at canopy height in the centre of each chamber and outside, using cross-calibrated quantum sensors (LI-COR). Air vapour pressure deficit, inside and outside the chambers, is calculated using water concentration and air temperature, measured both inside and outside the chambers.

ADVANTAGE AND DISADVANTAGES

A - Shapes, dimensions and materials

Especially in North Europe, inclined sides help to collect part of the heat within the chamber like a greenhouse, to increase the temperature of the environment. Furthermore, they are useful to transmit solar radiation into the chamber (optimal transmittance occurs when solar radiation strikes the surface at a right angle) and are designed to shield plants from wind, thereby providing a heating effect immediately around the plant in the absence of strong sunlight.
All chambers need to be staked to the ground. Where strong winds are expected, one might also consider guy wiring, especially in a windward

direction, for additional protection (Bokhorst *et al.*, 2007).
The cone shape (Fig. 4) (Marion *et al.*, 1997; Molau and Mølgaard, 1996) appears really interesting since it is characterized by a simpler design (one piece) which should be structurally stronger with less ground shading than the hexagon (Fig. 5).
On the other side a more complex shape like the hexagonal can be built with larger sizes and is less wasteful in the use of fibre-glass material.
A disadvantage of both designs is that some form of portable scaffolding is needed to provide access to the interiors of the chambers for monitoring purposes.
As far as covering materials are concerned:
- Fibreglass is characterized by high solar transmittance in visible wavelengths (86%) and low transmittance in the infra-red (heat) range (< 5%). It is flexible enough to be cold bent into the proper cone shape and is held together with nuts and bolts.
- Polycarbonate can be cold bent and is almost unbreakable affording the use of simpler design. This material is more expensive than fibre-glass material.
- Plexiglas: the 2 mm thick sheets are cheaper than 3 mm ones but they are less stable and some momentary deformation may be caused by heavy snow pressure during winter on OTCs placed on slopes. However, shields of 2 mm thick translucent Plexiglas transmits about 90% of photosynthetically active radiation (PAR) and is sufficiently flexible to be bent at a right angle.

Plants that are grown in pots have only a small volume of soil available to roots, which necessitates frequent watering and application of nutrients, whereas plants growing in soil are under conditions which are close to the natural environment.

B - Gas fluxes

The bottom half of OTCs cover is double-walled and the inside wall is perforated and serves as a duct to distribute air uniformly throughout the chamber.
Unfortunately, the large opening at the top of OTCs makes it difficult to sample the exhaust gas concentration accurately. During conditions of high wind, the entry of outdoor air through the top opening can contaminate gas concentration inside the OTC. This problem is more pronounced in CO_2-enriched chambers, where large differences in CO_2 concentrations exist between the chamber and outside air.
Another problem with the open-system approach is to quantify the air flow rate through the chamber. This measurement is often difficult and expensive in OTCs because of the complex nature of the air management systems. Leadley and Drake (1993) overcame the problem of turbulent incursion by temporarily adding a top or "chimney" to their 1.5 m diameter OTCs that restricted the opening to 0.2 m in diameter. This procedure eliminated incursions and allowed accurate CO_2 sampling required for the net carbon exchange measurements in both local environment and CO_2 enriched chambers. A similar solution was adapted by Grünhage *et al.* (1993), who used OTCs with a "rain exclusion cap".
Unfortunately, no techniques are currently available in order to obtain continuous measurements of CO_2 flux during long-term CO_2 enrichment experiments, even though this is crucial in determining whether ecosystems are sequestering or outgassing C in response to elevated CO_2 and climate change.

C - Measurement instruments

CO_2 measurements must be carried out at the maximum height of the canopy. In fact, Hymus *et al.* (2003) report that while photosynthesis of the light-limited leaves within the canopy will still be stimulated by elevated atmospheric CO_2 concentration, due to the competitive suppression of photorespiration, the stimulation will be much less than that of sun-exposed leaves.
The combination of this physiological response with the fact that light penetrating the thicker canopy will be greatly reduced in conditions of elevated CO_2 is extremely important. It has been shown that through the combination of these two factors, photosynthesis of *Quercus myrtifolia* leaves within the canopy was only 6% higher in elevated CO_2 compared with the 34% stimulation of sun-exposed leaf photosynthesis.
The measurements of net ecosystem CO_2 exchange must be carried during the hours of maximum light (between midday and 4p.m.), when the differences of exchange are reduced. This is due to the fact that in the morning increased air temperature inside the chamber enhances photosynthesis and during this period light is saturated (Dore *et al.*, 2003).

CONCLUSIONS

There is a stringent need to confirm crop responses to CO_2 variations observed in a large number of controlled-environment experiments using OTCs that guarantee more realistic conditions. OTCs are infrastructures which are especially useful for field crops whose cycles are not excessively long to carry out experiments on CO_2 effects on crop growth and yield.
The comparison between the environmental conditions in most of the controlled-environment growth chambers with those in the field highlights

substantial differences in the absolute values of key factors (controlled environments are often hot, wet, humid and poorly illuminated compared with the field), and also in their variability and coupling. A field-grown crop may experience rapid changes in water and radiation, and therefore assimilate supply, whereas nutrition may alter more slowly.

OTCs have the advantages of providing the crop with conditions that closely correspond to reality, can be placed in the field for several seasons and are easy to transport. In OTCs the conditions (e.g. temperature) may be manipulated to achieve interaction with CO_2, but there is little evidence of this reported in literature. They have the advantage of being simple, inexpensive systems, permanent structures that can be left in place year-round and structurally strong enough to withstand high winds and extreme cold, providing a significant temperature enhancement and minimizing unwanted ecological effects. Molau and Mølgaard (1996) also noted the advantages of OTCs as having lower temperature extremes, especially on sunny days, better light quality and quantity due to more direct solar radiation to plants, more natural levels of humidity and CO_2 levels around plants, more direct precipitation, easier access of pollinators and herbivores to plants, lower cost, ease of installation, and easier access to plants.

OTCs are influenced by climatic variables (temperature, solar radiation, wind speed and cloud cover) whereas latitude has an effect on day length and solar angles so affecting the radiation load impinging on the chambers. Vegetation and soil influence the heat flux within the chambers through ground shading and heat conduction through the soil. Among the disadvantages, literature reports lower levels of CO_2 inside the OTC compared to its normal concentration in the air as well as the fact that the temperature tends to be higher than that found externally. Furthermore, if the chambers in the field permit a solar radiation approach similar to normal field crops, the humidity and temperature inside the OTCs may be atypical. The environment itself may be altered (temperatures may be warmer, radiation is reduced and wind profiles are changed, thus affecting evapotranspiration, as well as isolation from the rest of the crop affecting pests and diseases) but conditions are closer to reality than in closed systems.

The effects may be minimized (Norris and Bailey, 1996), in an open-top chamber 3 m wide and 3 m high by reducing the frustum aperture diameter from 2.2 m to below 1 m so that the ventilation rate of 6 air changes minute^{-1} is double the ventilation rate currently used in OTCs. A reduction in carbon dioxide consumption is possible by using controlled ventilation which involves ventilating the chamber to limit the temperature excess (temperature above ambient of 2 °-C) during conditions of high solar flux and recirculating the chamber air at other times to conserve the enrichment gas.

In conclusion, open top chambers represent the best compromise between the need to control climatic conditions in closed environments and the high cost and complex technical demands of the unrestricted release of CO_2 in a FACE systems.

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Relationships between vegetative-reproductive phases of plant species and the meteorological variables in a phenological garden of Central Italy

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Abstract: *In the last few centuries phenological observations were commonly considered as useful and inexpensive 'plant-instruments' which respond to many meteorological and environmental factors. At first, phenological observations were carried out by volunteers interested in nature, while in the last century the first phenological networks were instituted in different countries. The present study was carried out at the Phenological Garden located in central Italy (Perugia, Umbria Region) which contains indicator species, common to all International Phenological Gardens. The aim of this study was to determine and analyse the average trends of vegetative and reproductive development of seven plant species, adapted to the Mediterranean environment, over an eleven-year period (1997-2007). Two periods ("effective leaf assimilation" ELA and "effective flowering period" EFP) were considered to show the meteorological influence on plants development during the same periods. High correlation values were seen between ELA and rain amounts recorded at the 40th week (autumn season) which show that rain events delay the beginning of leaf colouring extending in this manner the ELA period. Though the reproductive phases demonstrated lower variability in comparison to the vegetative ones, a certain lengthening of the effective flowering period was evidenced.*
Keywords: *phenology, tree plants, climate*

Riassunto: *Negli ultimi secoli i rilievi fenologici sono stati particolarmente considerati sia per la loro utilità che per il fatto di essere poco costosi permettendo di interpretare le relazioni che legano i fattori meteorologico-ambientali agli organismi vegetali. In un primo momento, le osservazioni fenologiche erano effettuate da volontari interessati agli aspetti naturalistici, mentre nel secolo scorso, alcune reti fenologiche venivano ad essere istituite in diversi paesi. Il presente studio è stato effettuato presso un Giardino fenologico situato nel centro Italia (Perugia, Regione Umbria), dove sono presenti alcune specie vegetali indicatrici comuni a tutti i giardini fenologici internazionali. Lo scopo di questo studio è stato quello di determinare e analizzare le tendenze medie di sviluppo vegetativo e riproduttivo relative a sette specie di piante, adattate all'ambiente mediterraneo, in un periodo di undici anni (1997-2007). Due periodi ("periodo di effettiva crescita vegetativa" ELA e "periodo effettivo di fioritura" EFP) sono stati considerati per evidenziare l'influenza meteorologica sullo sviluppo delle piante durante il periodo di studio. Sono stati osservati alti valori di correlazione tra ELA e gli eventi precipitativi registrati durante la 40° settimana dell'anno (stagione autunnale) interpretabili con il fatto che forti accumuli di pioggia possono ritardare l'inizio della fase di senescenza delle foglie stesse estendendo in questo modo il periodo di vegetazione. Anche se le fasi riproduttive hanno dimostrato minore variabilità rispetto a quelle vegetative, è stato comunque registrato un certo allungamento del periodo di fioritura.*
Parole chiave: *Fenologia, specie arboree, clima*

INTRODUCTION

Phenology in its present meaning is the study of the events that lead to the manifestation of phenomena associated with the functioning of some plant organs or of the plant as a whole. The observed phenomena (the phenological stages) include flowering, the appearance of leaves, leaf drop or any other observable cyclic phenomenon with their exact occurrence during the year. In temperate zones the reproductive cycle of plants is mostly controlled by temperature and day length, while at lower latitudes rainfall and evapotranspiration must also be taken into account. The timing of spring events in mid to high latitude plants such as budding, leafing and flowering is mainly regulated by temperatures after dormancy and a number of studies have found good correlation between spring phases and air temperatures (Chmielewski and Rötzer 2001; Chmielewski et al. 2004; Estrella et al. 2006; Fornaciari et al 1998, 2000; Makrodimos et al. 2008). Thus, phenological phases may serve as proxies for spring temperatures. While the climate signal controlling spring phenology is quite well understood, autumn phenology is less clearly explained.

