

Chapter 10

Mediterranean Phenology

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Abstract This chapter describes the five Mediterranean zones around the world and discusses vegetation and environmental factors, including climate, that make the Mediterranean Climate zones unique. Several key reports on the role of climate and climate change on phenological development of Mediterranean ecosystems are presented and discussed. The chapter talks about the impact of current and projected temperature and precipitation on phenology and emphasizes the importance of precipitation patterns on response to higher temperature. One conclusion is that more studies are needed on drought impact on phenology since water stress can increase plant temperature and result in even faster phenological development. Drought can speed up phenological development, but it can also impede growth and lead to reduced productivity.

10.1 Mediterranean Characteristics

Mediterranean-type ecosystems are found in the far west regions of continents between 30° and 40° north and south latitude (Fig. 10.1). They cover about 2.73 million km² (IUCN 1999), with the majority (i.e., 73 %) of the ecosystem in the Mediterranean Basin including parts of Spain, Turkey, Morocco, and Italy

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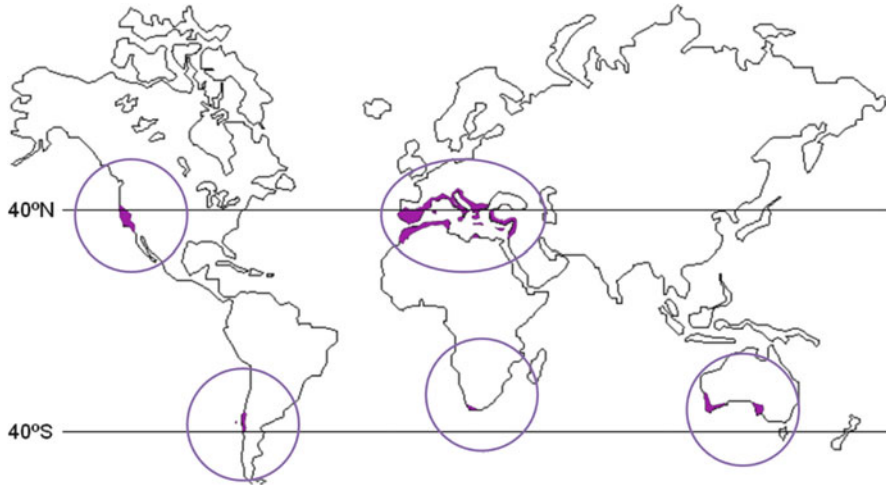


Fig. 10.1 Geographical distribution of Mediterranean-type ecosystems

(Rundel 1998). Areas are also found in California, Chile, Southwest and Southern Australia, and South Africa. In response to the climate, similar woody, shrubby plants, with evergreen sclerophyll leaves, have developed in communities of varying density. The names for the shrub vegetation vary by region because of language and plant structure. Common names for the vegetation include: *maquis* and *garrigue* in the Mediterranean Basin, *chaparral* in California, *matorral* in Chile, *fyfios* or *renosterveld* in South Africa, and *mallee* (*kwongan* or *heathlands*) in Australia.

Mediterranean ecosystems formed as a result of the unique climate, which falls in a transition between dry, tropical and temperate zones (Fig. 10.1).

The main characteristics are (1) variable winter rainfall, (2) summer droughts of variable length, (3) intensive summer sunshine, (4) mild to hot summers, and (5) cool to cold winters. Commonly, there is a cold ocean current off the West coast of regions with a Mediterranean climate that strongly influences the weather. The range of summer and winter temperatures mainly depends on proximity to the ocean (or sea) with higher temperatures near the coast during cooler periods and higher temperatures inland during warmer periods. Temperatures also vary with elevation having consistently cooler temperature in the mountains. Excluding mountains, the annual precipitation range at lower elevations typically varies between 250 and 900 mm with most falling in the winter and spring (i.e., November–April in the Northern Hemisphere and May–October in the Southern Hemisphere). Outside of the Mediterranean Sea region, westerly winds over cold ocean currents often lead to heavy marine fog that maintain low temperatures on the coast during summers. In the winter, the coastal areas tend to be fog free, whereas inland valleys that receive winter rainfall are prone to high-inversion radiation fog. Differences in relative humidity are mainly related to temperature variations over the zone rather than absolute humidity. Because the Mediterranean Sea has variable and warmer surface temperatures, the dew point temperatures are more variable over the Mediterranean Sea region.

Table 10.1 Climate classification based on length of summer drought period

Classification	Drought period (months)
Perarid	11–12
Arid	9–10
Semiarid	7–8
Subhumid	5–6
Humid	3–4
Perhumid	1–2

The five Mediterranean zones have similar characteristics, but there are important differences within each of the regions. Differences within a region are mainly related to the length of the summer drought period, which generally decreases as one moves poleward. For example, di Castri (1973, 1981) described a six-zone climate classification based on the length of drought period after Emberger (1962), as shown in Table 10.1.

Soil and climate both influence the development of natural vegetation, so a short discussion of soils is included here. More extensive discussions are presented by Thrower and Bradbury (1973), Zinke (1973), di Castri et al. (1981), Davis and Richardson (1995), Joffre et al. (1999), and Joffre and Rambal (2002). Most Mediterranean soils exhibit (1) considerable erosion, (2) alluvial deposition, (3) limited profile development, and (4) decreased soil development with increasing elevation. Because limestone is deficient in some areas, those soils often have water infiltration problems. Due to the lower precipitation, parent materials weather slower in Mediterranean zones than in more humid regions. Because of seasonal drying, some soils are dominated by shrinking and swelling processes and produce Vertisols. The soils tend to vary from reddish to brownish with increasing elevation. Higher precipitation and cooler temperatures at higher elevations have led to the development of predominant brownish podzolic soils with higher organic matter and moderate lime accumulations at middle elevations (500–1,000 m). At low elevations (0–500 m) with less precipitation and higher temperature, older *terra rossa* soils, which have lower organic matter and a reddish color due to iron oxidation, developed from limestone. In the river valleys, alluvial soils are found as highly weathered soils in terraces, light and well-drained in alluvial fans, and heavy and poorly drained in the valley floors. In some valley basins, fine textured soils have greatly inhibited drainage. In many areas within Mediterranean zones, older paleosols, which were formed under different climate conditions, are prevalent.

10.2 Vegetation Types

Although the climate developed relatively recently in geologic time, distinctive flora with similar characteristics has evolved in the five Mediterranean zones. While the climate is similar within the five Mediterranean zones, high heterogeneity in plant communities is common. This heterogeneity developed because of large

variations in landforms, microclimate, soils, phylogenetic origin, evolutionary strategy, ecological tolerance, and land use within the ecosystem.

The appearance of natural vegetation and landscape forms is strikingly similar between the five Mediterranean zones. The plants are woody, shrubby, and evergreen. The plant leaves tend to be small, broad, stiff, thick, and waxy or oily. In some locations, there are small trees with or without an understory of annual and herbaceous perennials. The vegetation represents different successional stages in relation to climate, topographical features, and human impact (di Castri et al. 1981), and it is prone to wildfires.

di Castri et al. (1981) presented a classification of six Mediterranean climate types (Table 10.1), based on the length of summer drought, and provided information on the structure of vegetation in each of the climate types. He noted that there were several overlapping clusters of characteristics between the five regions. However, the similarities between vegetation structures were most apparent between California and Chile, and between Australia and South Africa.

Mediterranean ecosystems have a large plant diversity including about 48,250 species, which is approximately 20 % of the world total (Cowling et al. 1996). The Mediterranean Basin, South Africa, Southwestern Australia, and California have about 25,000; 8,550; 8,000; and 900 species, respectively (Archibold 1995; Rundel 1998).

