# IMPACT OF CLIMATE CHANGE ON THE PHENOLOGY OF TYPICAL MEDITERRANEAN CROPS

## L'IMPATTO DEL CAMBIAMENTO CLIMATICO SULLA FENOLOGIA DI COLTURE MEDITERRANEE

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## Abstract

Increases in temperature, as already observed and simulated by General and Regional Circulation Model (RCMs and GCMs) in the Mediterranean basin, are expected to have a great impact on agriculture. Since crop phenology is one of the most important plant process in determining final yield and allowing adaptation of crops to climate change, the effect of warming climate on crop phenology, has been indicated as a key-point for assessing the impact of climate change on agricultural crops. Accondingly, in this work we reviewed the effect of increasing temperature, as simulated by RCMs and GCMs in the Mediterranean basin, on the phenology of typical Mediterranean crops (e.g. durum wheat, sunflower, grapevine, olive tree). The results indicated an earlier development of crops and a reduction of the length of growing season. These responses may allow some crops to escape summer drought stress (e.g. winter crops), but at the same time they may determine an increase in the frequency of extreme climate events (e.g. frost and heat waves) at sensitive pehnological stages (e.g. budbreak and anthesis) that will affect final yield quantity and quality. Moreover, changes in crop phenology and its interaction with the changing environments was highlighted as a basis for formulating reliable adaptation policies.

**Keywords:** events, anthesis, global warming, agriculture, adaptation

## *Riassunto*

*L'aumento di temperatura nel bacino del Mediterraneo, così come già osservato e simulato dai modelli di circolazione Generale e Regionale (GCM e RCM), avrà notevoli ripercussioni sull'agricoltura. Poiché la fenologia è uno dei fattori principali da cui dipende la qualità e quantità della resa finale di una coltura, l'effetto del riscaldamento climatico sullo sviluppo colturale è stato indicato come un passaggio-chiave per la valutazione degli impatti del cambiamento climatico in agricoltura. Su queste basi, lo scopo del presente lavoro è di valutare gli impatti dei cambiamenti climatici sulla fenologia di colture tipicamente mediterranee come frumento, girasole, vite ed olivo. I risultati di questa analisi evidenziano come l'incremento di temperatura acceleri lo sviluppo delle colture, determinando una complessiva riduzione del periodo di crescita. Questa tendenza permetterà ad alcune colture di evitare lo stress idrico estivo (es. colture invernali); mentre  per altre colture (es. colture estive) l'aumento della frequenza di eventi estremi come gelate al germogliamento ed ondate di calore durante la fase di fioritura aumenterà potrs' incidere fortemente sulla qualità e quantità della resa finale. Inoltre, le interazioni fra fenologia e variazioni ambientali giocheranno un ruolo fondamentale per la determinazione delle strategie di adattamento piu' adeguate ai cambiamenti climatici.*

*Parole chiave:* *eventi estremi, fioritura, riscaldamento globale, agricoltura, adattamento*

## Introduction

It is definitively accepted that our climate is changing due to increased 'greenhouse gases' atmospheric concentrations and this change is expected to have important impact on different economic sectors (e.g. agriculture, forestry, energy consumptions, tourism, etc.) (Hanson *et al.*, 2006). In particular, for agriculture, such a change in climate may have significant impacts on crop growth and yield, since these are largely determined by the weather conditions during the growing season.

According to these premises, the assessment of cropping systems response to a warmer climate plays an important role for the evaluation of near future economic assets and the study of crop phenology response was indicated as a key stage for a better formulation of adaptation policies and options (Duchene and Schneider, 2005; Wolfe *et al.*, 2005; Sadras and Monzon, 2006). Phenology is in fact the most important attribute involved in the final yield assessment and consequently in the adaptation of crops to the changing environment. Both the timing of phenological stages and the relative duration of the pre and post-flowering phases (vegetative and reproductive phases, respectively) are in fact critical determinant of yield (Sadras and Connor, 1991). The activity that is most demanding for a crop (i.e. reproductive phase) should take place at the time of optimal conditions (i.e. temperature and rainfall) (Visser and Both, 2005), whereas its duration should be as long as possible for optimal biomass partitioning to the fruit (Bindi *et al.*,

**Tab. 1** - Summary of the papers included in this review. For each reference the type of climatic dataset used, the crop growth model, the crop type and the period analysed are shown. Legend: GCM = General Circulation Model; RCM = Regional Ciriculation Model; ED = Empyrical Downscaling; OBS = observed data.