Several studies have linked inter annual variability in phenology to large-scale weather features such as the North Atlantic Oscillation (NAO) and El Nino-

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Southern Oscillation (ENSO). Changes in plant phenology are considered to be the most sensitive and observable indicator of plant responses to climate change.
In climatology and ecology, phenology and syn-phenology are used to determine the degree of climatic changes that have occurred and to consider their potential consequences (Kramer et al. 2000; Mutke et al. 2003; Orlandi et al. 2005a, b).
In his pioneer work in 1955, Schnelle discussed the value of phenological observations and concluded that these inexpensive and useful 'plant-instruments' are integral instruments which respond to many meteorological and environmental factors. He concluded that the best method to analyse impacts on plants would be to ask the plants themselves. In most cases, phenological observations have been carried out by volunteers interested in nature. The great advantage of phenological observations is that they are extremely suitable to illustrate and communicate climate change impacts. Another important application of phenology models is to evaluate species distribution from the perspective of future climatic change. Phenological studies interpret the reproductive success of a plant population each year, the growth and survival probability of individuals and their fitness under particular climatic conditions (Cleland et al. 2007).
The present study was carried out at a phenological garden located near Perugia, central Italy, which contains indicator species, common to all International Phenological Gardens (Orlandi et al. 2007). These species were obtained from mother plants received from the German Weather Service, the European coordinator for the distribution of IPG clones. The National Working Group for Phenological Gardens selected the species which were adopted as indicator species from those proposed by the IPG. Since all the species are typically from northern European climates, which are characterised by cold winters, mild summers and abundant rainfall, the group selected species that would adapt easily to the Mediterranean climate.
The phenological garden also contains indicator species that are common to the Italian Phenological Gardens and that are representative of the geographical area. Aims of this study were to determine and analyse the average development trends of the considered plant species and to evidence plant adaptability to the Mediterranean environment, over an eleven-year period (1997-2007). In addition, phenology was used as a tool to investigate the climate/plant relationships.

MATERIALS AND METHODS

The tree indicator species examined were those suggested by the International Phenological Garden Network:

1) *Cornus sanguinea* L.; Common name: dogberry, dogwood;

2) *Crataegus monogyna* Jacq., Common names: hawthorn, thornbush;

3) *Corylus avellana* L., Common name: hazel;

4) *Ligustrum vulgare* L., Common name: privet;

5) *Robinia pseudoacacia* L. Common names: robinia, acacia;

6) along with common IPG species such as *Salix acutifolia* Willd. Common name: willow;

7) *Sambucus nigra* L Common name: elder.

The phenological sampling was carried out according to the basic criteria (every phenological stage interprets a distinct biological event, the data must be objective, so that they can be compared with those of other researchers, etc.) using phenological keys described by various authors (Chmielewski and Rötzer 2001; Spano et al. 1999).
In particular, for the vegetative cycle the following phenological phases were considered:
V3) bud break and leaf unfolding; V5) young unfolded leaf; V7) adult leaves; V8) beginning of leaf colouring.
For the reproductive cycle, the following phenological phases were considered:
R3) swollen buds and open flowers, mature and immature aments; R4) full blooming: open buds and flowers, mature aments; R5) withering begins: open and withered flowers, mature and withered aments; R6) complete withering: withered flowers and aments.
The observations were conducted on three individuals for each plant species to limit the random variability, possible even in genetically similar plants. The mean date for the onset of each phenophase was calculated mathematically considering contemporary the three plants (phenoids) of the same species.
The average dates thus obtained provide a mean model of development in relationship to the species and to the year of observation. The mean values of the phenological data were computed for the different species in relationship to the eleven-year period of observation (1997-2007) in order to obtain the mean developments in the study area.
Moreover, by the meteorological point of view, the minimum, maximum temperatures and rain amounts were calculated every 10 weeks of the year (10^{th}; 20^{th};

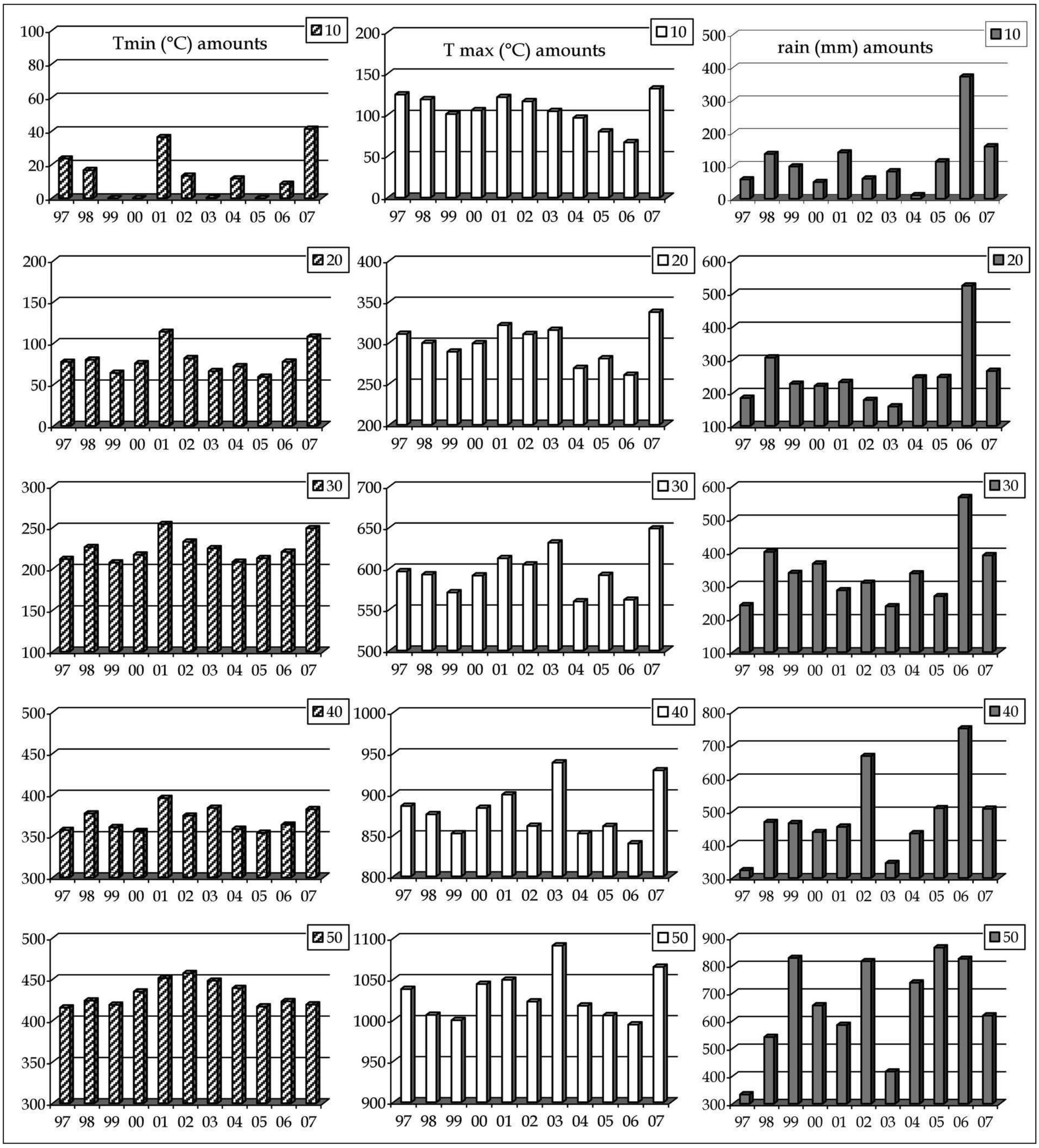

Fig. 1 - Minimum, maximum temperatures and rain summation calculated every 10 weeks of the year.
Fig. 1 - Accumuli delle temperature minime, massime e precipitazioni ogni 10 settimane dell'anno.

30th; 40th; 50th) for each study year to evidence the differences of the principal meteorological behaviours among the study years.
Once the dates of each phenological phase were determined, we examined the daily values of the temperature units expressed in GDD (Growing Degree Days) in order to determine the relationship between spring and summer temperature trends and the plants' vegetative and reproductive development. For the calculation of GDD, two different methods were applied. The first method (Single triangle) uses the minimum and the maximum temperature of the *n* day and the minimum temperature of the *n+1* day. The other method evaluated the hourly temperature trend by means of the Single Sine function (Zalom et al., 1983).

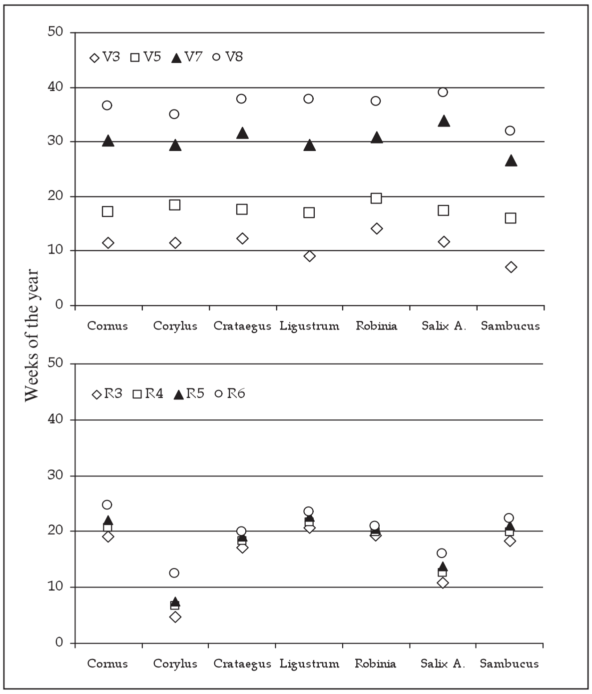

Fig. 2 - Mean values during the study period of vegetative and reproductive phenological phases for each plant species.
Fig. 2 - Valori medi delle fenofasi vegetative e riproduttive per ciascuna specie vegetale.