The Mediterranean Basin is mainly covered by scrub, sparse grass, or bare rock. However, there are scattered evergreen trees that suggest earlier presence of mixed forests. Several species of *Quercus* including the holm oak (*Quercus ilex*) prevail in the west with cork oak (*Q. suber*) dominant on non-calcareous soils. *Arbutus unedo* and other shrubs are found in the same plant communities. As aridity increased in the east, Kermes oak (*Q. coccifera*) became more prevalent than holm oak. Stone pine (*Pinus pinea*), cluster pine (*P. pinaster*), and Aleppo pine (*P. halepensis*) are common at higher elevations in the west. In the drier eastern region (e.g., Syria, Lebanon, and Israel), *Q. calliprinos*, which is an evergreen oak, and deciduous oaks are common. Corsican pine (*P. nigra*) and *P. brutia* often dominate in locations where wildfires occurred. *Q. ilex* is also found on the Atlas Mountains of North Africa at the elevation of 2,000 m. Shrublands are divided into *maquis*, which comprises evergreen shrubs and small trees about 2.0 m tall, *garrigue* on calcareous soils, and *jaral* on siliceous soils. All communities have representative species and the size depends on local conditions.

South African sclerophyll plant communities include mountain and coastal types (Moll et al. 1984). The mountain *fynbos* mainly consists of broad-leaved proteoid shrubs, which are found at elevations up to about 1,000 m and grow to heights between 1.5 and 2.5 m. At higher elevations, 0.2–1.5 m tall ericoid shrubs are dominant. In addition, 0.2–0.4 m tall shrubs and tussocky hemicryptophytes are present in the high elevation communities. Tussocky restioid shrubs, which reach 0.3 m, dominate communities at higher elevations. In high-elevation, arid regions, abundant succulent forms of karoo are the most common vegetation. The west coast is dominated by open ericoid cover with shrubs growing to 1.0 m tall. Small shrubs, grasses, and annuals form an open heath with 1–2 m tall proteoids along the south coast.

Western Australia is dominated by forests of karri (*Eucalyptus diversicolor*) and jarrah (*E. marginata*). Karri is restricted to regions with acidic soils (Rossiter and Ozanne 1970) and it grows in association with other tall eucalyptus. *Casuarina decussata* and species of *Banksia* are common in the understory of these forests. Jarrah forests occur on lateritic soils in areas with lower precipitation. These forests change to wandoo (*E. rudunca*) woodland as the annual precipitation decreases. The western region is separated from South Australia by the acacia shrubland. *Mallee* is the dominant cover in the southeastern Mediterranean zone. The prevalent species are *E. diversifolia* and *E. incrassata*. In more favorable sites, species such *E. behriana* grow with ground cover of herbs and grasses with few sclerophyllous shrubs (Specht 1981). These communities integrate with sclerophyll forests of stringbark (*E. baxteri*) and messmate (*E. obliqua*).

The Chilean *matorral* communities occur in the coastal lowlands and on the west facing slopes of the Andes. Most *matorral* species are 1–3 m tall, evergreen shrubs with small sclerophyllous leaves. Many spinescent species and drought-deciduous shrubs are also important in these regions (Rundel 1981). *Salix chilensis*, *Cryptocarya alba*, and other trees are found in wetter regions with shrubs forming a cover. *Matorral* evergreen shrubs (e.g., *Lithaea caustica* and *Quillaja saponaria*) dominate coastal regions. In more arid locations, succulent species and *Flourensia thurifera* are common. The central valley of Chile is dominated by *Acacia caven* (Ovalle et al. 1990, 1996).

California *chaparral* typically consists of a dense cover of 1–4 m tall, evergreen shrubs. In California, and particularly in the south, chamise (*Adenostoma fasciculatum*) is common and California lilac (*Ceanothus cuneatus*) is sometimes associated. In the Sierra Nevada foothills, *chaparral* occurs above 500 m elevation. Pure stands of California lilac are considered a fire-successional form in Southern California, but it is a dominant species of *chaparral* in Northern California (Hanes 1981). Manzanita (*Arctostaphylos spp.*) occurs throughout California, especially where there is snow and temperatures drop below freezing in winter. Various *Quercus* species may be present on lower hillsides. Coastal sage scrub (e.g., *Artemisia californica*) is the main vegetation along the coast.

Common characteristics of Mediterranean zones are summer drought, fire, tectonic instability, and variable floods and erosion during winter. Perhaps the most important of these is summer drought; however, drought tends to be more severe in California, Chile, and the subarid region of the Mediterranean Basin (Rundel 1995, 1998). In fact, the Mediterranean climate exhibits extreme year-to-year variability. In the last century, the rainfall trends were relatively consistent showing a general decrease. Mediterranean ecosystems are likely to be highly affected by climate change (Cubasch et al. 2001; IPCC 2001, 2007) with a higher variability of precipitation in many areas (Rodrigo 2002; Gao et al. 2006; Beniston et al. 2007; Giorgi and Lionello 2008; Somot et al. 2008). In the Mediterranean Basin, rainfall is projected to decrease by approximately 15 % for March–May, 42 % for June–August and 10 % for September–November (Somot et al. 2008). Concurrently, inter-annual variability is expected to increase (Gao and Giorgi 2008), and the frequency of long drought periods (4–6 months) to be multiplied

by 3 at the end of this century (Sheffield and Wood 2008). In addition, warmer conditions may increase evapotranspiration demand by 200–300 mm in the south, which will intensify the characteristic summer drought of the Mediterranean region (Valladares et al. 2004). The drier summers could seriously impact on plant activity (Christensen et al. 2007) and ecosystem productivity (Valladares et al. 2004; Ogaya and Peñuelas 2007). Warming will also affect the other seasons and, although less intense, drought will probably extend farther into the spring and autumn (Giorgi et al. 2004). Since spring is the main vegetation growth season, changes in temperature and precipitation could strongly affect the structure and functioning of Mediterranean ecosystems effects on plant phenology and growth (Bernal et al. 2011).

Although less well documented, it is likely that more aridity will not eliminate the intermittent rainy years (Beniston et al. 2007) that occur in some regions. These sporadic rainy years have a strong impact for regeneration (Castro et al. 2005; Holmgren et al. 2006; Mendoza et al. 2009). Despite its importance, the role of intermittent rainy years in maintenance of ecosystem structure needs more study (Castro et al. 2005; Holmgren et al. 2006).

Dense cover and high woody biomass of shrublands of Mediterranean ecosystems make them prone to wildfire, which is an important disturbance regime in Mediterranean climates. Frequency of natural wildfire differs greatly between and within Mediterranean zones depending on many factors (Mooney and Conrad 1977; Rundel 1981, 1983; Trabaud and Prodon 1993; Oechel and Moreno 1994).

Although fire is a natural disturbance in Mediterranean ecosystems, the frequency and intensity of wildfires has increased dramatically in recent decades (Rundel 1998). This has led to changes in forest vigor, structure and soil stability (Kuzucuoglu 1989; Naveh 1990). Climate change is likely to increase fire frequency and fire extent (Fischlin et al. 2007). Greater fire frequencies are noted in Mediterranean Basin regions (Pausas and Abdel Malak 2004) with some exceptions (Mouillot et al. 2003). Double CO₂ climate scenarios increased projected wildfire events by 40–50 % in California (Fried et al. 2004), and doubled the fire risk in Cape Fynbos, South Africa (Midgley et al. 2005), favoring re-sprouting plants in Fynbos (Bond and Midgley 2003), fire-tolerant shrub dominance in the Mediterranean Basin (Mouillot et al. 2002), and vegetation structural change in California (e.g., from needle-leaved to broad-leaved trees and from trees to grasses) and reducing productivity and carbon sequestration (Lenihan et al. 2003). Studies by Viegas et al. (1992) helped to identify critical periods of high potential fire risk of Mediterranean shrubland ecosystems.

Pellizzaro et al. (2007) in Italy and Viegas et al. (2001) in Portugal and Spain showed that knowledge of both the mean moisture content and the phenology of plants are useful for fire risk assessment. Two groups of Mediterranean species were identified for different ranges of leaf fuel moisture content (LFMC) values throughout the year and different relationships between LFMC, seasonal changes of meteorological conditions and phenological stages. The experimental data reveal the different physiological and morphological responses by vegetation to cope with the summer drought season typical of the Mediterranean climate. Species such as *Cistus* and *Rosmarinus* avoid water stress by adjusting the growing period or by

limiting water loss by reducing their transpiring surface. These species generally grow as shallow rooted shrubs and, therefore, are particularly affected by variations in moisture content of the surface soil layers (Correia et al. 1992; Munné-Bosch et al. 1999; Gratani and Varone 2004). *Pistacia lentiscus* and *Phillyrea angustifolia* are evergreen deep-rooted sclerophyllous species, tolerant to water stress and affected by drought conditions only when particularly severe (Kummerow 1981; Correia et al. 1992; Manes et al. 2002; Alessio et al. 2004). These species showed the highest values of LFMC in spring during sprouting and flowering phases. In summer, they partially reduced their vegetative activity that again increased in autumn. Consequently, *Pistacia* and *Phillyrea* showed a seasonal pattern of LFMC, although it was characterised by a range of values narrower than others such as *Cistus monspeliensis* and *Rosmarinus officinalis*.