*Tab. 1 - Elenco dei lavori analizzati. Per ciascun riferimento sono stati evidenziati il tipo di dato utilizzato, il tipo di modello di sviluppo e crescita, la coltura e la finestra temporale analizzata. Legenda: GCM = General Circulation Model; RCM = Regional Ciriculation Model; ED = Downscaling Empirico; OBS = dati osservati.*

| Reference | Climate Data | Model | Crop | Present Period | Future Period |
|---|---|---|---|---|---|
| Moriondo (2003) | ED* | Moriondo *et al.* (2001) | Olive tree | 1974-1989 | 2084-2099 |
| Osborne *et al.*, 2000 | ED** | Osborne *et al.*, (2000) | Olive tree | 1960-1990 | 1991-2100 |
| Bindi and Moriondo (2005) | GCM[1] | Cropsyst | Maize, Bean, Lentil, Sunflower, Tubers, Barley, Wheat | 1960-1990 | 2031-2060 |
| Moriondo and Bindi (2005) | ED*** | Bindi *et al.* (1997) | Grapevine | 1990-2005 | 2006-2100 |
| Moriondo and Bindi (2006) | RCM[2] | Cropsyst | Wheat, Sunflower | 1977-1990 | 2087-2100 |
| Moriondo *et al.* (2007) | RCM[2] | Cropsyst | Wheat, Sunflower | 1960-1990 | 2070-2100 |

[1]HadCM3. This GCM is a coupled atmosphere-ocean general circulation model whose atmospheric component has a spatial resolution of 2.5° latitude by 3.75° longitude. The model run was forced between 1860-1990 including observed changes in greenhouses gases and aerosols. From 1990 to 2100, a number of scenarios of future changes in greenhouse gases and aerosols were used to drive the model run. In A2 scenario, HadCM3 roughly simulated an increase of +2°C and +5°C respectively for the time slices 2030-2060 and 2070-2100 respect to the present (1960-1990) (for the Mediterranean basin).

[2]HadRM3P. This RCM has a spatial resolution of 0.44° latitude by 0.44° and its run are available for 1960-1990 and 2070-2100 time slices. In A2 scenario, the difference between future and present time slices is about +5°C (for the Mediterranean basin).

*Performed using the relationship between observed large-scale atmospheric variables and local climate (see appendix).
**Performed using Delta approach (see appendix)
***Performed via stochastic weather generator (see appendix)

1996). Since crop development rate is highly temperature dependent, a warmer climate is expected to affect both these terms, by advancing phenological stages (shifting crop-growing period into a new climatic window) and by reducing the time for biomass accumulation (Peiris *et al.*, 1996; Harrison and Butterfield, 1996; Bindi and Moriondo, 2005).

Additionally, a changing climate may exhibit increased climatic variability and this can produce relatively large changes in the frequency of extreme climatic events. Accordingly, the increase of extreme events centred at the time of sensitive growth stages are expected to have a great impact on final yield. Warmer and wetter future winters, as prospected in some areas, may cause advanced bud-burst leaving plants vulnerable to spring frosts. On the other hand, increased dry spell may lead to a greater frequency of dry summers requiring irrigation for summer crops. Heat waves at anthesis should be also taken into account due to their effect on yield quality and quantity (Porter and Gawit, 1999).

Accordingly, cultivated plants, as well as natural vegetation, will face environmental conditions never experienced before and the actual magnitude of climate change impact needs to be assessed for specific organism-environment combinations.

On these basis, in this paper the effect of global change on phenology of the major crops cultivated in the Mediterranean basin, was reviewed. The interactions phenology-environment in a changing climate were highlighted in order to explain the possible impact on final yield and to formulate feasible adaptation strategies. In particular, papers dealing with climate change impact on the crop phenology of typical Mediterranean annual

(sunflower, maize, potato and durum wheat) and perennial (grapevine and olive tree) crops were reviewed.

The approach generally used in these papers (Osborne *et al.*, 2000, Moriondo and Bindi, 2006; Moriondo et al, 2007; Moriondo and Bindi, 2005, Bindi and Moriondo, 2005; Moriondo, 2003) lied on the use of crop growth and phenology simulation models coupled to the outputs (Tmin, Tmax, rainfall and radiation) of a GCM. In particular, the phenology and yield of annual crops were simulated using the CropSyst model (Stockle *et al.* 2003); whereas the phenology of grapevine (i.e. budbreak, anthesis, veraison, maturity) and olive (i.e. anthesis stage) was reproduced using the grapevine model developed by Bindi *et al.*, 1997 and growing degree-day accumulation models (Osborne *et al.*, 2000, Moriondo *et al.* 2001), respectively. The GCM data were directly used as model inputs or downscaled at higher resolution dynamically (RCMs) or empirically (ED), for a better climate simulation at local scale (see Appendix 1 for an overview about GCM and main downscaling procedures).

All the results reported in this review were referred to the scenario A2, characterized by a medium-high greenhouse gases emission ($[CO_2]\sim700$ ppm in 2070-2100) (Tab. 1)