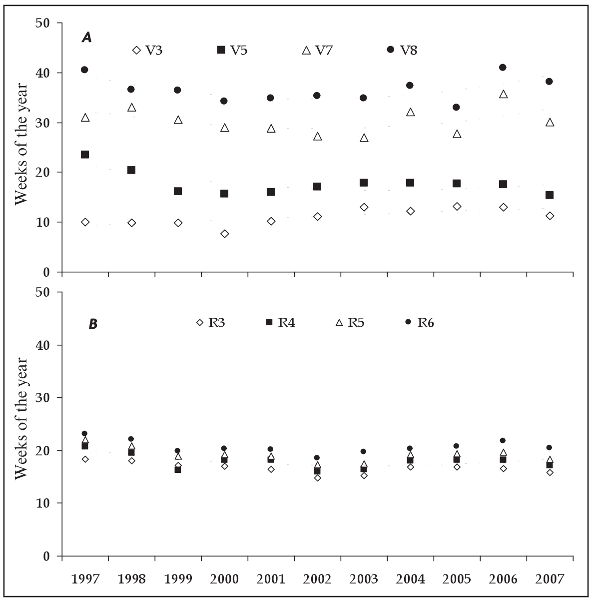

Fig. 3 - Mean values of vegetative and reproductive phases calculated considering contemporary all the plant species.
Fig. 3 - Medie delle fasi vegetative e riproduttive considerando contemporaneamente tutte le specie vegetali.

The GDD formulas were calculated using 5 different temperatures threshold (5-7-9-11-13°C). In different observation years the summations of GDD values were calculated, derived from the combination between the starting date of accumulation (January 1), the final dates related to the phenological phases investigated and the five threshold temperatures utilized in daily GDD calculation.

We then compared, for each species, the variability of yearly GDD summations obtained considering the same GDD method, start-end dates and the same threshold. This comparison was made using the calculation of the root mean square error (RMSE), which is considered the best instrument for the variation analysis of the distributions relative to the GDD summations (Ashcroft et al. 1977). In this phase of our research, the RMSE calculation allowed us to determine which thresholds minimized the variability among yearly GDD summations. The best threshold temperature is the one above which the heat useful for the formation of vegetative and reproductive structures is accumulated. Moreover a regression analysis was conducted considering contemporarily all the studied species to validate the results obtained with RMSE evaluation.

For the GDD calculations the daily minimum and maximum temperatures were used, provided by the local meteorological station of the National Agro-Meteorological Network, situated near the phenological garden (inside the farm of the Agraria Faculty - Perugia University) at 211 meters above sea level with coordinates of 43° 00' North and 12° 18' East. In particular the phenological garden was realized during 1994 in that area considering the nearness of the meteorological station which furnish daily values of all the principal meteorological variables.

We also considered the entire period when the leaves are in full activity, which is from the appearance of the first leaves with photosynthesis activity (V3) until the leaves wither and do not assimilate any more (V8). The present period was named as "Effective Leaf Assimilation" (ELA).

Moreover, we considered the duration of the effective flowering period, from the moment when the reproductive structures are ready for the fecundation process until their withering and death. This period was named the "Effective Flowering Period" (EFP). The influences of principal meteorological variable amounts, calculated to the moment of vegetative (V5-V8) and reproductive (R3-R6) phases, on ELA and EFP have been considered through Pearson correlation analyses.

RESULTS AND DISCUSSION

To better understand the extent of variations observed during the study period (1997-2007), a

Tab. 1 - RMSE (Root-mean-squared-error) values (expressed in GDD) for the first vegetative (V3) and the first reproductive (R3) phases considering all the plant species. Two GDD calculation methods and five (5-7-9-11-13 °C) threshold temperatures were considered.
Tab. 1 - RMSE (radice dell'errore quadratico medio, espresso in GDD) per la prima fase vegetativa (V3) e riproduttiva (R3) per tutte le specie vegetali. Sono stati considerati due metodi di calcolo e cinque (5-7-9-11-13 °C) temperature soglia.

		Single T.	Single S.		Single T.	Single S.		Single T.	Single S.		Single T.	Single S.
TT 5_V3	CORNUS	65.7	70.0	CORYLUS	77.4	74.8	CRATAEGUS	59.2	63.9	LIGUSTRUM	64.0	64.0
TT 7_V3		50.6	61.1		52.0	55.8		47.1	52.2		44.4	53.4
TT 9_V3		42.7	59.0		36.6	52.2		40.0	51.2		36.5	57.4
TT 11_V3		45.6	62.3		37.7	58.7		43.8	55.6		40.9	68.8
TT 13_V3		57.3	69.9		51.6	67.8		56.1	62.4		54.9	83.5
TT 5_R3		55.1	57.9		19.6	31.1		52.3	64.3		57.8	51.2
TT 7_R3		56.1	61.8		17.0	35.2		53.5	63.0		41.1	33.7
TT 9_R3		60.9	70.5		26.1	47.1		59.5	70.6		42.0	43.3
TT 11_R3		67.0	78.6		39.3	64.8		63.7	71.5		52.2	58.8
TT 13_R3		74.3	78.0		56.9	85.9		71.6	66.8		65.5	65.1
TT 5_V3	ROBINIA	78.6	78.5	SALIX A.	62.3	64.4	SAMBUCUS	32.5	36.6			
TT 7_V3		63.9	67.7		47.7	54.8		23.5	27.9		LEGEND:	
TT 9_V3		52.7	64.0		40.6	54.0		27.6	30.9		TT = Threshold T°	
TT 11_V3		50.4	61.2		44.2	58.5		38.2	39.3		TT 5,7,9,11,13	
TT 13_V3		58.8	63.5		56.3	64.8		52.6	47.1			
TT 5_R3		63.5	61.7		43.8	49.7		92.5	84.6		V3 = Leaf bloom	
TT 7_R3		55.1	51.6		37.0	42.9		75.4	71.9		R3 = Flowering	
TT 9_R3		55.3	60.2		36.2	47.7		64.5	72.1			
TT 11_R3		58.9	66.2		42.9	56.2		61.5	75.0			
TT 13_R3		67.4	67.4		56.1	63.7		67.5	73.9			

complete picture of all the meteorological trends can be very useful. The charts (Figure 1) represent the thermal accumulations of the maximum and minimum temperatures and the rainfall summations. The values were calculated on a 10 week basis, until reaching the 50th week of the year (practically the central period of december).
Examining the graphs of the maximum and the minimum temperatures it can be noted that at the 50th week the central years (2001-2003) are the warmest (highest temperature amounts) during the study period.
On the whole, the rainfall amounts at 20th and 30th weeks represent an opposite behaviour with regard to the temperature. Indeed, in the central study years (2001-2003) lowest amounts were recorded above all during spring and summer periods. Examining the latter behaviour together with the temperature summations it can be affirmed clearly that the warmest and the driest year was 2003.
Figure 2 represents the mean dates of vegetative and reproductive phases for each examined species, calculated during the 11-year study period. The mean dates were calculated considering the exact days of phenological phases realization year by year, even if they were presented as weekly data.
The charts show that the Cornus species reaches in 13 weeks the adult leaf phase, and it reaches rather quickly the autumn leaf colouring phase. The Corylus species shows similar behaviour, but it presents leaf colouring earlier. The Crataegus species reaches the adult leaf phase and the successive phase about two weeks later than Corylus.
The Ligustrum species shows the longest vegetative cycle: it starts with opening buds in April before the 10th week and it reaches the leaf colouring phase in the 37th week, with a mean time from the V3 phase to the V8 phase of about 200 days. The Robinia species has the colouring phase in the same week as the Ligustrum, though it needs about 23 weeks (160 days) to reach it. This plant has the shortest vegetative cycle; it reaches the V3 phase only on the 14th week, sprouting young leaves very quickly. It then has a very uniform development of the vegetative cycle, slightly slowing down during the passage to the adult leaf phase. The Salix species needs about 16 weeks to pass from the V5 phase to the V7 phase, after which it reaches the V8 phase in only 5 weeks. Among the examined species, it is the last to reach the adult leaf and colouring phases.
The Sambucus species is the first one to show young leaves on the 7th week and it is the earliest to reach the colouring phase on the 32nd week. Thus,

Regression Equation Section (database 1997-2005)						
R2	0.8565		Mean Square Error		0.4984	
Adj R2	0.8360		Square Root of MSE		0.7060	
Coeff. of Variation	0.0655		Ave Abs Pct Error		4.2540	
Independent Variable	Regression Coefficient b(i)	Standard Error Sb(i)	T-Value to test H0:B(i)=0	Prob level	Reject H0 at 5%?	Power of Test at 5%
Intercept	6.3659	0.7213	8.8260	0	Yes	1
C2	0.0522	0.0081	6.4640	0.0003	Yes	0.9997
Out-of-sample test of predictability (database 2006-2007)						
	Actual C1	Predicted C1	Residual	Sqrt(MSE)		
1997	10.04	9.92	0.12	0.76		
1998	9.88	9.59	0.29	0.75		
1999	9.86	10.41	-0.56	0.72		
2000	7.71	7.75	-0.04	0.76		
2001	10.13	11.16	-1.04	0.61		
2002	11.07	11.47	-0.40	0.74		
2003	12.94	13.00	-0.06	0.76		
2004	12.21	10.91	1.23	0.51		
2005	13.12	12.72	0.40	0.73		
2006	13.07	14.84	-1.77			
2007	11.29	12.29	-1.01			

Tab. 2 - Regression equation considering vegetative phase (V3) and GDD amounts (TT 9°C) from 1997 to 2005. Out-of-sample test of predictability in 2006-2007 to calibrate the regression relationships.
Tab. 2 - Equazione di regressione per la fase vegetativa (V3) e gli accumuli di GDD (TT 9°C) dal 1997 al 2005. Test di significatività "fuori campione" nel 2006-2007 per valutare i rapporti di regressione.