Deforestation, grazing, agriculture, fire events, and fire suppression have changed vegetation community structure especially in recent decades. Increased urbanization and land abandonment has led to uneven management more frequent and larger wildfire disturbances (Rundel 1998).

Livestock grazing has greatly influenced Mediterranean ecosystems. A good example is in California, where livestock grazing converted much of the grassland from native perennials to exotic annuals from the Mediterranean Basin even prior to immigration by large numbers of people of European ancestry (Rundel 1998). In the late 1800s, agricultural expansion into the Central Valley and Southern California caused extensive changes in natural communities. Later, agricultural and urban expansion led to large changes in vegetation along the coast. Human activities influenced grassland and oak woodlands of the State mainly by replacing native perennial grasses with introduced annual grasses from Europe. Native Americans purposely set fires to control vegetation, but European immigrants introduced fire suppression as a management strategy in the late 1800s. This change in management has led to fewer but more intense wildfires (Minnich 1983; Rundel and Vankat 1989).

When Spanish settlers arrived in Chile in the mid-1500s, they introduced grazing and agriculture that greatly changed the natural ecosystems. The impact is most obvious in the semi-arid transition region where over-grazing has caused devegetation and desertification (Ovalle et al. 1990, 1996). Also, much of the Central Valley now is covered with exotic annual grasses rather than the native grasses (Gulmon 1977). Recently, Chile has become more urban having a plethora of abandoned farms and ranches as the population leaves rural areas. This has led to a big increase in mainly anthropogenic wildfires that have grown in size and intensity. Even more recently, the planting of winegrape vineyards has expanded dramatically in Chile and in California at the expense of native woodlands (Rundel 1998).

Agricultural development in Southwest Australia has resulted in widespread fragmentation of *mallee* ecosystems mixed in with agricultural lands (Rundel 1998). The fragmented habitats tend to be too small to maintain viable plant populations, which are also impacting on animal diversity. Deforestation is a big problem in native eucalypt forests, and the resulting rise in water tables has led to problems with saline paleosol profiles (Rundel 1998), which threatens agriculture as well as the replanting of forests. The introduction of exotic species has resulted in

problems with biological diversity in the Mediterranean climate zones (Thuiller et al. 2005; Gritti et al. 2006; García-de-Lomas et al. 2010).

Anthropogenic impacts on the Mediterranean ecosystems in South Africa are less obvious than in the other regions to a large extent because the soils of the region are not conducive to support cereal and vegetable production (Rundel 1998). However, large animal hunting and deforestation have impacted on the vegetation. A large introduction of non-native trees, especially Australian acacias, along rivers and streams, has occurred.

10.3 Phenology in the Mediterranean Climate

Mediterranean regions show seasonal changes in resource availability, which affect growth and reproductive activities of vegetation. Resource fluctuations have a strong influence not only on the structure and composition of the vegetation but also on the seasonal behavior pattern of the species. For example, the sclerophyllous forest can remain active throughout the year, but there is a distinct annual growth rhythm because photosynthesis is limited by drought and nutrients. However, several other species shed leaves during summer drought period.

Over recent decades, the economic, ecological, and cultural value of Mediterranean vegetation was increasingly recognized (Quezel 1977; Joffre and Rambal 2002; Rundel 2007), and many studies were devoted to improving management and protection of Mediterranean areas. In particular, comparative research on the structure of Mediterranean region ecosystems, which included a detailed assessment of phenological species behavior in the different areas, was performed. The first systematic study on Mediterranean vegetation was presented by Mooney et al. (1977) within the International Biological Program (IBP), which started in 1970. The authors summarized the results of the comparison of the structural, functional, and evolutionary features of California and Chile ecosystems. At the plant community level, there is a longer protraction of each phenological event in Chile than in California due to both the greater diversity of growth form and more moderate climate in Chile (Mooney et al. 1977). In addition, di Castri et al. (1981) pointed out that there were more species with non-overlapping phenological activities in Chile.

As more information on the phenology of ecosystems in the Mediterranean Basin, South Africa and Australia became available, it was noted that there is a pronounced seasonal rhythm in the vegetative growth throughout the year in Mediterranean regions. However, less similarity in phenological pattern was found when comparing Chile, California, and Mediterranean Basin with South Africa and Australia. In South Africa and Australia, shrubs grow in the summer as well as in the spring (Cody and Mooney 1978) because of differences in origin of the biota (Specht 1973) and nutrient availability in the soils (Specht 1979, 1981).

Comparative analysis of Mediterranean species development was intensified during the 1980s with more emphasis on the interactions between temperature and water as limiting factors. Tenhunen et al. (1987) summarized the results of

years of cooperative work between several scientists on functional analysis in Mediterranean ecosystems. The work included studies on plant growth and development. Montenegro (1987) discussed the difficulty in comparing these ecosystems because of different methodologies used to quantifying phenology and growth. In Portugal, phenological observations conducted on different species (*Quercus coccifera* and *Q. suber*, *Arbutus unedo*, and *Cistus salvifolius*) showed that the flowering stage occurred during all times of the year except the driest months in late summer and the coldest months in winter. Shoot growth was intense in the absence of water stress, and leaf drop was possibly more intense during drought (Pereira et al. 1987). Similar results were obtained on *Q. coccifera* and *Arbutus unedo* in Greece (Arianoutsou and Mardilis 1987), although the responses to the physical environment were not synchronous for the two species. Moll (1987) observed that the differences between vegetation in South Africa and in other Mediterranean regions reported by Mooney and Kummerow (1981) were mostly due to the fact that they compared non-heath shrubland in Chile, California, and the Mediterranean Basin with heath shrubland in South Africa.

The occurrence of vegetative primary growth in spring is observed in the Mediterranean climate regions of the Northern hemisphere, and in Chile. In the South African *fynbos*, however, this phenophase is observed throughout the year, mainly due to the milder winters (Orshan 1989). The protraction of stem vegetative growth towards sub-optimal periods, like the end of winter or the beginning of summer, seems difficult to avoid for species with long phenological cycles, such as *Lonicera implexa*, *Buxus fruticosum* or *B. sempervirens* (Milla et al. 2010).

In recent decades, more attention was directed to the relationship between phenological events and seasonal fluctuations in nutrient and water uptake. A phenological survey conducted in central Italy (de Lillis and Fontanella 1992) showed the effect of increasing water stress and nutrient limitations on several species (*Cistus monspeliensis*, *Pistacia lentiscus*, *Calicotoma villosa*, *Quercus ilex*, *Erica arborea*, *Arbutus unedo*, *Phillyrea media*, *Smilax aspera*, and *Ruscus aculeatus*). Phenological rhythm of the community was closely correlated with changes in environmental conditions, and large variation occurred among species. In all species, peak growth was reached between March and early July, flowering occurred before July except for *A. unedo* and *S. aspera*, which flowered in autumn and winter, and fructification was unrelated to summer aridity. An analysis of water availability and growth modulation allowed for division into drought-tolerant species (*Pistacia lentiscus*, *Phillyrea media*, *Arbutus unedo*, and *Ruscus aculeatus*), drought-deciduous species (*Calicotoma villosa*), and semi-deciduous species (*Cistus monspeliensis*). Carbon leaf concentration peaked and nitrogen decreased when growth stopped. Correia et al. (1992) compared the phenological characteristics of four summer semi-deciduous (species of *Cistus*) and evergreen (*Pistacia lentiscus*) shrubs in Portugal, corresponding to earlier and later successional stages of vegetation. The *Cistus* species were similar in growth, flowering, and fruiting phenology, showing a long period of leaf emergence relative to *P. lentiscus*, which had a flush-type leaf emergence and an almost simultaneous leaf fall. In general, *Pistacia* showed lower leaf nitrogen contents than the *Cistus*

species, with minimum value in winter, when the *Cistus* species had the highest concentrations of nitrogen. However, increased drought frequency and intensity is likely to greatly affect phenology of these species in the future. Little information is known about the relationship between phenological stage occurrence and duration and intensity of drought period.