## Impact of mean climate change on crop phenology

Even though the effect of climate change on crop phenology was assessed using different climate data, on different crops and at different spatial resolution, the review of these papers highlighted some common trends. GCMs, RCMs and ED climate outputs indicated for the Mediterranean basin a gradual increase of temperature
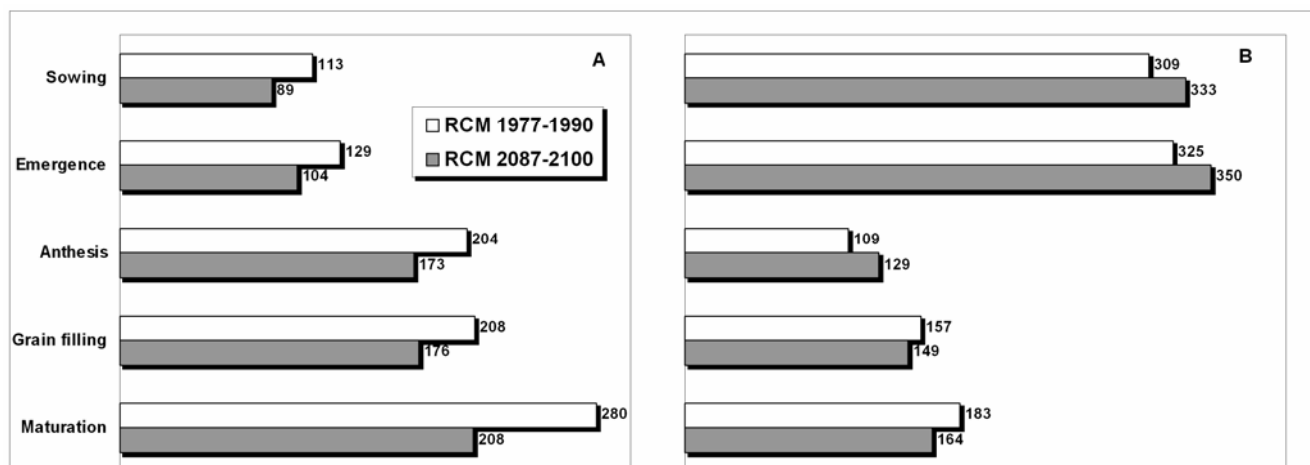
**Fig. 1** - Average day of year of sunflower (subfigure A) and durum wheat (subfigure B) development stages computed using RCM data as phenological models inputs for present (1977-1990) and future climate scenario A2 (2087-2100) (Moriondo and Bindi, 2006).
*Fig. 1 - Data delle fasi fenologiche (giorno dell'anno) di girasole (A) e grano duro (B), calcolate da un modello fenologico sulla base dei dati di un RCM per il presente (1977-1990) e futuro (2087-2100, scenario A2) (Moriondo and Bindi, 2006).*

**Tab. 2 -** Crop growing cycle reduction (number of days) in response to an increase of 2°C (2031-2060) respect to present scenario (1960-1990). Legend: C4 crops = maize; Legumes = bean, lentil; C3 summer crops = sunflower; Tuber crops = potato; Cereals = barley, wheat. (Bindi and Moriondo, 2005).
*Tab. 2 - Riduzione del ciclo vegetativo colturale (n° di giorni) in risposta ad un aumento della temperatura di 2°C (2031-2060) rispetto al periodo presente (1960-1990). Legenda: colture C4=mais; legumi=fagiolo, lenticchia; colture C3 estive= girasole; tuberose=patata; cereali= orzo e frumento. (Bindi and Moriondo, 2005).*

| Country | C4 summer crops | Legumes | C3 summer crops | Tuber crops | Cereals |
|---|---|---|---|---|---|
| Algeria | -12.3 | -8.0 | -9.9 | -7.6 | -3.3 |
| Egypt | -9.5 | -6.0 | -7.5 | -7.4 | -4.2 |
| France | -13.6 | -10.6 | -16.2 | -19.6 | -8.3 |
| Jordan | -8.3 | -4.9 | -6.2 | -4.9 | -10.3 |
| Greece | -4.5 | -2.6 | -3.6 | -1.9 | -7.1 |
| Italy | -4.1 | -2.3 | -5.0 | -5.4 | -10.1 |
| Lybia | -7.9 | -5.0 | -6.5 | -6.7 | -5.7 |
| Morocco | -14.0 | -10.1 | -11.2 | -9.0 | -8.8 |
| Portuga | -12.1 | -8.3 | -10.0 | -9.5 | -8.9 |
| Serbia | -2.9 | -1.7 | -1.6 | -10.2 | -12.2 |
| Spain | -19.4 | -7.1 | -15.7 | -15.4 | -7.3 |
| Tunis | -9.2 | -5.4 | -7.7 | -12.1 | -1.2 |
| Turkey | -18.1 | -11.6 | -18.4 | -17.6 | 8.6 |

and lower rainfall by the end of this century. Moreover, at a finer resolution (RCM), increased average temperatures were coupled to an increase in extreme events frequency and magnitude (heat waves and dry spell) (data not shown).
Accordingly, since plant phenology is largely temperature dependent, there was an overall trend for earlier occurrence of key phenological events, and consequent short-

ening of crop growing cycle for winter and summer annual crops, grapevine and olive tree (Osborne *et al.*, 2000; Bindi and Moriondo, 2005; Moriondo *et al.*, 2007; Moriondo, 2003).
The magnitude of the shortening varies according the dataset used (GCM, RCM, ED), the time-slices included in the analysis, the geographical areas and the crop type (Tab. 2, Figs. 1-4). In one case (durum wheat), sowing time resulted delayed instead of advanced in response to a warmer climate (Fig. 1B). Durum wheat in fact requires cold temperature in early development stages to meet its vernalization[1] requirements and thus it is sown when low temperatures are most effective. As a consequence of higher temperatures, the optimal period for sowing is then shifted respect to present period.
More interestingly, when the effect of higher temperatures on the single phenological phase duration was investigated, an asymmetric impact on the length of vegetative and reproductive phases was evident both in annual and perennial crops, resulting in large fitness consequences. In winter crops, for instances, higher temperatures as simulated for the future scenarios, shortened the pre-flowering phase and this allowed grain filling periods to take place in cooler periods that favorites a longer time period for biomass partitioning to grains (Sadras and Monzon, 2006) (Fig. 5a). Additionally, a shorter vegetative phase allowed the crop to escape the summer drought resulting finally in an increased final yield when compared to the present period (including the $CO_2$ effect, data not shown). In contrast, the grain filling period resulted highly reduced for a typical summer crop (Fig. 5b). The same trend was simulated for grapevine, where higher temperatures, advancing bud-break phase, shifted post bud break development to earlier, relatively cooler conditions that cancelled out the increasing temperature trend. As a consequence, higher temperatures did not de-