Sambucus anticipates the other plants in all the vegetative phases, completing its biological cycle in about 25 weeks.
Regarding the reproductive phases, we can note a great similarity among the various plant behaviours, with a maximum duration of about 8 weeks.
Considering the examined plants individually, it can be noted that Corylus is the first one to differentiate its reproductive organs, in this case the aments, which are well developed from the 4th week. It is the only plant which emits the reproductive organs first and the vegetative ones successively. The full flowering and the beginning of withering occur in a few days, while complete withering takes place after five weeks from the precedent phase. Among all the examined species, Corylus has the longest reproductive cycle, with a duration of about 8 weeks.
The second plant showing early flowering is the Salix, which shows the well-developed aments from the 10th week. It is interesting to note that this phase coincides with the appearance of the first leaves. Compared to Corylus, this species shows a more uniform trend and concludes its entire cycle in less than 35 days, reaching complete withering in the 15th week.
For Crataegus, the bud appearance and opening was registered on the 17th week. Its reproductive cycle is concluded within 18 days. Therefore, the phases are extremely close, especially the two central phases, R4 and R5.
One day after the beginning of flower opening of Crataegus, the same process starts for Sambucus, which completes the entire cycle in 27 days. The cycle is characterized by well differentiated phases, at a distance of about one day from each other.
Cornus carries out its flowering phases in about 39 days: the opening of the flower head starts on the 19th week, the two successive phases occur with the frequency of about one week, while complete withering takes place on the 24th week.
The flowering of Robinia occurs two days later than in the Cornus. This species presents the shortest reproductive phase of only 11 days. The phases change at an interval of about 3 days, until reaching complete withering at the end of the 20th week.
Ligustrum is the last species to start flowering, 9 days later than Robinia. The phases are distant from one another of about one week, completing the entire cycle and reaching a withering phase in about 3 weeks.
In Figure 3 the mean values of vegetative and reproductive phases calculated considering contemporarily all plant species are shown. In Figure 3A the mean vegetative phases are simply described with the use of second degree polynomial trend lines which evidence different behaviours. The first phase (V3) shows a phenomenon of dates

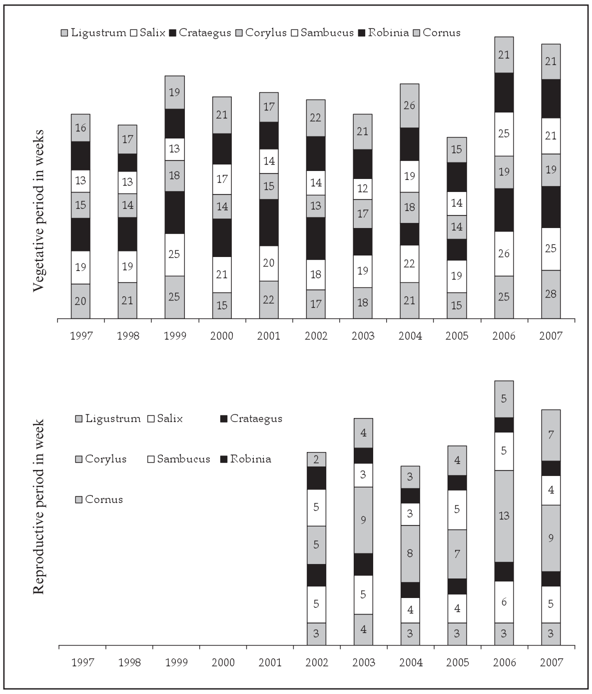

Fig. 4 - Effective leaf assimilation (ELA) and flowering period (EFP) represented for all the plant species during the study period (the number indicate the vegetative and reproductive period in weeks).

Fig. 4 - Periodo vegetativo di crescita fogliare (ELA) e periodo di fioritura (EFP) per tutte le specie vegetali durante il periodo di studio (i numeri indicano la lunghezza dei periodi vegeto-riproduttivi in settimane).

delay with a minimum value in 2000. The second vegetative phase (V5) appears to be less variable with a last date in 2007 which shows a marked advance, probably linked to the particular meteorological values (high temperature) during the first months of the year. The last two vegetative phases (V7-V8) show a dual behaviour with a first advancing part from 1997 to 2003 and a second one delaying to 2007. In Figure 3B the reproductive phases evidence a higher homogeneity in comparison to the vegetative ones even if all the phases show their minimum values during 2002-2003 following the previous trends on a smaller scale.

To estimate the best GDD calculation method (single triangle, single sine) and the threshold temperatures (5-7-9-11-13°) which minimize the GDD amount variability over the years, the RMSE values (expressed in GDD) for the first vegetative (V3) and the first reproductive (R3) phases are shown in Table 1. The best results in terms of minor variance over the years were obtained with the use of single triangle in the GDD calculation considering all the plant species, and both the vegetative and reproductive phases. Only the Ligustrum species presented the best result (with a minimum value of RMSE) with the use of single sine for the R3 reproductive species (although the difference between the two GDD calculation methods was very low).

In quite all the cases analyzed the better threshold temperatures (for the amount of "useful warm temperature") were represented by 7°C and 9°C, with the exceptions of Robinia vegetative phase and Sambucus reproductive phase, both with an optimal temperature of 11°C.

In addition a regression analysis was realized considering the best GDD method (triangle) and the best threshold temperature (9°C) related to vegetative phase (V3) considering all the studied species contemporarily. The regression was conducted to validate the best method for GDD calculation, carried out through RMSE evaluation, by using a first set of data (1997-2005). Moreover other two years of the historical series (2006-2007) were utilized to validate the regression results. In Table 2 the regression equation section is presented and both interpretative and predictability power of

Meteorological variable summation			ELA (V8-V5)	Vegetative phase V5
	Pre-V5	Tmax	-0.45*	0.9***
		Tmin	0.00	0.48*
		Rain	0.22	0.21
			ELA (V8-V5)	Vegetative phase V8
	Pre-V8	Tmax	0.78**	0.95***
		Tmin	0.82**	0.94***
		Rain	0.58**	0.53**
			EFP (R6-R3)	Reproductive phase R3
	Pre-R3	Tmax	-0.33*	0.35*
		Tmin	-0.15	-0.06
		Rain	-0.03	0.17
			EFP (R6-R3)	Reproductive phase R6
	Pre-R6	Tmax	0.57**	0.44*
		Tmin	0.41*	0.17
		Rain	-0.03	0.21

Tab. 3 - Correlation results (r) between principal meteorological variable (Tmax, min and rain) amounts, calculated to vegetative (V5-V8) and reproductive (R3-R6) phases and ELA-EFP periods. Pearson correlation method (Prob-level * 0.05 - ** 0.01 - *** 0.001).

*Tab. 3 - Risultati della correlazione (r) tra le principali variabili meteorologiche (Tmax, min e pioggia), calcolate fino alla comparsa delle fenofasi vegetative (V5-V8), riproduttive (R3-R6) e per i periodi ELA-EFP. Per le correlazioni è stato utilizzato il metodo Pearson (Prob-level * 0.05 - ** 0.01 - *** 0.001).*

GDD amounts are shown in relation to the vegetative phase of all the considered plant species. On the contrary, the regression analysis realized with reproductive phase (R3) did not reach significance standards probably because of the partial independence of reproductive processes respect to meteorological annual trends.

In Figure 4 the Effective Leaf Assimilation (ELA) and the Effective Flowering Period (EFP) are shown for all plant species and their different trends during the whole study period. The ELA had a decreasing trend from 1999 to 2005, while during the two last years (2006-2007) the leaf assimilation period increased to the maximum values of about 160 days considering contemporary all the plant species. The minimum complex duration of ELA was recorded in 2005 with a value of about 100 days. This characteristic trend of ELA is very similar to those evidenced by the minimum T° and rain summations recorded during the 20th and 30th week of the year. A specific correlation analysis among ELA and the temperature and rain summations showed the highest values with rain sums, which cumulated at the 10th, 20th, 30th and 40th week (the highest value was r=0.71 with the rain sum at 30th week).

On the other hand, the EFP trend constantly increased from 1999, when the complex period of flowering (considering all the species) was of about 15 days. In the last study years (2006-2007) this complex duration arrived at 30 days and even more. This phenomenon is due to the lengthening of the Corylus flowering, which was not registered in the first two years. The EFP trend seems to be influenced by internal (physiological) processes of the plants, which in their first years of development are still not quite mature and stabilized.

The meteorological variable amounts, calculated from 1st January to the dates when vegetative and reproductive phases (V5-V3 and R3-R6) were recorded yearly, were related to the two periods of "ELA" and "EFP".

In Table 3 the influences of principal meteorological variable amounts, calculated to the dates of vegetative (V5-V8) and reproductive (R3-R6) phases, on ELA and EFP are shown. The correlation results show a high influence of Tmax amount calculated to the V5 phase (r=0.9) on the V5 realization dates, but a low influence on ELA. All the temperature variables and rain amounts calculated to the V8 phase are highly related (r values are always higher than 0.5) to V8 realization dates and with the same ELA.

Considering the reproductive phases, it can be noted that only the temperature variable amounts (above all, Tmax) calculated until the last phase (R6) are related to the EFP, but the correlation values are lower than those calculated for the vegetative phases.

CONCLUSIONS

The observations realized during the study period let us say that climate is subject to more or less evident fluctuations, depending on the period of the year. Regarding the seasons, a lengthening of typical summer parameters with detriment of the spring ones was observed, while the winter and autumn seasons were practically unchanged. The observed variations can influence the plants' bio-rhythms determining their adaptation.

The results obtained during the study period demonstrated that all the examined species had a similar behaviour: they showed, in different degrees, a similar shift of phases (anticipation / delay), depending on climatic conditions. In general, we can note a slight delay in the manifestation of the open bud phase and a parallel anticipation of the young open leaves phase, with a shortening of the period of leaf opening. On the contrary, the V7 (adult leaves) and the V8 (autumn leaf colouring) phases tend to remain constant, with the exception of some species such as Crataegus which shows a shortening of these phases, confirming that, in contrast to spring events, the signal for leaf colouring in fall is quite ambiguous and less evident (Menzel et al. 2006).

In dependence of meteorological features, the adult leaves show the tendency to remain longer on the trees in consequence of the fact that warm season and mild temperatures favour the delaying of the successive vegetative phases, postponing the plant's seasonal rest period.

These behaviours were confirmed by the high correlation values calculated between ELA and rain amounts recorded at the 40th week which show as the rain events retard the V8 phase extending in this manner the ELA period. Moreover, the influences of temperature and rain on the V8 dates confirmed that the ELA duration is above all linked to a delaying phenomenon of the V8 phase.

The reproductive phases are quite stable; however, they show a gradual lengthening of duration. The flowering period follows the development of the first vegetative phases, to which it seems strictly connected, while the weather influences more markedly the extension of single phases.

Observing the single species, we can note that the plant which suffered fewer modifications was the Corylus. Sambucus had a weak tendency to delay the phases, excepting the last two years. Cornus, Crataegus, Robinia and Salix manifested slow oscillations, depending on the variations of atmospheric conditions. Ligustrum also showed these oscillations, but with greater modifications.