Spano et al. (1999) recorded weekly phenology observations for a period of 11 years on the common species *Pistacia lentiscus*, *Olea europea*, *Myrtus communis*, *Quercus ilex*, *Spartium junceum*, and *Cercis siliquastrum*, and on the exotic species *Robinia pseudoacacia*, *Salix chrysocoma*, and *Tilia cordata* in Sardinia to investigate the impact of drought on phenology. The range of phenological event dates for the nine species varied widely, especially for flowering of the exotic species. The authors showed that difference in accumulated degree-days could not explain the variations in observed phenological development. During the winter and spring, there seemed to be little difference in the flowering dates of common species. However, the non-native species *Salix chrysocoma* and *Tilia cordata* showed more inter-annual variability and both exhibited later flowering when there was more rainfall during March (i.e., prior to flowering). There was no relationship with rainfall recorded two or more months prior to flowering.

Duce et al. (2000) conducted phenological observations on three *maquis* species and oak trees over the period 1997–1999 at *Giara di Gesturi*, a nature reserve located in Southern Sardinia, Italy. About 46 % oak trees (*Quercus suber*) and about 32 % successional Mediterranean *maquis* with four dominant species (*Arbutus unedo*, *Pistacia lentiscus*, *Phillyrea angustifolia*, and *Myrtus communis*) cover the reserve. Flowering and full ripe fruit stages occurred about 1 month later in 1997 for *Quercus suber* and *Pistacia lentiscus* and the response was related to rainfall distribution and water deficit. In 1997, both species were affected by the lack of spring rainfall, which led to a longer and more intense drought period. In 2002, Duce et al. showed a large species variation in terms of observed flowering dates and cumulative degree-day values, indicating that other factors in addition to heat units affected plant development (Duce et al. 2002). In general, the flowering date was postponed when the soil water was not limiting, so flowering occurred earlier during drought years.

Simões et al. (2008) analyzed the phenological patterns, growth and internal nutrient cycling of the Mediterranean shrubs *Cistus salvifolius* and *Cistus ladanifer* during 2 years of contrasted precipitation to compare their life responses and their competitive potential to cope with future climate change and drought. The two species exhibited different responses to summer drought. *C. salvifolius* showed high seasonal dimorphism in plant structure, with greater leaf shedding before summer drought, while the structure and biomass of *C. ladanifer* showed little change throughout the year. The increase in length and intensity of drought also caused greater variation on growth rates and leaf duration and shedding in *C. salvifolius* than in *C. ladanifer*. The results suggest that *C. ladanifer* has greater stress-tolerance ability against drought. The phenological pattern of *Halimium atriplicifolium* and *Thymus vulgaris* were analyzed by Castro-Díez et al. (2005) to provide information on their response to unfavorable periods of Mediterranean

climate (winter and summer). The two species arrested all phenological activities, during colder months, probably due to a cold-induced decrease of meristem activity (Kozłowski and Pallardy 1997). In contrast, a species-dependent response to summer drought was found, as *T. vulgaris* ended all phenophases in June, while *H. atriplicifolium* extended most of them into a period with virtually no rainfall (July and August). *T. vulgaris* seems suffer from more severe water stress than *H. atriplicifolium* due to its shallower root system and arrested phenological activity earlier in the summer. The different morphological and phenological traits of long and short shoots in the two species suggest a specialization in carbon gain along different time periods of the year.

10.4 Phenology and Climate Change

The last IPCC AR4 report (Christensen et al. 2007) stated that the Mediterranean ecosystems may be one of the most impacted by global change drivers (Sala et al. 2000). Diverse Californian vegetation types may show substantial cover change for temperature increases greater than about 2 °C. For example, mixed deciduous forest may expand at the expense of evergreen conifer forest (Hayhoe et al. 2004). The bioclimatic zone of the Cape Fynbos biome could lose 65 % of its area under warming of 1.8 °C relative to 1961–1990 (2.3 °C, pre-industrial) with species extinction of 23 % in the long term (Thomas et al. 2004). For Europe, only minor biome-level shifts are projected for Mediterranean vegetation types (Parry 2000), contrasting with between 60 and 80 % of current species projected not to persist in the southern European Mediterranean region (global mean temperature increase of 1.8 °C) (Bakkenes et al. 2002). Inclusion of hypothetical and uncertain CO₂-fertilisation effects in biome-level modeling may partly explain this contrast. Land abandonment trends, however, facilitate ongoing forest recovery (Mouillot et al. 2003) in the Mediterranean Basin, complicating projections.

In Southwestern Australia, substantial vegetation shifts are projected under double CO₂ scenarios (Malcolm et al. 2002). Knowledge of the vegetation behavior under extreme climatic events is important for understanding the response and evolution of ecosystems in future climatic scenarios. This is particularly true for areas such as those in the Mediterranean regions that are currently subjected to a high degree of water stress (Peñuelas and Boada 2003) or to a progressive aridification (Peñuelas et al. 2002; Peñuelas and Boada 2003), that currently exhibit a great geographical and temporal variability in precipitation and water availability (Peñuelas 2001).

Several papers have presented the possible effects of changing temperature and water availability on the growth of forests. Kramer et al. (2000) presented models simulating physiological features of the annual cycle for boreal coniferous, temperate-zone deciduous, and Mediterranean forest ecosystems. In Spain, Peñuelas et al. (2002) compared phenological data from 1952 to 2000 providing a complete record of common plants, migratory birds and a common butterfly.

A conservative linear treatment of data showed that, in 2000, leaves unfolded on average 16 days earlier, leaf fall occurred about 13 days later, and plants flowered an average of 6 days earlier than in 1952. In addition, fruiting occurred about 9 days earlier in 2002 than in 1974. Butterflies appeared 11 days earlier and spring migratory birds arrived 15 days later than 1952. The biggest change in both temperature and phenophase timing occurred in the last 25 years.

García-Mozo et al. (2010) present the phenological trend of several species in response to climate change at six sites in southern Spain from 1986 to the present. They focused on vegetative and overall reproductive phenology in *Olea europaea* L. and *Vitis vinifera* L., as well as in various species of *Quercus* spp. and *Poaceae*. A trend towards earlier foliation, flowering and fruit ripening was observed for the trees, and temperature increase was identified as the cause. Herbaceous species were more affected than trees by changes in precipitation.

Morin et al. (2010) analyzed the phenological response to artificial climate change, obtained through experimental warming and reduced precipitation on several populations of three European oaks in a Mediterranean site. Experimental warming advanced the seedlings vegetative phenology, which caused a longer growing season, and advanced the leaf unfolding date. Conversely, soil water content did not affect the phenology of the seedlings or their survival. Thus, the phenological response of trees to climate change may be nonlinear, which suggests that predictions of phenological changes in the future should not be built on extrapolations of current observations.

Pinto et al. (2011) showed that air temperature was the main environmental driver of *Q. suber* budburst timing. This was also reported for other oak species of the Iberian Peninsula (Morin et al. 2010; Peñuelas et al. 2002; Sanz-Pérez et al. 2009). High mean and maximum daily temperatures in periods close to budburst accelerate more effectively bud development than in January and February. In the period with the best fit between budburst date and temperature (late-March to budburst) minimum daily temperature had no influence on budburst. The current differences in the timing of the budburst (earlier in *Q. faginea* than in *Q. ilex*) would be reduced in a global warming scenario, which could modify the competitive relationships between seedlings of these two species in the regeneration phase of mixed forests.

In many locations and species, chilling temperature accumulation is necessary to break bud dormancy (Cannell and Smith 1983; Hänninen 1990; Kramer 1994). Results from studies on Mediterranean species (García-Mozo et al. 2008), and even considering longer periods of temperature averaging (Pinto et al. 2011), however, failed to show any evidence of the chilling effect requirement. Conversely, other authors noted the importance of chilling even under Mediterranean conditions (Cesaraccio et al. 2004; Jato et al. 2007; Morin et al. 2010).