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[1] Vernalization is a process required for certain plant species to enter the reproductive stage through an exposure to low, non-freezing temperatures. Thermal time accumulation is limited until vernalization requirements are met.

crease the length of bud break-anthesis phase (in many cases even a longer duration of the period was simulated) whereas the duration of anthesis-maturation phase was largely shortened respect to the present period (in average by 11%, 15% and 20% in the time slices 2007-2037; 2038-2068; 2069-2099 respectively).

This trend, confirmed by phenological observations over a long period reported by Duchêne and Schneider (2004) in Alsace, is of a major importance for grapevine yield that was simulated as progressively decreasing due to the combined effect of a shorter period for berry ripening and increased drought stress in summer (Moriondo and Bindi, 2005) (data not shown).

No specific analysis modelling climate change impact on olive tree yield was found in the literature whereas only statistical models regressing climate variables and final yield were available (Gonzalez-Minero *et al.*, 1998; Moriondo *et al.* 2001, Galan *et al.*, 2008). Even though these empirical models have only a very local applicability, some common trends may be highlighted to identify possible effect of advanced phenological stages on final yield. In particular rainfall amount at the time of anthesis and afterwards were generally indicated as positively correlated to final yield. Accordingly, advanced anthesis (which at the present time takes place around the first decade of June) might be considered a positive factor reducing drought stress that is expected having increasing severity in summer time respect to spring time. On the other hand, fruit ripening phase will be highly exposed to water shortage during summer.

## The role of increasing extreme climate events on sensitive phenological stages and their consequences for crop yield

In addition to the increase in mean temperature, also the change frequency of extreme events should be considered for a reliable climate change impact assessment on agriculture (Challinor *et al.*, 2005). A warmer climate may in fact exhibit an increased climatic variability and this can produce relatively large changes in the frequency of extreme climatic events. These, when occurring during key development stages of the crop may have a dramatic impact on final production even in case of general favourable weather conditions for the rest of the growing season (Porter and Gawit, 1999). Temperatures higher than 31 °C at anthesis stage, inducing a reduced pollen and floret fertility, were demonstrated to be detrimental for both wheat and sunflower yield (Porter and Gawit, 1999, Chimenti and Hall, 2001). For grapevine, heat stresses (Tmax>35°C) during berry ripening are associated to a lower photosynthesis (Kriedman, 1968) and yield through poor fruit set and small berries (Kliever, 1977), inhibition of colour development (Kliewer and Torres, 1972) and partial or total failure of flavour ripening (Mullins et al, 1992). Frost events (Tmin<-2°C) (Narciso *et al.*, 1992) at bud break are related to shoot loss and lower yield (Mullins et al, 1992). Temperature lower than –8°C may be lethal for olive tree whereas severe water stress during fruit ripening may cause severe yield loss.
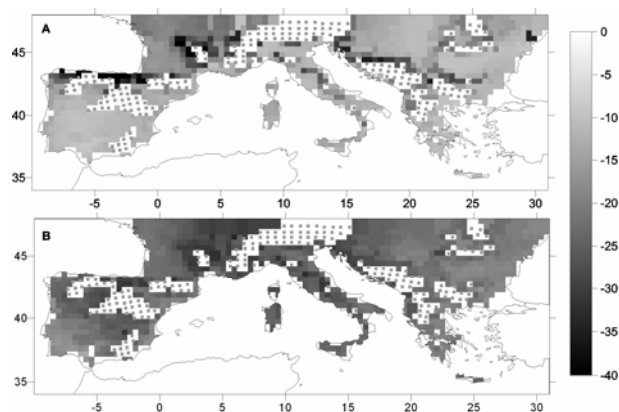


**Fig. 2** –Difference (number of days) in the length of sunflower (subfigure A) and wheat (subfigure B) growth season between future (future scenario A2) and present scenarios (1960-1990) (Moriondo *et al.*, 2007). Areas not suitable for crop cultivation are also indicated (dotted areas).