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Climatic variability in Tuscany: omogeneity methods of climatic data and analysis of impacts on grapevine and olive trees

Annalena Puglisi[*1], *Giorgio Bartolini*[1], *Simone Orlandini*[1]

Abstracst: *To perform climatic analysis, climatic data must be as homogeneous as possible, not affected by non-climatic factors that make data unrepresentative of climate variations during the relevant time period. The aim of this study is to homogenise temperature time series of the Tuscany region (Italy) and to analyse their past and present climatic trends and variability.*
Such analysis has been performed through the study of numerous climatic and agroclimatic indices. Subsequently, considerations about the impacts of climatic trends and variability on growth and reproduction of grapevine and olive trees have been made.
Keywords: *homogenisation, time series, climatic variability, grapevine, olive trees*

Riassunto: *Per realizzare analisi climatiche è necessario che i dati climatici utilizzati siano il più omogenei possibile, non viziati, quindi, da fattori non-climatici che rendono questi dati non rappresentativi della variazione del clima nel corso del tempo. Il presente studio ha lo scopo di omogeneizzare le serie storiche di temperature di stazioni meteorologiche sparse sul territorio della regione Toscana (Italia) e di analizzarne la variabilità climatica passata ed attuale. Tale analisi è stata realizzata attraverso lo studio di numerosi indici climatici.*
Successivamente, sono state fatte alcune analisi ed ipotesi sull'impatto di questo andamento e di questa variabilità climatica sul comportamento fenologico e qualitativo della vite e dell'olivo, due delle più importanti colture della regione Toscana. A tale scopo sono stati scelti alcuni indici agroclimatici calcolati su periodi temporali diversi in base al loro legame con la crescita e riproduzione della vite e dell'olivo.
Parole chiave: *omogeneizzazione, serie storiche, variabilità climatica, vite, olivo*

INTRODUCTION

To perform climatic analysis, climatic data must be as homogeneous as possible. A homogeneous historic series is defined as a series in which data fluctuations are due only to climatic changes.

Unfortunately, most time series are affected by non-climatic factors that make data unrepresentative of climate variations during the relevant time period. Such factors include changes in instrumentation, observation practices, the formula used to calculate averages, the location of stations and the environment surrounding them.

Many methods of homogenisation, including some that adopt different concepts of data correction, have been developed, depending on the aim, the input data and the type of results required by the study.

Peterson et al. (1998) give a complete overview of the different methods. Szalai (1997) and Szalai et al. (1999) summarize the different methods used in Europe. Recently, Aguilar et al. (2003) have provided specific information about metadata and homogenisation methods, with an overview of the different approaches used for detection of inhomogeneity and temperature and precipitation time series homogenisation (Wijngaard et al., 2003).

If homogenisation results are good, even though a single datum may still be incorrect, the new homogenised series describes the data temporal variation better than the original series.

The aim of this study is to homogenise temperature time series of the Tuscany region (Italy) and to analyse their past and present climatic trends and variability.

Such analysis has been performed through the study of numerous climatic and agroclimatic indices. Subsequently, considerations about the impacts of climatic trends and variability on growth and reproduction of grapevine and olive trees have been made.

MATERIALS AND METHODS

Twenty-two weather stations (Tab.1) were selected, with maximum and minimum daily temperatures. Stations were selected for their long time duration,

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N.	Station	Distr	Altitude (m asl)	X-UTM	Y-UTM	Organization
1	Arezzo	AR	249	730805	4815384	Uff. Idrografico di Pisa
2	Boscolugo	PT	1340	633977	4888891	Uff. Idrografico di Pisa
3	Camaldoli	AR	1110	727025	4853030	Uff. Idrografico di Pisa
4	Castel del Piano	GR	596	706920	4752060	Uff. Idrografico di Pisa
5	Castelnuovo Garfagnana	LU	280	613275	4885305	Uff. Idrografico di Pisa
6	Elba Calamita	LI	380	614306	4731893	Aereonautica Militare
7	Firenzuola	FI	454	689640	4888022	Uff. Idrografico di Bologna
8	Grosseto	GR	5	669415	4735216	Aereonautica Militare
9	Livorno	LI	9	606140	4822595	Uff. Idrografico di Pisa
10	Lucca	LU	25	620990	4855580	Uff. Idrografico di Pisa
11	Massa	MS	38	591800	4875450	Uff. Idrografico di Pisa
12	Massa Marittima	GR	362	653850	4768500	Uff. Idrografico di Pisa
13	Montepulciano	SI	575	726520	4774950	Uff. Idrografico di Pisa
14	Orbetello	GR	1	681025	4699970	Uff. Idrografico di Pisa
15	Peretola	FI	38	676985	4852101	Uff. Idrografico di Pisa
16	Pisa	PI	3	613017	4838671	Uff. Idrografico di Pisa
17	Pistoia	PT	88	653080	4867535	Uff. Idrografico di Pisa
18	Pontremoli	MS	247	570117	4913436	ex-UCEA
19	San Miniato	PI	132	647740	4838630	Uff. Idrografico di Pisa
20	Siena	SI	346	687630	4799185	Uff. Idrografico di Pisa
21	Vallombrosa	FI	972	706000	4845450	Uff. Idrografico di Pisa
22	Volterra	PI	465	649965	4808235	Uff. Idrografico di Pisa

Tab. 1 - Weather stations used for the study.
Tab. 1 - Stazioni meteorologiche utilizzate per lo studio.

low percentage of missing data and were spread over the Tuscany region. To ensure a well populated dataset of stations, the period studied was 1955-2002, since few stations have data (or available data) before and after those years.
Time series were provided by Biometeorology Institute (IBIMET – CNR) and belong to several organizations: Ufficio Idrografico - Pisa, Aereonautica Militare, ex-UCEA, Ufficio Idrografico - Bologna.
For the homogenisation procedure, many further stations were used. Although they have shorter time duration, they are useful for sub-periods homogenisation. The total dataset consists of 38 stations.

Quality data checking
Above all, data quality control is necessary, in order to identify anomalous, missing, or inverted values and outliers.
The following thresholds of absolute values and continuous observations were choosen:

– Tmax >= 42 °C
– Tmin < - 15° C
– Range >= 25 °C
– Tmin or Tmax = for 5 or + days
– Tmin and Tmax = for 3 or + days
– Tmin>Tmax

TIME SERIES HOMOGENISATION
For the homogenisation procedure we have used the method developed by the study group of researchers of the Institute of General Applied Physics, of the Institute of Atmospheric Sciences and Climate, of the Brera Astronomical Observatory and of the Unit for Research for Climatology and Meteorology Applied to Agriculture (ex UCEA).
In particular, we followed the procedure described in Brunetti et al. (2006) in which the analysis and corrections were applied using a revised version of the HOCLIS procedure (Auer et al., 1999).
Time series are homogenised to monthly and daily resolution according to the Craddock test for the detection of inhomogeneity and statistical methods used for their correction. The method consists in testing each series against other series by the application of the Craddock test. The candidate time series is compared with a group of 10 neighbouring stations that have good correlation. The Craddock test (Craddock, 1979) is based on the hypothesis of the constancy of temperature differences. The test accumulates the normalized between the candidate series and the reference series according to the fomula: $s_i = s_{i-1} + a * (b_m/a_m) - b_i$ where a is the reference series, b the candidate series, and a_m and b_m the averages of the whole period of the two series. The result of the Craddock

test is a bundle of lines representing the accumulated differences dependant on time; each line is the comparison between the candidate series and one of the reference series of the group. In the ideal case of a homogeneous candidate series, the result should be an horizontal line. However, differences between climatic trends of the two series lead to a "climatic noise" that cause slight deviations from the theoretical horizontal line. If, instead, the line move a lot away from the "zero value", and a clear variation in the slope of the curve is shown, it is very probable that in that point there is an inhomogeneity. For this reason, breaks detection is made by probability. Breaks detection is performed by probability. When available, metadata support decisions about breaks location.
When inhomogeneity is detected, it is corrected using some of the neighbouring stations that are homogeneous on a sub-period centered in the break.
The use of more than one station for the calculation of correcting coefficients guarantees better steadiness in the values and avoids any single errors not detected leading to a faulty correction.
Correcting coefficients are calculated on a monthly basis, and then interpolated with a trigonometric function to reduce the noise and extract only the physic signal.
The final set of correcting coefficients is calculated by averaging all the annual cycles, excluding those stations with correcting factors having incoherent behaviour in respect of the others.
For daily series, the correcting factors are calculated on a monthly basis and then distributed across all the days with a trigonometric fitting.
Any missing data inside the series are subsequently reconstructed, to avoid the risk of correction using wrong values. Missing data are reconstructed by comparing the same days of another station for at least five years centred on the missing days, using simple linear regression.
From the reconstructed daily series, monthly series were recalculated, because monthly series from daily data are more accurate than those from monthly data.

CLIMATIC AND AGROCLIMATIC INDICES

From homogenised daily maximum and minimum temperatures, 18 climatic and agroclimatic indices have been calculated, over different time periods related to the growth and reproduction of grapevine and olive trees *(Tab. 2)*.
Linear regression between time (independent variable) and each of the indices (dependent variable) shows annual rate of variation and its significance at three thresholds: $p<=0.05$, 0.01, 0.001.
The Growing Degree Days (GDD) index was further investigated to improve understanding of interannual variability. Five-years moving averages and moving standard deviations were calculated.

Abbreviation	*Description*	*Unit*
DGS 10 °C	Duration of Growing Season with 10 °C threshold	Number of days
DGS 0 °C	Duration of Growing Season with 0 °C threshold	Number of days
GDD	Growing Degree Days	°C
IH	Huglin Index (GRAPEVINE)	degrees
MTmin	Mean of the minimum temperatures	°C
MTmax	Mean of the maximum temperatures	°C
MTm	Mean of the mean temperatures	°C
MRan	Mean of the temperature range	°C
Sprout	Day of grapevine sprout (GRAPEVINE)	day of the year
Flowering	Day of grapevine flowering (GRAPEVINE)	day of the year
Maturation	Day of grapevine maturation (GRAPEVINE)	day of the year
FF	Frosts frequency	number of days
FP	Day of the last spring frost	day of the year
TminGP	Minimum temperature of the last spring frost	°C
GA	Day of the first autumn frost	day of the year
TminGA	Minimum temperature of the first autumn frost	°C
Tmin<-7	Days with minimum temperature below – 7 °C (OLIVE)	number of days
Chilling	Day for completino chilling (OLIVE)	day of the year

Tab. 2 - Climatic and agroclimatic indices used for climatic analysis, indicating those which are specific for grapevine or olive trees.
Tab. 2 - Indici climatici ed agroclimatici utilizzati per l'analisi climatica, con indicato in parentesi se sono specifici per una coltura.