The relationship between rainfall and budburst date is a controversial topic. Pinto et al. (2011) found no relationship for the budburst triggering mechanisms in *Q. suber*, which seem species specific regardless of local soil and water conditions. Spano et al. (1999) found little effect of rainfall on budburst of Mediterranean species. Peñuelas et al. (2004), however, reported an overall relationship between

October to February rainfall and budburst date for a range of Mediterranean species.

Miranda et al. (2002) found that budburst in Mediterranean evergreen oaks is likely to occur earlier although probably within a range of species-specific photoperiod limits. Moreover, with respect to shoot elongation, two main situations may arise: (a) in water-limited areas, a drier spring and summer will lengthen the tree water stress period and restrict shoot elongation; (b) in fully watered places, shoot growth is limited by nutrient availability prior to budburst. Commonly, future phenology trends of Mediterranean evergreen oaks likely exhibit an earlier budburst and reduced shoot elongation (Pinto et al. 2011).

Temperature is the major factor responsible for phenological changes affecting flowering, fruit ripening, and leaf unfolding and shedding in plants (Peñuelas and Filella 2001); however, a delay in water supply is also of great importance (Dios Miranda et al. 2009). A long delay of the rainy season results in later flowering, as was shown for mesic Mediterranean environments (Peñuelas et al. 2002; Gordo and Sanz 2005). These papers reported significant correlations between precipitation and length of the life cycle. Importantly, changes in flowering date led to a reduction in the number of fruits, number of seeds, seed size, and seedling recruitment, affecting plant communities in the long term (Peñuelas et al. 2002).

The comprehensive analysis reported by Gordo and Sanz (2010) provides an essential tool to understand why flowering and leaf unfolding (spring phenophases) showed some of the largest phenological responses to climate change reported in plants (Menzel et al. 2006; Gordo and Sanz 2009). They used a dataset of more than 200,000 records for six phenological events of 29 perennial plant species monitored from 1943 to 2003. A comparison of sensitivity coefficients to temperature reported in literature for the same species in other parts of Europe suggests a higher sensitivity of populations in the Mediterranean. This fact would agree with the higher sensitivity found in plant populations from warmer regions (Menzel et al. 2005; Tryjanowski et al. 2006; Doi and Takahashi 2008), which could be a result of the lower probability of late frost damage (Askeyev et al. 2005). Differences in temporal responses of plant phenology to recent climate change are due to differences in the sensitivity to climate among events and species. Spring events are changing more than autumn events as they are more sensitive to climate and they are also undergoing the greatest alterations of climate relative to other seasons.

The phenology of Mediterranean plants is as responsive as the phenology of plants in colder biomes (Osborne et al. 2000; García-Mozo et al. 2002; Peñuelas et al. 2002; Mutke et al. 2003; Gordo and Sanz 2005). Prieto et al. (2009) analyzed the changes in the onset of spring growth in shrubland species in response to experimental warming along a north–south gradient in Europe. ‘Bud break’ was monitored in eight shrub and grass species in six European sites under control and experimentally warmer conditions generated by automatic roofs covering vegetation during the night. This study showed that warmer temperatures projected for coming decades have substantial potential to advance the spring growth of dominant species in different European shrublands. It also demonstrated the overall difficulties of applying simple predictive relationships to extrapolate the effects of global change

on phenology. Various combinations of environmental factors occur concurrently at different European sites and the interactions between different drivers (e.g. water and chilling) can alter phenology significantly.

Results from Prieto et al. (2009) underscore the species-specific nature of the responsiveness of spring growth to temperature (Peñuelas et al. 2002, 2004; Hollister et al. 2005). The acceleration of the 'bud break' dates of the Spanish species is particularly noticeable. In general, the 'bud break' is related to the period when water first becomes available (Peñuelas et al. 2004). In a Mediterranean forest, the influence of water availability and temperature in the control of leaf development and spring flowering varies depending on the species (Ogaya and Peñuelas 2004). The spring growth for both tree species was associated with the mean temperature of the previous months, although only the 'bud break' of *Erica multiflora* was accelerated by warming treatment. The lack of significant acceleration in the 'bud break' of *Globularia alypum* in warming plots can be a consequence of its stronger dependence on the soil water status described for some ecophysiological parameters (Llorens et al. 2003) as well as for growth phenology. For *Erica multiflora*, the relationship with water availability was not significant, although the dry period between late winter and early spring in 2005 accelerated the onset of growth in *Erica multiflora* in control plots compared with 2003 and 2004. *Erica multiflora* is a species with a conservative strategy regarding water use (Llorens et al. 2003) and, in the light of the warming effects described in this study, the earlier growth in 2005 might be a consequence of an increased leaf temperature resulting from reduced stomatal conductance under lower water availability. The lower stomatal conductance reached in *Erica multiflora* in 2005 (winter and spring) relative to the rates in 2003 and 2004 support this hypothesis (Prieto 2007).

Plant responses to warming also depended on specific combinations of environmental drivers in particular years. For example, plant response depends on the temperature or the amount and distribution of rainfall throughout the season and preceding years. In *Erica multiflora*, in spite of the clear acceleration of 'bud break' dates in warming plots in 2003 and 2004, no significant change was observed in 2005, which was the year with the driest late winter and spring during of the 7 years. Moreover, the earlier 'bud break' date in 2003 and 2004 was only accompanied by greater spring shoot elongation in 2004 (Prieto 2007). This was partly due to the high temperature reached during the European heat wave in 2003, which enhanced evapotranspiration and reduced water availability for shoot growth.

Different phenological patterns of the various species partially help to explain their various productivity responses to warming reported by Peñuelas et al. (2007). Rainfall frequency reductions projected for some Mediterranean regions (Cheddadi et al. 2001) will exacerbate drought conditions, and these conditions have now been observed in the eastern Mediterranean (Körner et al. 2005). Soil water content controls ecosystem water and CO₂ flux in the Mediterranean Basin system (Rambal et al. 2003), and reductions are very likely to reduce ecosystem carbon and water flux (Reichstein et al. 2002). Many studies on the behavior of Mediterranean species in response to drought are reported in the IPCC (2007) report. Established *Pinus halepensis* (Borghetti et al. 1998) showed high drought resistance, but

Ponderosa pine forests had reduced productivity and evapotranspiration during a 1997 heat wave. The Ponderosa pine did not recover for the rest of the season, indicating threshold responses to extreme events (Goldstein et al. 2000). Mediterranean Basin pines (Martinez-Vilalta and Pinol 2002) and other woody species (Peñuelas et al. 2001) showed species-specific drought tolerance under field conditions. Experimental drying differentially reduced productivity of Mediterranean Basin shrub species (Llorens et al. 2003, 2004; Ogaya and Peñuelas 2004) and tree species (Ogaya and Peñuelas 2007), but delayed flowering and reduced flower production of Mediterranean Basin shrub species (Llorens and Peñuelas 2005), suggests complex changes in species relative success under drying scenarios. Drought may also act indirectly on plants by reducing the availability of soil phosphorus (Sardans and Peñuelas 2004).

Seasonal and inter-annual variation in climatic patterns (e.g., rainfall regimes) impacts on the pollination pattern in some anemophilous sub-desert plants. Alba-Sanchez et al. (2010) explored the effect that seasonal and inter-annual variation of rainfall regimes on pollination patterns in six anemophilous taxa located in the semiarid area of Almería (SE Spain), which is one of the most arid locations in Europe. The sampling from 1998 to 2005 showed that the pulsed and discrete rainfall events interspersed with drought periods are closely related to the alteration of the pollination in certain species. This is manifested in: (i) delayed onset of flowering until reaching the minimum threshold of soil water, in the case of some annual plants (*Plantago*, *Rumex*, and *Poaceae*), or (ii) scant variability both in the flowering period in plants with drought tolerance (*Chenopodiaceae* and *Artemisia*) or plants often linked to soil-moisture availability (*Urticaceae*).

As cited by Matias et al. (2011), under a global-change scenario where habitat as well as climatic conditions are altered (Houghton et al. 2001), the effect on dynamics of soil nutrients and its interaction with the plant community are not well known (Jensen et al. 2003; Andresen et al. 2010).