**Fig. 2** - Riduzione del ciclo vegetativo (n° di giorni) di girasole (A) e frumento (B) nello scenario A2 (2070-2100) rispetto allo scenario presente (1960-1990) (Moriondo *et al.*, 2007). Le aree punteggiate rappresentano zone non adatte alla coltivazione
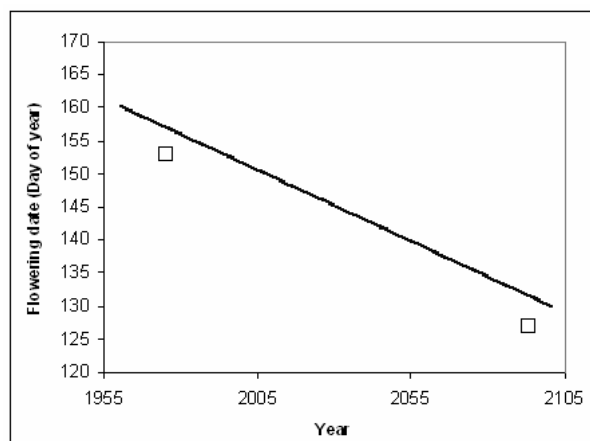


**Fig. 3** –Model simulations of future olive flowering date (day of the year) simulated for present and future periods in the western Mediterranean (Osborne *et al.,* 2000; trend line from 1960 to 2100) and in Florence province (43.77° Lat N, 11.25° Lon E, Italy) (Moriondo *et al.* 2001; open squares representing the average of 1974-1989 and 2084-2099 respectively). In both cases minimum and maximum temperature empirically downscaled were used as input data of the phenological model.

**Fig. 3** - Fioritura dell'olivo (giorno dell'anno) simulata per il periodo presente e futuro nel bacino del Mediterraneo occidentale (Osborne *et al.* 2000, linea di tendenza dal 1960 al 2100) e per la provincia di Firenze (43.77° Lat N, 11.25° Lon E, Italia) (Moriondo *et al.* 2001, i quadrati rappresentano la media dei periodi 1974-1989 e 2084-2099 rispettivamente). In entrambi i casi, il modello fenologico ha utilizzato come dati di input il risultato di un downscaling empirico della temperatura a partire da dati di un GCM.
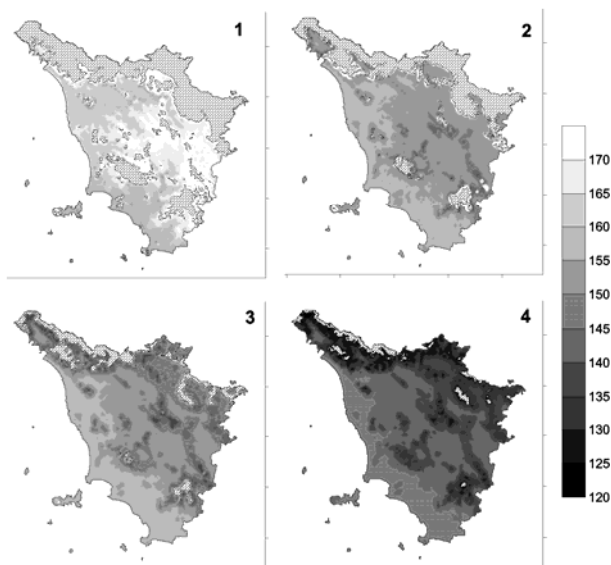
**Fig. 4** –Average grapevine growing cycle length (number of days from bud-break to harvest time) calculated for present (1,1990-2006) and future scenarioA2 (2, 2007-2037; 3, 2038-2068; 4, 2069-2099) (Moriondo and Bindi, 2005). Areas not suitable for grapevine cultivation are also indicated for the different time-frames (shaded areas).

**Fig. 4** *Lunghezza media del ciclo colturale della vite (n° di giorni compresi fra germogliamento e fine maturazione) nel periodo presente (1,1990-2006) e nello scenario futuro A2 (2, 2007-2037; 3, 2038-2068; 4, 2069-2099) (Moriondo and Bindi, 2005). Per ciascuna finestra temporale sono indicate le aree non adatte alla coltivazione della vite (aree tratteggiate)*
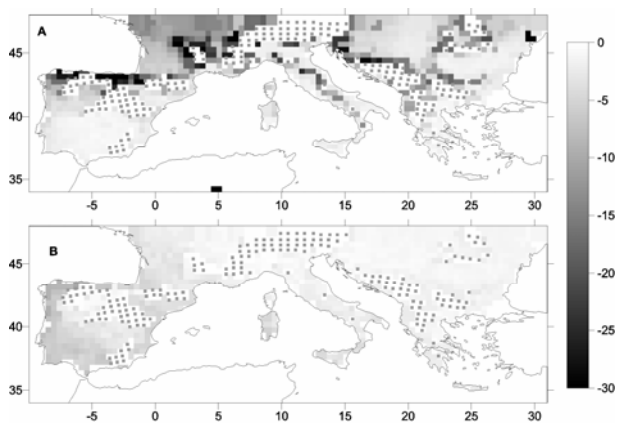


**Fig. 5** – Variation (number of days) of grain filling duration in sunflower (A) and durum wheat (B) in 2070-2100 (future scenario A2) as compared to the present period (1960-1990) (Moriondo *et al.*, 2007). Areas not suitable for crop cultivation are also indicated (dotted areas).