The greater the standard deviation, the greater the amount of interannual variability.

RESULTS

Homogenisation

Many breaks and inhomogeneities were detected by time series homogenisation. Because of missing metadata, only the more evident and substantial breaks were homogenised.
During the homogenisation procedure, many cases have been found, related to the number and distribution of breaks in the time series, to the way of viewing the Craddock curves at different resolutions and to the correcting coefficients trend.

1) Homogenisation of a single period different from the rest of the time series.
Time series homogenisation concerned only a single period deviating from the rest of the time series. For Boscolungo station *(Fig. 1 and 2)* the 1960s have shown much higher minimum and maximum temperatures than the rest of the series. Change of instrumentation, station reallocation or the influence of an unknown factor surrounding the station are possible reasons for this break. Unfortunately, without metadata we can make only suppositions here. The use of original time series would lead to errors in the evaluation of climatic trends because the 1960s values would falsify the whole series. This is why the time series has been homogenised, providing more plausible values.

2) A single break heavily affects the entire time series.
In some cases, a single break heavily affects the entire time series, such as for maximum temperatures of Pontremoli station *(Fig. 3)*.

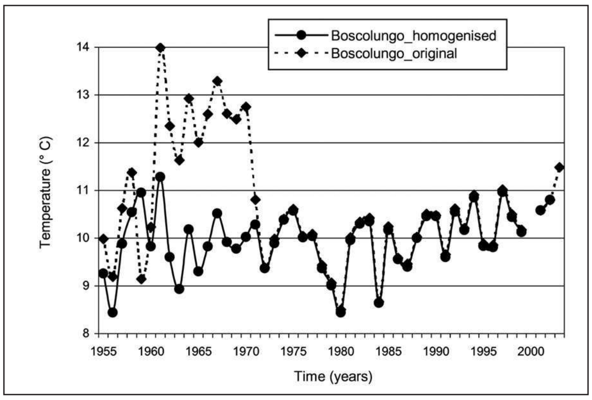

Fig. 1 - Maximum temperatures of Boscolungo station before (dotted line) and after (continuous line) homogenisation.
Fig. 1 - Andamento delle temperature massime per la stazione di Boscolungo, prima (linea punteggiata) e dopo l'omogeneizzazione (linea continua).

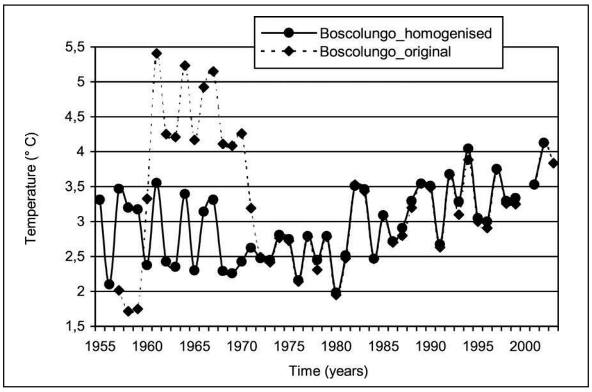

Fig. 2 - Minimum temperatures of Boscolungo station before (dotted line) and after (continuous line) homogenisation.
Fig. 2 - Andamento delle temperature minime per la stazione di Boscolungo, prima (linea punteggiata) e dopo l'omogeneizzazione (linea continua).

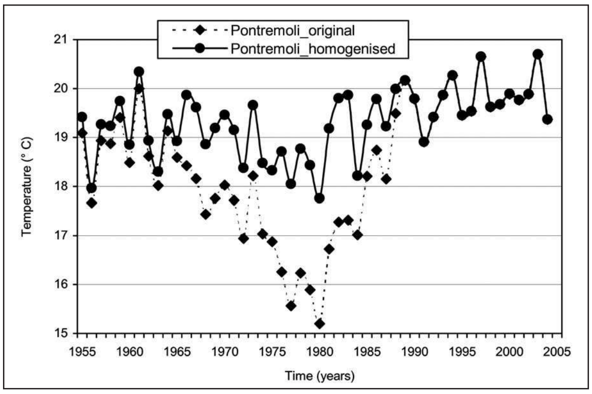

Fig. 3 - Maximum temperatures of Pontremoli station before (dotted line) and after (continuous line) homogenisation.
Fig. 3 - Andamento delle temperature massime per la stazione di Pontremol, prima (linea punteggiata) e dopo l'omogeneizzazione (linea continua).

The lack of metadata does not enable to know the reasons of the particular behaviour of this time series; we can only make suppositions as change in instruments calibration, disturbance around the station, change in detectors of data, and so on. Without homogenisation, climatic analysis of Pontremoli time series would lead to large errors of evaluation. Homogenisation procedure allows correction of the time series, eliminating the break.

3) Time series with many inhomogeneities and some of which are apparent in one season only.
Some time series have many inhomogeneities which makes homogenisation procedures long and delicate. For each break detected, the best correlated dataset of stations is chosen. Breaks and their related periods are homogenised one by one. After each homogenisation, the Craddock test is performed to evaluate homogenisation results and

to see if the other breaks are still present. If this is found to be the case, the second break is homogenised, and so on.
See the example of San Miniato station for maximum temperatures *(Fig. 4, 5, and 6)*. The time series has six evident breaks. Six homogenisation procedures were necessary to correct this series. For break detection, division of the series into two seasons (winter: October-March; summer: April-September) was very useful. In this manner it is easier to place the change of the slope of the Craddock curve at the right month. In the example, the break in 1967 is evident only in the winter trend, while it is less visible in the summer trend. The winter trend is therefore used to determine the placement of the break. In the following plots (Fig. 4, 5, 6, 7, 8) each coloured curve is the comparison of the candidate series with a reference series: ten curves for ten reference series. Craddock curves represent the accumulated differences dependant on time (See paragraph "Time series homogenisation" for explanation).

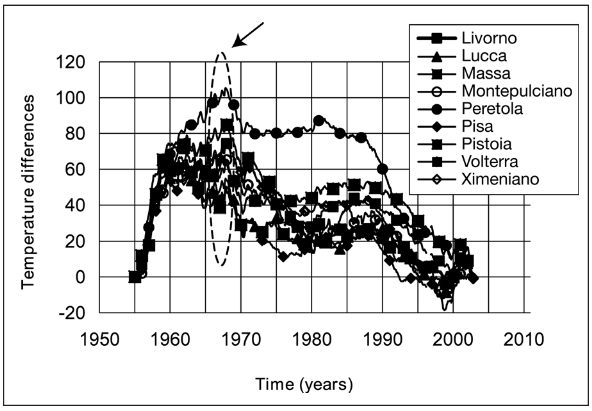

Fig. 4 - Craddock test for maximum temperatures of San Miniato station. Annual trend. The break in the 1967 is marked and clearly visible.
Fig. 4 - Test di Craddock per le temperature massime di San Miniato. Andamento annuale. Il break dell'anno 1967 è evidenziato e chiaramente visibile.

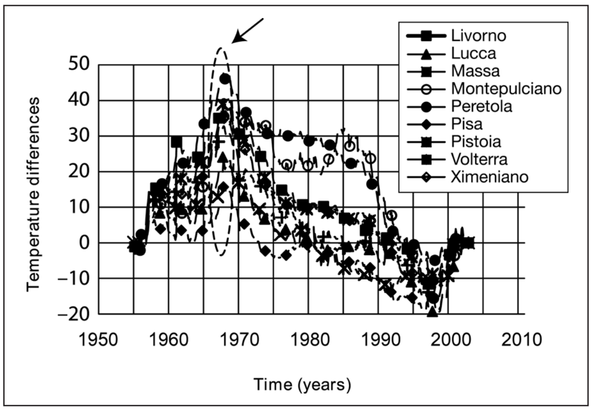

Fig. 5 - Craddock test for maximum temperatures of San Miniato station. Winter trend. The break in the 1967 is marked and clearly visible.
Fig. 5 - Test di Craddock per le temperature massime di San Miniato. Andamento invernale. Il break dell'anno 1967 è evidenziato e chiaramente visibile.

4) Analysis of sub-periods
Viewing Craddock curves graphs over the entire period of study (1955-2002) may lead to missing some breaks which occur over short periods. Therefore, after analysing graphs related to the entire period, this must be done for sub-periods which can be standard or arbitrary according to the course of the curves. See minimum temperatures of Grosseto station as an example *(Fig. 7 and 8)*.
This time series shows a break in the 1995 that cannot be evaluated from the 1955-2002 graph. The course of the curves is better observed when a shorter period is used.

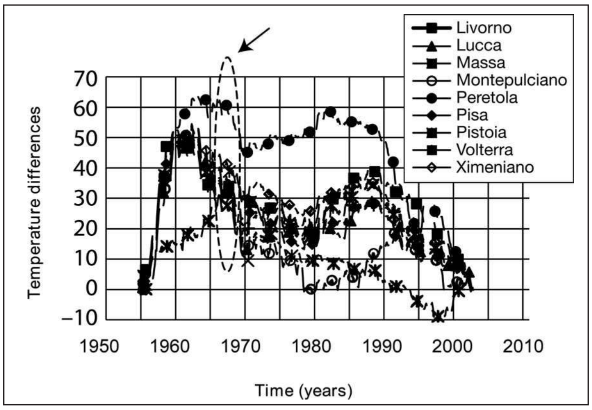

Fig. 6 - Craddock test for maximum temperatures of San Miniato station. Summer trend. The break in the 1967 is marked but not clearly visible.
Fig. 6 - Test di Craddock per le temperature massime di San Miniato. Andamento estivo. Il break dell'anno 1967 è evidenziato ma non chiaramente visibile.

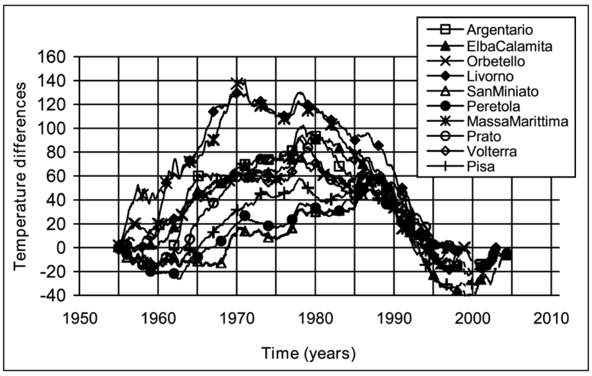

Fig. 7 - Craddock test for minimum temperatures of Grosseto station. Annual trend.
Fig. 7 - Test di Craddock per le temperature minime della stazione di Grosseto. Andamento annuale.