It is increasingly clear that changes in temperature or precipitation provoked by climate change will alter nutrient cycles (Sardans and Peñuelas 2007), and therefore nutrient availability for plants. Differences in carbon (C), nitrogen (N), and phosphorus (P) availability have severe effects for plant communities as these are fundamental nutrients for plant growth. Because P has strong implications in the water-use efficiency (Graciano et al. 2005), this modulates plant vulnerability to drought stress.

A dryer climate reduces microbial nutrient uptake, but increases soil nutrient availability. Higher nutrient availability in dry soil, however, cannot be exploited by plants due to the water deficit. This higher nutrient pool in soil, together with the higher torrential rainfall predicted for the coming decades (Houghton et al. 2001) may increase the risk of nutrient loss by leaching or erosion (De Luis et al. 2003; Ramos and Martinez-Casasnovas 2004), leading to a short to middle-term nutrient loss and soil impoverishment.

Matias et al. (2011) investigated the effect of three contrasting climatic scenarios on different carbon (C), nitrogen (N), and phosphorus (P) fractions in soil and microbial compartments among three characteristic habitats in a Mediterranean-type ecosystem:

forest, shrubland, and open areas. The climatic scenarios were (1) using a 30 % summer rainfall reduction, (2) simulating summer storms to reach the maximum historical records and (3) current climatic conditions. The results support the idea that higher rainfall boosts microbial and plant-nutrient uptake, and hence nutrient cycling. The rainfall reduction led to an accumulation of nutrients in the soil, increasing the risk of nutrient loss by leaching or erosion.

10.5 Conclusions

There are five Mediterranean zones around the world that are located near the west coasts of continents between 30° and 40° latitude. The climate represents a unique transition between arid zones towards the equator and temperate zones poleward. It is characterized by cold to cool, wet winters and warm to hot summers with varying periods of drought. The vegetation is similar in each region with woody, shrubby and evergreen shrubland plants, sparse grass, scattered evergreen trees, and many species of oak trees. In all zones, anthropogenic disturbances including deforestation, grazing, agricultural development, and fire starting and suppression have changed the vegetation community structure. In general, phenology in the five Mediterranean zones presents a pronounced seasonal rhythm related to vegetation and environmental characteristics, with large variation among species. Whereas heat unit accumulation is the main factor affecting phenology of well-watered plants, phenology of natural Mediterranean vegetation is influenced by drought and plant nutrition in addition to heat units. Climatic fluctuations and drought in particular, directly influence resources availability and indirectly phenology. Like other climate regions, more research is needed to better understand the interaction between weather factors and phenology.

The Gordo and Sanz (2009) analysis is a keystone to determine the role of recent climate change in the observed phenological shifts and to understand why plants are changing their phenology in Mediterranean ecosystems and how responses vary among species and events. Differences in temporal responses of plant phenology to recent climate change are due to differences in the sensitivity to climate among events and species. Spring events are changing more than autumn events as they are more sensitive to climate and are also undergoing the greatest alterations of climate relative to other seasons.

In Mediterranean climate regions, water availability and temperature are both key factors determining plant performance. For instance, water can restrict the length of growing season and affect flowering phenology. However, there are few studies on drought and phenology, so more research is needed to better characterized climate change effects on vegetation.

A drier climate will affect growth but also spring phenology of some Mediterranean species. A reduction in the cooling effect of transpiration could have the same effect as atmospheric warming and it could advance the initiation of growth in sensitive plants. Lengthening of the growing season, due to earlier phenological development may not result in higher productivity because drought can impede growth.

References

- Alba-Sanchez F, Sabariego-Ruiz S, De La Guardia CD, Nieto-Lugilde D, De Linares C (2010) Aerobiological behaviour of six anemophilous taxa in semi-arid environments of southern Europe (Almería, SE Spain). *J Arid Environ* 74(11):1381–1391
- Alessio GA, de Lillis M, Brugnoli E, Lauteri M (2004) Water source and water use efficiency in Mediterranean coastal dune vegetation. *Plant Biol* 6:350–357
- Andresen LC, Michelsen A, Jonasson S, Schmidt IK, Mikkelsen TN, Ambus P, Beier C (2010) Plant nutrient mobilization in temperate heathland responds to elevated CO₂, temperature and drought. *Plant Soil* 328:381–396
- Archibold OW (1995) Ecology of world vegetation. Chapman & Hall, London
- Arianoutsou M, Mardilis TA (1987) Observations on the phenology of two dominant plants of the Greek maquis. In: Tenhunen JD, Catarino FM, Lange OL, Oechel WC (eds) Plant response to stress: functional analysis in Mediterranean ecosystems, vol 15, NATO Adv Sci Inst Ser G Ecol Sci. Springer, Berlin/Heidelberg
- Askeyev OV, Tischin D, Sparks TH, Askeyev IV (2005) The effect of climate on the phenology, acorn crop and radial increment of pedunculate oak (*Quercus robur*) in the middle Volga region, Tatarstan, Russia. *Int J Biometeorol* 49:262–266
- Bakkenes M, Alkemade JRM, Ihle F, Leemans R, Latour JB (2002) Assessing effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. *Glob Chang Biol* 8:390–407
- Beniston M, Stephenson DB, Christensen OB et al (2007) Future extreme events in European climate: an exploration of regional climate model projections. *Clim Chang* 81:71–95
- Bernal M, Estiarte M, Peñuelas J (2011) Drought advances spring growth phenology of the Mediterranean shrub *Erica multiflora*. *Plant Biol* 13:252–257
- Bond WJ, Midgley JJ (2003) The evolutionary ecology of sprouting in woody plants. *Int J Plant Sci* 164:S103–S114
- Borghetti M, Cinnirella S, Magnani F, Saracino A (1998) Impact of long-term drought on xylem embolism and growth in *Pinus halepensis* Mill. *Trees* 12:187–195
- Cannell MGR, Smith RI (1983) Thermal time, chill days and prediction of budburst in *Picea sitchensis*. *J Appl Ecol* 20:951–963
- Castro J, Zamora R, Hodar JA, Gomez JM (2005) Alleviation of summer drought boosts establishment success of *Pinus sylvestris* in a Mediterranean mountain: an experimental approach. *Plant Ecol* 181:191–202
- Castro-Díez P, Milla R, Virginia Sanz V (2005) Phenological comparison between two co-occurring Mediterranean woody species differing in growth form. *Flora* 200:88–95
- Cesaraccio C, Spano D, Snyder RL, Duce P (2004) Chilling and forcing model to predict bud-burst of crop and forest species. *Agric Forest Meteorol* 126:1–13
- Cheddadi R, Guiot J, Jolly D (2001) The Mediterranean vegetation: what if the atmospheric CO₂ increased? *Landsc Ecol* 16:667–675
- Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment re-port of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, NY
- Cody ML, Mooney HA (1978) Convergence versus non-convergence in Mediterranean-climate ecosystems. *Annu Rev Ecol Syst* 9:265–321
- Correia OA, Martins AC, Catarino FM (1992) Comparative phenology and seasonal foliar nitrogen variation in Mediterranean species of Portugal. *Ecol Mediterr* 18:7–18
- Cowling RM, Rundel PW, Lamont BB, Arroyo MK, Arianoutsou M (1996) Plant diversity in Mediterranean-climate regions. *Trends Ecol Evol* 11:352–360