**Fig. 5 -** *Variazione (n° di giorni) nella durata del periodo di riempimento della granella di girasole (A) e frumento (B) nello scenario A2 (2070-2100) rispetto allo scenario presente (1960-1990) (Moriondo et al., 2007). Le aree punteggiate rappresentano zone non adatte alla coltivazione.*
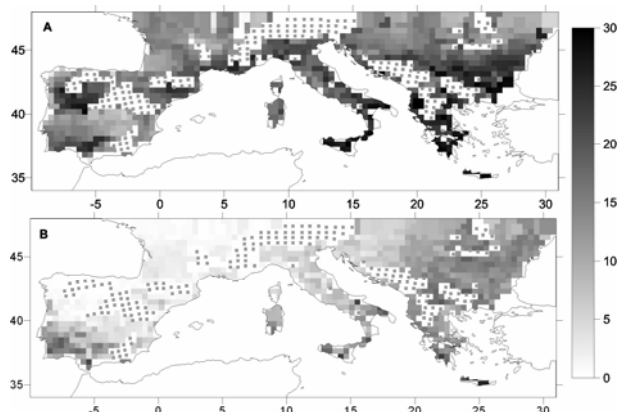


**Fig. 6 -** Variation (%) of heat stress events at anthesis stage in sunflower (A) and durum wheat (B) in 2070-2100 (future scenario A2) as compared to the present period (1960-1990). Heat stress events were calculated as the fraction (in %) of the flowering period (from -5 days to +8 days respect to anthesis beginning) with Tmax>31°C, (Moriondo *et al.*, 2007). Areas not suitable for crop cultivation are also indicated (dotted areas).

**Fig. 6 -** *Variazione (%) delle ondate di calore durante la fioritura di girasole (A) e frumento (B) nello scenario A2 (2070-2100) rispetto allo scenario presente (1960-1990) (Moriondo et al., 2007). Le ondate di calore sono state calcolate come frazione del periodo di fioritura (da –5 gg a +8 gg rispetto all'inizio della fase) in cui la Tmax>31°C. Le aree punteggiate rappresentano zone non adatte alla coltivazione.*



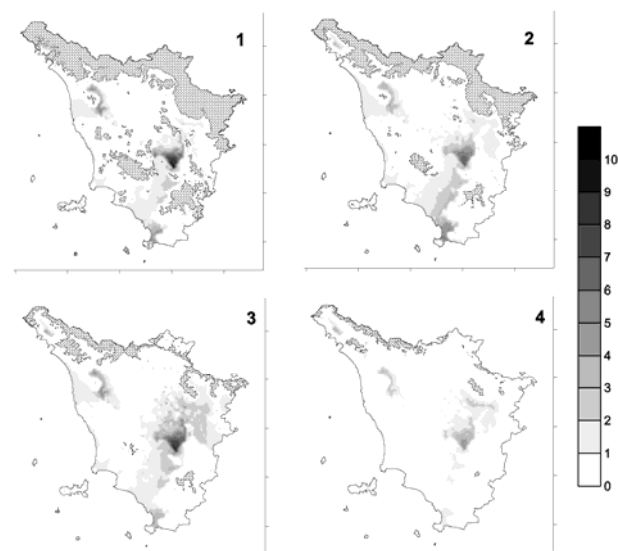**Fig. 7**- Average number of frost events (Tmin<-2°C) per year in a range ±30 dd around the bud-break stage for present (1990-2006) and future scenario A2 (2007-2037; 2038-2068; 2069-2099) (Moriondo and Bindi, 2005). Areas not suitable for grapevine cultivation are also indicated for the different time-frames (shaded areas).

**Fig. 7 -** *Gelate tardive (giorni con Tmin<-2°C) (numero medio annuale) durante la fase di germogliamento della vite (calcolate da –30 gg a +30 gg rispetto all'inizio della fase) nel periodo presente (1,1990-2006) e nello scenario futuro A2 (2, 2007-2037; 3, 2038-2068; 4, 2069-2099) (Moriondo and Bindi, 2005). Per ciascuna finestra temporale sono indicate le aree non adatte alla coltivazione della vite (aree tratteggiate).*

Accordingly, the shifting of phenological stages due to climate change may result in other important consequences when also change in extreme events frequency is taken into account. In particular, the predicted higher frequency of extreme events, as simulated both by GCM RCM and ED for the Mediterranean basin under future climate, may increase yield loss risks for those crops in which sensible growth stages are particularly exposed to climate extremes. Also in this case, summer crops and grapevine may be retained as the most risk–exposed crops since heat waves are expected to increase especially in summer time (Fig. 6a). Even advanced vegetative phases don't allow anthesis and grain philling phases to escape the prolonged heat waves and drought periods. In contrast, a shorter growth cycle allows a winter crop to reduce the exposure of both anthesis and grain filling to extreme temperatures. (Fig. 6b).