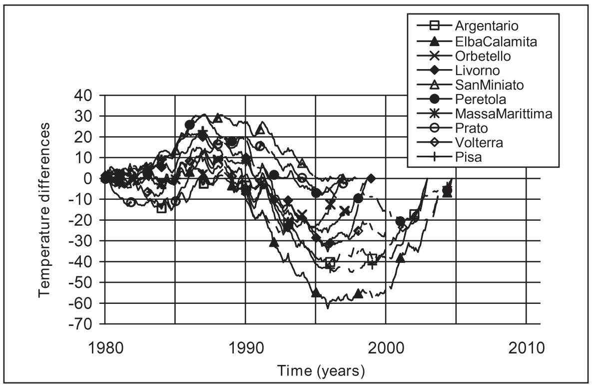

Fig. 8 - Craddock test for minimum temperatures of Grosseto station. Annual trend, sub-period 1980-2002.
Fig. 8 - Test di Craddock per le temperature minime della stazione di Grosseto. Andamento annuale, sottoperiodo 1980-2002.

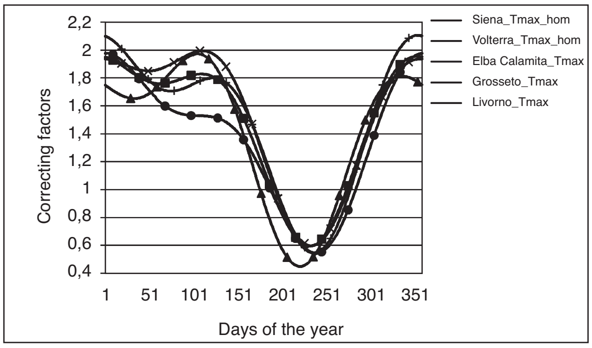

Fig. 9 - Correcting factors for minimum temperatures of Massa Marittima station. Each time series represents the correcting factors calculated from a reference series.
Fig. 9 - Coefficienti di correzione per le temperature massime della stazione di Massa Marittima. Ogni serie rappresenta i coefficienti di correzione calcolati a partire da una serie storica di riferimento.

Considering only the 1980-2002 period the break is evident and therefore easily identificable.
Once the breaks are detected, the next step is data homogenisation. The procedure is to correct inhomogeneities using neighbouring stations that are homogeneous in a sub-period centred in the break and well correlated with the candidate series. The use of several stations for the calculation of correcting factors guarantees a better stability of values and avoids outliers in the reference series leading to a wrong correction.
Monthly correcting factors are mediated on the years used for the correction and plotted.
In the better cases, the stations have the same trend, the curves of correcting factors are close to each other, as for Massa Marittima station *(Fig. 9)*.

Usually, however, the situation is more complicated, as in the case of a single station that behaves differently from the others. The curve for the Siena station *(Fig. 10)*, despite having the same trend as the other curves, is shifted by about one month, and therefore it is eliminated from the correcting factors calculation.
In the worst cases, the resulting plot is a crossing of curves that show no common behaviour, and to reduce the plot to only one or two stations is not advisable. In these cases the station chosen or the break detected must be reviewed. Probably there is an evaluation error to be corrected *(Fig. 11)*.
Once the stations are chosen, correcting factors are smoothed over time, as shown in the Fig. 12 corresponding to the Fig. 9. Smoothing advantages are described in Auer et al. (2005).
To understand how a Craddock test graph appears before and after the homogenisation, Firenzuola station is shown as an example *(Fig. 13 and 14)*.

Climatic analysis

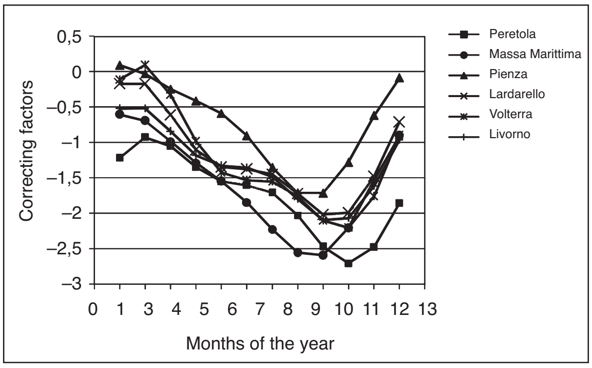

Fig. 10 - Correcting factors for minimum temperatures of Siena station. Each time series represents the correcting factors calculated from a reference series.
Fig.10 - Coefficienti di correzione per le temperature minime della stazione di Siena. Ogni serie rappresenta i coefficienti di correzione calcolati a partire da una serie storica di riferimento.

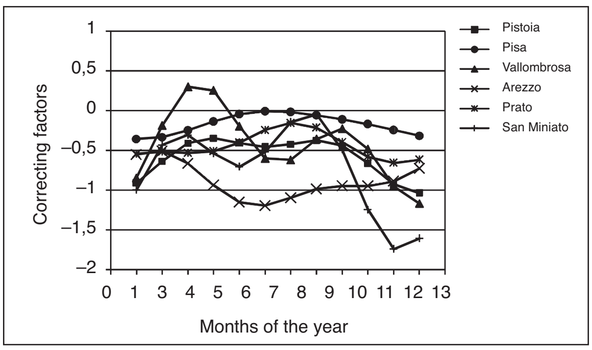

Fig. 11 - Correcting factors for minimum temperatures of Peretola station. Each time series represents the correcting factors calculated from a reference series.
Fig.11 - Coefficienti di correzione per le temperature minime della stazione di Peretola. Ogni serie rappresenta i coefficienti di correzione calcolati a partire da una serie storica di riferimento.

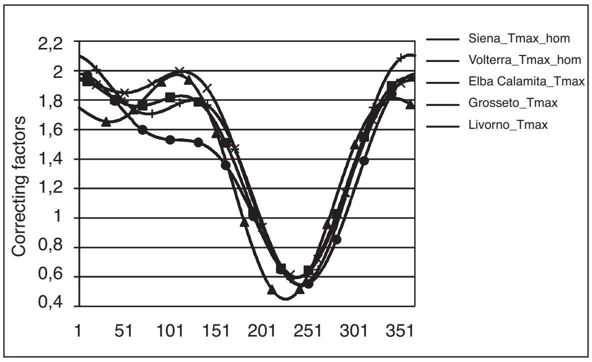

Fig. 12 - Smoothing of correcting factors for maximum temperatures of Massa Marittima station. Each time series represents the correcting factors calculated from a reference series.

Fig.12 - Smoothing dei coefficienti di correzione per le temperature massime della stazione di Massa Marittima. Ogni serie rappresenta i coefficienti di correzione calcolati a partire da una serie storica di riferimento.

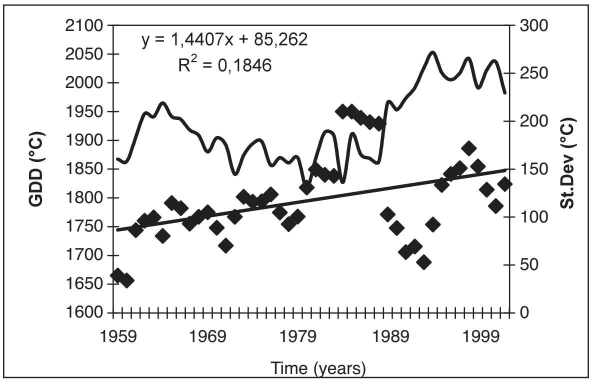

Fig. 15 - Moving averages (continuous line) and relative standard deviations (dots) for GDD Index for Montepulciano station. The 1955-1959 average is indicated at the year 1959. Standard deviation has a significant increase with $p<0.01$.

Fig. 15 - Medie mobili (linea continua) e relative deviazioni standard (punti) dell'indice STA per la stazione di Montepulciano. La media 1955-1959 è indicata con l'anno 1959. La deviazione standard presenta un aumento significativo con $p<0.01$.

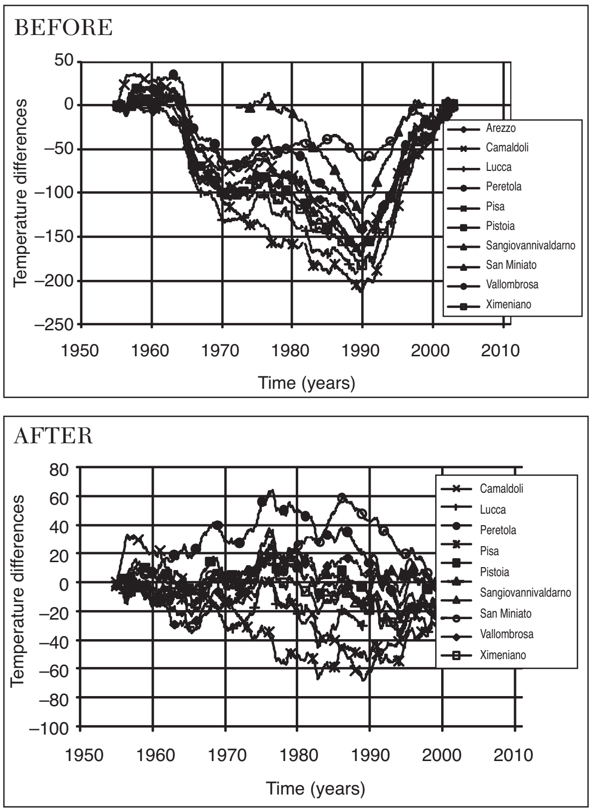

Fig. 13 and 14 - Craddock curves for Firenzuola station before and after homogenisation. Before homogenisation there are evident breaks, while after homogenisation only "noise" due to climatic trend remains.

Figure 13 e 14 – Curve di Craddock per la stazione di Firenzuola prima e dopo l'omogeneizzazione. Si nota come prima dell'omogeneizzazione sono presenti evidenti breaks, mentre dopo l'omogeneizzazione rimane solo "rumore" dovuto all'andamento climatico.

As pointed out before, inhomogeneity of data greatly affect the identification of trends in climatic data and agroclimatic indices. For this reason, the climatic analysis has been performed after the times series homogenisation. Analysis of the trend of climatic and agroclimatic indices has revealed several significant variations that may heavily affect the growth of grapevine and olive trees. For the sake of brevity, only a few indices are reported here, showing the results achievable after a proper homogenisation of climatic data.