- Cubasch U, Meehl GA, Boer GJ, Stouffer RJ, Dix M, Noda A, Senior CA, Raper S, Yap KS (2001) Projections on future climate change. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden P, Dai X, Maskell K, Johnson CI (eds) *Climate change 2001: the scientific basis, contribution of Working Group I to the third assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge
- Davis GW, Richardson DM (1995) *Mediterranean-type ecosystems. The function of biodiversity*. Ecological studies, vol 109. Springer, Berlin
- de Lillis M, Fontanella A (1992) Comparative phenology and growth in different species of the Mediterranean maquis of central Italy. *Vegetatio* 99–100:83–96
- De Luis M, Gonzalez-Hidalgo JC, Raventos J (2003) Effects of fire and torrential rainfall on erosion in a Mediterranean gorse community. *Land Degrad Dev* 14:203–213
- di Castri F (1973) Climatographical comparison between Chile and the western coast of North America. In: di Castri F, Mooney HA (eds) *Mediterranean type ecosystems, origin and structure*. Springer, Berlin/Heidelberg
- di Castri F, Goodall DW, Specht RL (eds) (1981) *Ecosystems of the world: Mediterranean-type shrublands*. Elsevier Scientific Publishing Company, Amsterdam
- Dios Miranda JD, Padilla FM, Pugnaire FI (2009) Response of a Mediterranean semiarid community to changing patterns of water supply. *Perspect Plant Ecol* 11:255–266
- Doi H, Takahashi M (2008) Latitudinal patterns in the phenological response of leaf colouring and leaf fall to climate change in Japan. *Glob Ecol Biogeogr* 17:556–561
- Duce P, Spano D, Asunis C, Cesaraccio C, Sirca C, Motroni A (2000) Effect of climate variability on phenology and physiology of Mediterranean vegetation. In: 3rd European conference on Applied Climatology, Pisa
- Duce P, Cesaraccio C, Spano D, Snyder RL (2002) Weather variability effect on phenological events in a Mediterranean-type climate. In: 15th conference on biometeorology/aero-biology and 16th international congress of biometeorology, Kansas City
- Emberger L (1962) Comment comprendre le territoire phytogéographique méditerranéen français et la position “systématique” de celui-ci. *Nationalia Monspeliensia. Série Botanica* 14:47–54
- Fischlin A, Midgley GF, Price JT, Leemans R, Gopal B, Turley C, Rounsevell MDA, Dube OP, Tarazona J, Velichko AA (2007) In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) *Ecosystems, their properties, goods, and services. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge
- Fried JS, Torn MS, Mills E (2004) The impact of climate change on wildfire severity: a regional forecast for northern California. *Clim Chang* 64:169–191
- Gao XJ, Giorgi F (2008) Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Glob Planet Chang* 62:195–209
- Gao XJ, Pal JS, Giorgi F (2006) Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. *Geophys Res Lett* 33:L03706. doi:10.1029/2005GL024954
- García-de-Lomas J, Cózar A, Dana ED, Hernández I, Sánchez-García Í, García CM (2010) Invasiveness of *Galenia pubescens* (Aizoaceae): a new threat to Mediterranean-climate coastal ecosystems. *Acta Oecol* 36:39–45
- García-Mozo H, Galán C, Aira MJ, Belmonte J, Díaz de la Guardia C, Fernández D, Gutierrez AM, Rodríguez FJ, Trigo MM, Dominguez-Vilches E (2002) Modelling start of oak pollen season in different climatic zones in Spain. *Agric Forest Meteorol* 110:247–257
- García-Mozo H, Chuine I, Aira MJ, Belmonte J, Bermejo D, Díaz de la Guardia C, Elvira B, Gutiérrez M, Rodríguez-Rajo J, Ruiz L, Trigo MM, Tormo R, Valencia R, Galán C (2008) Regional phenological models for forecasting the start and peak of the *Quercus* pollen season in Spain. *Agric Forest Meteorol* 148:372–380

- García-Mozo H, Mestre A, Galán C (2010) Phenological trends in southern Spain: a response to climate change. *Agric Forest Meteorol* 150(4):575–580
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Glob Planet Chang* 63:90–104
- Giorgi F, Bi X, Pal JS (2004) Mean, interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios (2071–2100). *Clim Dyn* 23:839–858
- Goldstein AH, Hultman NE, Fracheboud JM, Bauer MR, Panek JA, Xu M, Qi Y, Guenther AB, Baugh W (2000) Effects of climate variability on the carbon dioxide, water and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). *Agric Forest Meteorol* 101:113–129
- Gordo O, Sanz JJ (2005) Phenology and climate change: a long-term study in a Mediterranean locality. *Oecologia* 146:484–495
- Gordo O, Sanz JJ (2009) Long-term temporal changes of plant phenology in the Western Mediterranean. *Glob Chang Biol* 15:1930–1948
- Gordo O, Sanz JJ (2010) Impact of climate change on plant phenology in Mediterranean ecosystems. *Glob Chang Biol* 16:1082–1106
- Graciano C, Guiamet JJ, Goya JF (2005) Impact of nitrogen and phosphorus fertilization on drought responses in *Eucalyptus grandis* seedlings. *Forest Ecol Manag* 212:40–49
- Gratani L, Varone L (2004) Leaf key traits of *Erica arborea* L., *Erica multiflora* L. and *Rosmarinus officinalis* L. co-occurring in the Mediterranean maquis. *Flora* 199:58–69
- Gritti ES, Smith B, Sykes MT (2006) Vulnerability of Mediterranean Basin ecosystems to climate change and invasion by exotic plant species. *J Biogeogr* 33:145–157
- Gulmon SL (1977) A comparative study of grasslands of California and Chile. *Flora* 166:261–278
- Hanes TL (1981) California chaparral. In: di Castri F, Goodall DW, Specht RL (eds) *Eco-systems of the world: Mediterranean-type shrublands*. Elsevier Scientific Publishing Company, Amsterdam
- Hänninen H (1990) Modeling bud dormancy release in trees from cool and temperate regions. *Acta For Fenn* 213:1–47
- Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Cahill KN, Cleland EE, Dale L, Drapek R, Hanemann RM, Kalkstein LS, Lenihan J, Lulich CK, Neilson RP, Sheridan SC, Verville JH (2004) Emissions pathways, climate change, and impacts on California. *Proc Natl Acad Sci U S A* 101:12422–12427
- Hollister RD, Webber PJ, Tweedie CE (2005) The response of Alaskan arctic tundra to experimental warming: differences between short- and long-term responses. *Glob Chang Biol* 11:525–536
- Holmgren M, Stapp P, Dickman CR et al (2006) Extreme climatic events shape arid and semiarid ecosystems. *Front Ecol Environ* 4:87–95
- Houghton JT, Ding Y, Griggs DJ, Noguer M, Van der Linden PJ, Xiaosu D (2001) Climate change 2001: the scientific basis. Contribution of Working Group I to the third assessment report of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge
- Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Synthesis report, contribution of Working Groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change*. IPCC, Geneva
- Intergovernmental Panel on Climate Change, McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) (2001) *Climate change 2001: impacts, adaptation and vulnerability*. Cambridge University Press, Cambridge
- International Union for the Conservation of Nature (1999) *Biological diversity of dry land, Mediterranean, arid, semiarid, savanna, and grassland ecosystems*, World Conservation Union: fourth meeting of subsidiary body on scientific, technical, and technological advice, Montreal
- Jato V, Rodríguez-Rajo FJ, Aira MJ (2007) Use of *Quercus ilex* subsp. *ballota* and pollen-production data for interpreting *Quercus* pollen curves. *Aerobiologia* 23:91–105