Always related to the increase in temperature and the frequency of extreme events, the higher temperature resulted into two different trends for grapevine. As simulated for grapevine in Tuscany region, late spring frost at bud-burst increased in the time slices 2007-2037 and 2038-2068 as the result of earlier  budburst in periods where freezing temperature are still likely to occur (Fig. 7). On the other hand, fruit set and berry ripening stage will be more exposed to heat waves during summer time (Fig. 8). Even though no specific analysis was performed on olive tree, fruit ripening phase, taking place in summer time, is likely to be exposed to higher temperature and frequency of heat stress. More in general, climate delimiters indicated by Euverte (1967) for olive tree, (average temperature of July included in the range +22°C, +30°C and ranfall>200mm $y^{-1}$) suggest that olive tree cultivation may disappear in some southern areas shifting nortwards (Bindi *et al.*, 1992)

## Adaptation strategies to reduce the risk of mean and extreme changes in climate on crop phenology

According to the results obtained from the different studies of this review, a warming climate was shown to threaten crop yield and three major causes were identified: the change in relative duration of the pre- and post-flowering phases (1), increased drought (2) and heat stress frequency (3). Accordingly, strategies for adapting to climate change should concentrate on the use of drought-tolerant cultivars, increasing water-use efficiency, and better matching phenology to the new environmental conditions to avoid extreme events. Both breeding techniques and change in management practices may be adopted for such a purposes. In the Mediterranean basin, winter crops with an earlier anthesis may be selected, as this will allow grain filling period to occur in the cooler, wetter parts of the year. Final yield is likely to be increased as a consequence of favourable climatic conditions and $CO_2$ fertilization. Management practices promoting advanced phenological stages, such as early sowing, may be also adopted, provided that a reduction in the duration of the frost period is occurring.
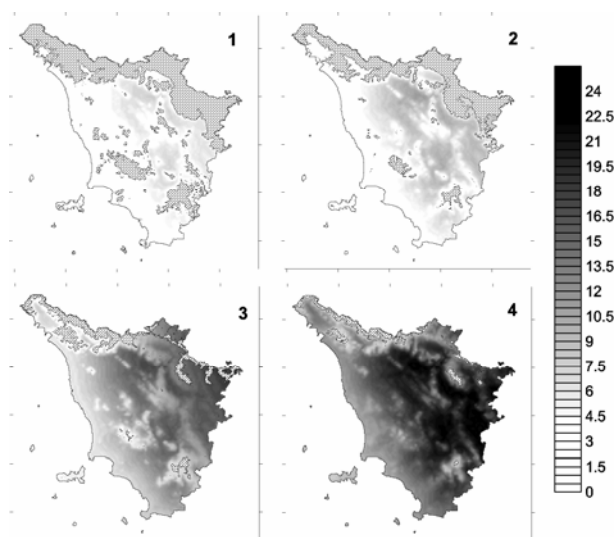


**Fig. 8** – Average number of heat stress events (Tmax>35°C) per year during grapevine maturation (period included between fruit-set and harvest time) for present (1, 1990-2006) and future scenarioA2 (2, 2007-2037; 3, 2038-2068; 4, 2069-2099) (Moriondo and Bindi, 2005). Areas not suitable for grapevine cultivation are also indicated for the different time-frames (shaded areas).

*Fig. 8* - Ondate di calore (giorni con Tmax>35°C) (numero medio annuale) durante la fase di maturazione della vite (periodo compreso fra allegazione e fine maturazione) nel periodo presente (1,1990-2006) e nello scenario futuro A2 (2, 2007-2037; 3, 2038-2068; 4, 2069-2099) (Moriondo and Bindi, 2005). Per ciascuna finestra temporale sono indicate le aree non adatte alla coltivazione della vite (aree tratteggiate).

Enhanced drought tolerance should be the characteristic most wanted in a typical rain-fed summer crop but other strategies should be considered to tackle the reduced time they have for biomass accumulation. This in fact is a noticeable reducing-yield factor and the selection or use of crops with a longer cycle may be suggested to compensate a shorter growing cycle. However, adopting or breeding slow maturing cultivars may be proposed only for those regions with adequate moisture conditions and low frequency of heat stress events. In a Mediterranean a prolonged time for biomass accumulation of a summer crop, that is supposed positive for final yield, would shift anthesis period in summer time increasing crop exposure to heat stress with a consequent reduction of yields respect to standard conditions (i.e climate change with no adaptation) even considering $CO_2$ fertilization (Fig. 9). In contrast, early sowing may partially reduce the growing season exposed to extreme events determining higher yield when compared to standard conditions.

These results would suggest that breeding effort should be addressed also to the development of more heat-tolerant varieties or varieties that flower outside the key risk periods.

The impact of climate change on wine quality is of great concern (Jones *et al.*, 2005) and both increased mean
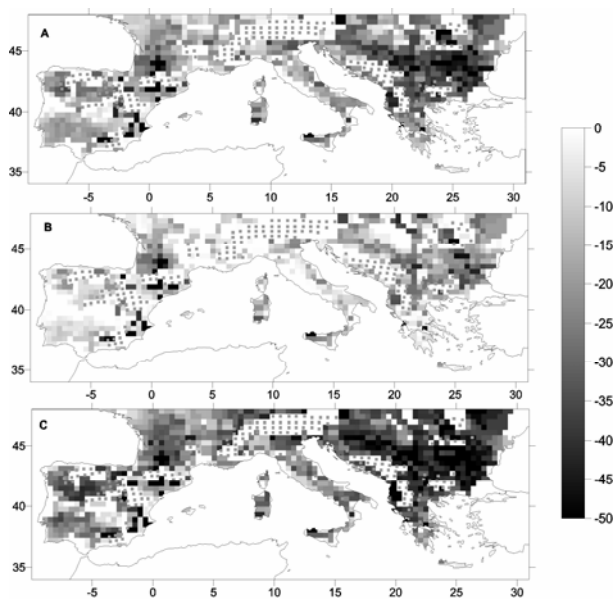
**Fig. 9** – Impact of different adaptation options on final yield of sunflower in future scenario A2 (2070-2100) respect to present (1960-1990). Legend: A) yield loss (%) using a standard cultivar and standard crop management practices; B) yield loss (%) using a standard cultivar and earlier sowing date; C) yield loss (%) using longer cycle cultivar and standard crop management practices.