In general, temperatures, both maximum and minimum, increase during the summer (July-August-September). Such an increase is due especially to the month of August which has high significant values all over the region. Minimum temperatures show a larger increase than maximum ones, with many stations having a significant level of 0.001. An example (Massa station) is shown in Fig. 16. The increase in temperatures is evident also for the GDD index which increases significantly for almost all the stations of the region, especially those at high altitudes. Significant levels are high ($p<0.001$, $p<0.01$), so that there are no stations with $p<0.05$. The GDD index also shows an increase in interannual variability in almost all the stations with high significant levels, respectively ($p<0.001$) for Arezzo, Firenzuola and Vallombrosa, ($p<0.01$) for Camaldoli and Montepulciano (*Fig. 15*), and ($p<0.05$) for Castel del Piano, Castelnuovo Garfagnana and Pisa. The only exceptions to the general trend are Massa ($p<0.05$), Livorno ($p<0.01$), Pisa, Pistoia and San Miniato ($p<0.05$) which have a decreasing standard deviation.

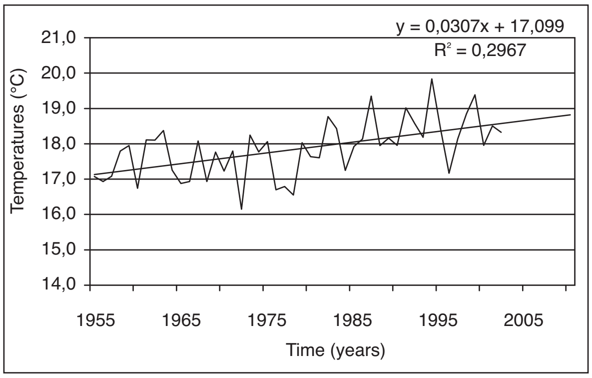

Fig. 16 - Minimum temperatures trend in the period July-August-September for Massa station ($p<0.001$).
Fig. 16 - Andamento delle temperature minime nel periodo nel luglio-agosto-settembre nella stazione di Massa ($p<0.001$).

CONCLUSIONS

Craddock test application and subsequent homogenisation of time series have shown the presence of many inhomogeneities and breaks within time series. They would certainly have led to incorrect evaluations of climatic trends. Because of the lack of metadata, only the more evident breaks have been homogenized, i.e. those in which a change or a shift in the data trend was evident.
On the whole, homogenisation procedure has resulted in time series with a better quality of data. Even though some single values may still be incorrect, the new homogenised series describe temporal variation of data better than the original ones. These data can therefore be used more safely in climatic analysis. Therefore, it is always necessary to homogenise time series before performing trend analysis.

Time series graphs performed with a specific software kindly supplied by Dott. Brunetti

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Scie Chimiche

Luigi Mariani[1]

Da anni si va diffondendo la leggenda secondo cui le nubi che vediamo ogni giorno in cielo, e cioè gli altocumuli, i cirri, i cumuli e gli strati che rendono così bella la volta celeste del nostro pianeta, sarebbero in realtà degli artefatti creati ad hoc da un'organizzazione segreta attiva a livello globale e che utilizzerebbe tali strutture per alterare il clima, generare malattie o condizionare la psiche dei nostri concittadini. Molti lettori l'avranno capito: sto parlando delle cosiddette scie chimiche.
Da tale argomento mi sono per molto tempo tenuto alla larga in virtù dell'innato scetticismo che caratterizza il mio approccio alle teorie catastrofiche.
Tuttavia negli ultimi mesi, sollecitato da un amico che per un caso di forza maggiore mi chiedeva un parere motivato sull'argomento, ho avuto la ventura di leggere con attenzione il libro "Scie misteriose: la verità nascosta. Le prove" di Antonio e Rosario Marcianò (Draco Edizioni, pagg. 134 - € 18,00) ed ho così raggiunto il convincimento che si tratti di una colossale raccolta di sciocchezze, che nel caso specifico sono per di più espresse con scarso rispetto per la sintassi.

Possibile che gli aerei misteriosi di cui parla il libro diffondano degli Pseudomonas (batteri che in natura sono da sempre presenti in tutti i comparti ambientali, compresa l'atmosfera) oppure i sali di litio (vicissitudini familiari mi hanno dato modo di apprezzare l'efficacia dei sali di litio per la cura di sindromi depressive; mi sa tanto che chi oggi scrive di "scie chimiche" abbia avuto in passato problemi di quel tipo) o che le antenne per cellulari siano le prove di un complotto globale? O che gli aerei diffondano micoplasmi responsabili di Alzheimer o di altre terribili malattie?

Confesso che per andare un poco oltre le fantasiose tesi del libro mi sono anche provato ad "intervistare" un anziano ingegnere che si mostrava possibilista rispetto alla storia delle "scie chimiche", chiedendogli apertamente quali prove potesse addurre. La risposta è stata:

1. scie in zone dove non ci sono aerei (mia risposta: in quota ci sono venti violenti che trasportano le scie anche lontano dalle zone di emissione);
2. il fatto che gli americani sono cattivi, per cui fanno esperimenti segreti assai inumani (mia risposta: degli Stati Uniti non mi fido fino in fondo; tuttavia so che si tratta di una grande nazione democratica e dunque molto meno inumana nei suoi comportamenti rispetto ai tanti regimi autoritari di destra o di sinistra o di matrice integralista islamica che hanno terrorizzato il mondo nel 20° secolo e che in vari casi continuano nelle loro azioni).

Insomma: le argomentazioni addotte mi paiono davvero debolissime e portano a concludere che ci troviamo di fronte all'assenza di prove scientifiche sull'argomento delle "scie chimiche". Ciò mi porta a ritenere che qualcuno per motivi che non sto qui ad indagare stia conducendo un'operazione di falsità, in cui mezze verità e palesi menzogne vengono associate allo scopo di avvalorare tesi fantasiose.
Fra l'altro leggendo il libro mi sono venute in mente due similitudini che possono forse rivelarsi utili per interpretare in chiave antropologica la storia delle "scie chimiche":

1. quella con la vicenda degli UFO, che dalla fine della seconda guerra mondiale popolano le allucinazioni di migliaia di nostri concittadini;
2. quella con uno stravagante personaggio della Milano degli anni 70-80 che girava con un carrettino scrivendo sui marciapiedi lunghissime frasi che recitavano cose di questo tipo: "Popolo bue, il clero ti uccide con l'onda. Nella Città del Vaticano ci sono enormi antenne che diffondono onde che fanno impazzire.....".

Abbiamo la fortuna di vivere nel mondo sviluppato, in cui la qualità della vita è incommensurabilmente migliore rispetto a quella del passato: ce lo dicono le statistiche sulla vita media della nostra popolazione, cresciuta enormemente negli ultimi 50 anni e ce lo confermano i ricordi d'infanzia che ci rimandano i visi di persone che allora avevano 60 anni e che apparivano vecchie come le persone di 80-90 anni oggi, vuoi per la cattiva alimentazione (il buon cibo

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di una volta) vuoi per cure mediche assai approssimative. Possibile che si trascuri tutto ciò e ci si inventino cose come le "scie chimiche", il "cibo avvelenato" il "clima impazzito" o le "pandemie sempre dietro l'angolo" per creare atmosfere di paura che non aiutano a vivere con serenità il nostro tempo, rendendoci per di più incapaci di affrontare le emergenze vere (fame, povertà, sfruttamento, violenza, ecc.)?

Se qualcuno dice di vedere gli asini volare è difficilissimo dimostrargli con metodo scientifico che non è vero. Si potrebbe infatti prendere un certo numero di asini, portarli su una torre e di lì lanciarli nel vuoto condannandoli a morte certa. Tuttavia, non appena gli asini piomberanno a terra morti, colui che vede gli asini volare concluderà immancabilmente con un ottuso "i tuoi asini non volano, i miei si". Di esperienze simili ne ho accumulate un certo numero, ad esempio cercando di dialogare con gli agricoltori che sparano con i cannoni alle nuvole pensando di sbriciolare la grandine prima che giunga a terra (metodo senza alcun fondamento scientifico e che tuttavia in varie zone del nostro Paese è applicato da oltre un secolo). Sono inoltre conscio che lottare contro le credenze diffuse dai mezzi di comunicazione di massa sia particolarmente arduo e scarsamente appagante per chi se ne assume l'onere. Tuttavia penso che nel caso specifico non ci si debba arrendere: il cielo del nostro pianeta e le sue nubi sono fra le cose più belle e commoventi che esistono, un vero e proprio inno alla creazione, per cui sarebbe un grave peccato permettere che tutto ciò venisse "sporcato" e reso ostile agli esseri umani da teorie balzane, frutto di persone cattive o malate.

Il sistema internazionale di classificazione delle nubi (quello che cioè consente di dar loro un nome e di parlare ad esempio di *Cumulonimbus capillatus* o *Altocumulus lenticularis*) è del 1803 e fu creato dal britannico Luke Howard. Da allora migliaia di meteorologi scrutano il cielo con continuità, rilevando entità della copertura nuvolosa e tipologia dei corpi nuvolosi; anch'io nel mio piccolo faccio questo, per passione e tradizione. Svolgendo tale attività siamo tutti aiutati dall'Atlante Internazionale delle Nubi dell'Organizzazione Meteorologica Mondiale, la cui prima edizione risale alla fine dell'800. Avendo sott'occhio le foto dei diversi generi e specie di nubi proposte nelle diverse edizioni dell'Atlante, si può cogliere con immediatezza che le nubi di fine '800 sono del tutto analoghe alle nubi dell'ultima edizione. Le stesse scie di aereo (*condensation trails* ovvero *contrails*) compaiono in foto di diverse edizioni. In questo momento ad esempio ho sott'occhio una foto con almeno 14 scie d'aereo riprese nel 1944 (epoca in cui suppongo che gli aerei misteriosi che diffondono le scie chimiche non fossero ancora all'opera) in uno spicchio di cielo a Farnborough - Hampshire – U.K. (WMO, International Cloud Atlas, edizione 1987, volume 2, pag. 167). E qui come non cogliere la palese falsità della frase riportata a pag. 85 del libro sulle scie chimiche: "contrails che sono – lo ribadiamo – un fenomeno rarissimo". Scordiamoci dunque le scie chimiche e cerchiamo invece di vivere con serenità il nostro tempo, magari mettendo in pratica la vecchia ma sempre attuale massima "Il faut cultiver notre jardin" che chiude il Candido di Voltaire.

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