**Fig. 9 -** Impatto di diverse opzioni di adattamento sulla produzione di girasole nello scenario A2 (2070-2100) rispetto al presente (1960-1990). Legenda: A) perdita di produzione (%) utilizzando una cultivar standard e pratiche colturali comuni; B) perdita di produzione (%) utilizzando una cultivar standard ed una semina anticipata; C) perdita di produzione (%) utilizzando una cultivar con ciclo colturale più lungo e pratiche colturali comuni.

temperature and frequency of extreme events may reduce vintages quality of most appreciated varieties (Jones *et al.*, 2005, White *et al.*, 2006). In particular, increase in temperature may determine a decrease of quality for those varieties that are cultivated close to their optimum climatic conditions. Additionally, the increase of heat stress frequency during berry ripening may affect vintage quality throughout the inhibition of berry colour development and partial or total failure of flavour ripening. Precocity may be a key word also for grapevine to escape both drought and heat stress during fruit ripening phase and the choice of the plant material is the first key for a warmer climate adaptation. Within rootstocks, there is a genetic variability for induced precocity and for tolerance to dry conditions (Duchêne and Schneider, 2005). For the scion-variety, there is also a wide variability for precocity and drought tolerance. However, for premium wine production, adaptation options may include the shift of varieties from their original cultivation areas to match their climatic requirements and to escape extreme events. For instance in Tuscany region, an increase of temperature of 4°C would shift premium-wine varieties towards higher elevations (400-800 m asl) whereas flat or low hilly areas (0-200 m asl) are likely to be suitable for low quality va-

rieties (producing high alcoholic wines) (Moriondo and Bindi, 2005).

Olive tree is a drought tolerant crop (200 mm y$^{-1}$ is the minimum water requirement) but for optimal yield, anthesis-fruit set period should occur in a relative wet period. Accordingly, the choice of earlier anthesis varieties, shifting fruit-set stage to relative wetter condition, may be a suitable adaptation option for this crop.

## Conclusion

Climatic models indicated that in this century, both average temperatures and extreme events frequency will increase in the Mediterranean basin. These changes are expected to have a great impact on agriculture in general and on crop phenology in particular.

Consistent with the increasing temperatures, crop development is expected to be faster, thus phenological stages will be reached early and the length of the growth period of crops with determinate cycle (i.e. cereals, grapevine, etc.) will be shorter.

These impacts, together with the higher risk to have climate extreme events during sensitive phonological phases, may have strong negative effects on final yield and on yield quality. However, these conclusions cannot be generalized, since the actual impact of phenological change needs to be assessed for specific crop-environment combinations, providing the basis to formulate feasible adaptation options to climate change. In other terms, the simulated changes in phenology cannot be interpreted without considering the environmental context in which a species lives.

For winter crops, the effect of predicted prolonged summer drought periods and heat weaves for the next decades may be smoothed or prevented due to the faster development that will allow escaping these and then avoiding reduction in final yields.

In contrast, crops whose growing cycle takes place in summer time are likely to experience a severe reduction of final yield as the result of increased frequency of extreme climatic events and a reduced time for biomass accumulation to yield.

## Appendix

GCMs represent the state of the art methodology in producing future climate scenarios on the global scale (Pope *et al.*, 2000). However, it should be stressed that in general their simulations are computed for wide grids (e.g. 2-3° latitude and longitude grid resolution) and the results are not directly suitable for local impact studies. Accordingly, tools are needed for downscaling GCM data to the required scale and several techniques have been developed.

They can be clustered into two conceptually distinct approaches: dynamical (RCMs) and empirical downscaling (ED) (Trigo and Palutikof 1999). In the first approach, the outputs of GCMs grid cells are used to provide boundary conditions for other models that, operating at a higher resolution inside the grid (0.5°X0.5°), provide higher spatial resolution of local topography and a more realistic simulation of fine scale weather features.

There are different types of ED: the simply differences in temperature, rainfall and radiation between baseline and future GCM runs may be applied directly to observed meteorological data in the relevant region to reproduce future climate (Delta change approach). However in this case the future meteorological data do not incorporate change in climatic variability so that possible changes in climate extreme events are not well simulated. Stochastic weather generators have been then used in climate change studies to produce daily site-specific scenarios of future climate (Semenov and Barrow 1997). These tools represent a large improvement respect to Delta approach to the extent that change in both climate mean and climate variability may be considered in the downscaling procedure. A different approach of ED is based on the assumption that GCMs are reliable predictors of both large-scale variables and atmospheric conditions that are sufficiently far removed from the surface of the earth. Accordingly, this procedure is based on seeking significant relationships between observed large-scale atmospheric variables (e.g. geo-potential height or sea level pressure provided by reanalysis) and the local climate. To reproduce the future climate, the transfer function is then applied to the relevant large-scale atmospheric variables as simulated by GCM for the future scenarios.

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