- Jensen KD, Beier C, Michelsen A, Emmett BA (2003) Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. *Appl Soil Ecol* 24:165–176
- Joffre R, Rambal S (2002) Mediterranean ecosystems. In: *Encyclopedia of life sciences*. Wiley, Chichester. <http://www.els.net>. doi: 10.1038/npg.els.0003196
- Joffre R, Rambal S, Ratte JP (1999) The dehesa system of southern Spain and Portugal as a natural ecosystem mimic. *Agrofor Syst* 45:57–79
- Körner C, Sarris D, Christodoulakis D (2005) Long-term increase in climatic dryness in the East Mediterranean as evidenced for the island of Samos. *Reg Environ Chang* 5:27–36
- Kozlowski TT, Pallardy SG (1997) *Physiology of woody plants*. Academic, San Diego
- Kramer K (1994) Selecting a model to predict the onset of growth of *Fagus sylvatica*. *J Appl Ecol* 31:172–181
- Kramer K, Leinonen I, Loustau D (2000) The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forest ecosystems: an overview. *Int J Biometeorol* 44:67–75
- Kummerow J (1981) Structure of roots and root systems. In: Di Castri F, Goodall DW, Specht RL (eds) *Ecosystems of the world – Mediterranean-type shrublands*. Elsevier, Amsterdam
- Kuzucuoglu C (1989) Fires in Mediterranean region. *Blue Planet Ecol* 72:371–412
- Lenihan JM, Drapek R, Bachelet D, Neilson RP (2003) Climate change effects on vegetation distribution, carbon, and fire in California. *Ecol Appl* 13:1667
- Llorens L, Penuelas J (2005) Experimental evidence of future drier and warmer conditions affecting flowering of two co-occurring Mediterranean shrubs. *Int J Plant Sci* 166:235–245
- Llorens L, Penuelas J, Estiarte M (2003) Ecophysiological responses of two Mediterranean shrubs, *Erica multiflora* and *Globularia alypum*, to experimentally drier and warmer conditions. *Physiol Plant* 119:231–243
- Llorens L, Penuelas J, Estiarte M, Bruna P (2004) Contrasting growth changes in two dominant species of a Mediterranean shrubland submitted to experimental drought and warming. *Ann Bot* 94:843–853
- Malcolm JR, Markham A, Neilson RP, Garaci M (2002) Estimated migration rates under scenarios of global climate change. *J Biogeogr* 29:835–849
- Manes F, Capogna F, Puppi G, Vitale M (2002) Ecophysiological characterization of *Phyllirea angustifolia* L. and response of sprouts to different fire disturbance intensities. In: Trabaud L, Prodon R (eds) *Fire and biological processes*. Backhuys Publishers, Leiden
- Martinez-Vilalta J, Pinol J (2002) Drought-induced mortality and hydraulic architecture in pine populations of the NE Iberian Peninsula. *Forest Ecol Manag* 161:247–256
- Matias L, Castro J, Zamora R (2011) Soil nutrient availability under a global change scenario in a Mediterranean mountain ecosystem. *Glob Chang Biol* 17:1646–1657
- Mendoza I, Zamora R, Castro J (2009) A seeding experiment for testing tree-community recruitment under variable environments: implications for forest regeneration and conservation in Mediterranean habitats. *Biol Conserv* 142:1491–1499
- Menzel A, Estrella N, Testka A (2005) Temperature response rates from long-term phenological records. *Clim Res* 30:21–28
- Menzel A, Sparks TH, Estrella N et al (2006) European phenological response to climate change matches the warming pattern. *Glob Chang Biol* 12:1969–1976
- Midgley GF, Chapman RA, Hewitson B, Johnston P, De Wit M, Ziervogel G, Mukheibir P, Van Niekerk L, Tadross M, Van Wilgen BW, Kgope B, Morant PD, Theron A, Scholes RJ, Forsyth GG (2005) A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the western Cape. Report to the Western Cape Government, Cape Town, South Africa. CSIR Report No. ENV-S-C 2005–073, CSIR Environmentek, Stellenbosch
- Milla R, Castro-Díez P, Montserrat-Martí G (2010) Phenology of Mediterranean woody plants from NE Spain: synchrony, seasonality, and relationships among phenophases. *Flora* 205:190–199

- Minnich RA (1983) Fire mosaics in southern California and northern Baja California. *Science* 219:1287–1294
- Miranda P, Coelho FES, Tomé AR, Valente MA (2002) 20th century Portuguese climate and climate change scenarios. In: Santos FD, Forbes K, Moita R (eds) *Climate change in Portugal. Scenarios, impacts and adaptation measures*. Gradiva, Lisboa
- Moll EJ (1987) Phenology of Mediterranean plants in relation to fire season: with special reference to the Cape Province South Africa. In: Tenhunen JD, Catarino FM, Lange OL, Oechel WC (eds) *Plant response to stress: functional analysis in Mediterranean ecosystems*, NATO Adv Sci Inst Ser G Ecol Sci. Springer, Berlin/Heidelberg
- Moll EJ, Campbell BM, Cowling RM, Bossi L, Karman ML, Boucher C (1984) A description of major vegetation categories in and adjacent to the Fynbos biome. Report No. 83, S Afr Nat Sci Program
- Montenegro G (1987) Quantification of Mediterranean plant phenology and growth. In: Tenhunen JD, Catarino FM, Lange OL, Oechel WC (eds) *Plant response to stress: functional analysis in Mediterranean ecosystems*, NATO Adv Sci Inst Ser G Ecol Sci. Springer, Berlin/Heidelberg
- Mooney HA, Conrad CE (1977) Symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystem. USDA Forest Service General, Technical report WO-3, U.S. Government Printing Office
- Mooney HA, Kummerow J (1981) Phenological development of plants in Mediterranean climate regions. In: di Castri F, Goodall DW, Specht RL (eds) *Ecosystems of the world: Mediterranean-type shrublands*. Elsevier Scientific Publishing Company, Amsterdam
- Mooney HA, Johnson A, Parson D, Keeley S, Hoffman A, Hays R, Giliberto J, Chu C (1977) The producers-their resources and adaptive response. In: Mooney HA (ed) *Convergent evolution in Chile and California Mediterranean climate ecosystems*. Dowden Hutchinson & Ross, Stroudsburg
- Morin X, Roy J, Sonié L, Chuine I (2010) Changes in leaf phenology of three European oak species in response to experimental climate change. *New Phytol* 186(4):900–910
- Mouillot F, Rambal S, Joffre R (2002) Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Glob Chang Biol* 8:423–437
- Mouillot F, Ratte JP, Joffre R, Moreno JM, Rambal S (2003) Some determinants of the spatio-temporal fire cycle in a Mediterranean landscape (Corsica, France). *Landsc Ecol* 18:665–674
- Munné-Bosch S, Nogués S, Alegre L (1999) Diurnal variations of photosynthesis and dew absorption by leaves in two evergreen shrubs growing in Mediterranean field conditions. *New Phytol* 144:109–119
- Mutke S, Gordo J, Climent J, Gil L (2003) Shoot growth and phenology modeling of grafted stone pine (*Pinus pinea* L.) in inner Spain. *Ann Forest Sci* 60:527–537
- Naveh Z (1990) Fire in the Mediterranean: a landscape perspective. In: Goldammer JG, Jenkins MJ (eds) *Fire in ecosystem dynamics*. SPB Academic Publ, The Hague
- Oechel WC, Moreno MJ (1994) *The role of fire in Mediterranean ecosystems*. Springer, Berlin/Heidelberg
- Ogaya R, Peñuelas J (2004) Phenological patterns of *Quercus ilex*, *Phillyrea latifolia*, and *Arbutus unedo* growing under a field experimental drought. *Ecoscience* 11:263–270
- Ogaya R, Peñuelas J (2007) Tree growth, mortality, and above-ground biomass accumulation in a holm oak forest under a five-year experimental field drought. *Plant Ecol* 189:291–299
- Orshan G (1989) *Plant pheno-morphological studies in Mediterranean type ecosystems*. Kluwer Acad Pub, Dordrecht
- Osborne CP, Chuine I, Viner D, Woodward FI (2000) Olive phenology as a sensitive indicator of future climatic warming in the Mediterranean. *Plant Cell Environ* 23:701–710
- Ovalle C, Aronson J, Del Pozo A, Avendano J (1990) The espinal: agroforestry system of the Mediterranean-type climate region of Chile. *Agrofor Syst* 10:213–239
- Ovalle C, Aronson J, Del Pozo A, Avendano J (1996) Land occupation patterns and vegetation structure of the anthropogenic savannas (espinales) of central Chile. *For Ecol Manage* 86:129–139

- Parry ML (ed) (2000) Assessment of potential effects and adaptations to climate change in Europe: the Europe Acacia Project. Report of concerted action of the environment programme of the Research Directorate General of the Commission of the European Communities, Jackson Environmental Institute, University of East Anglia, Norwich
- Pausas JG, Abdel Malak D (2004) Spatial and temporal patterns of fire and climate change in the eastern Iberian Peninsula (Mediterranean Basin). In: Arianoutsou M, Papanastasis VP (eds) Ecology, conservation and management of Mediterranean climate ecosystems of the world. 10th international conference on Mediterranean climate ecosystems, Rhodes, Greece. Millpress, Rotterdam
- Pellizzaro G, Cesaraccio C, Duce P, Ventura A, Zara P (2007) Relationships between seasonal patterns of live fuel moisture and meteorological drought indices for Mediterranean shrubland species. *Int J Wildland Fire* 16:232–241
- Peñuelas J (2001) Cambios atmosféricos y climáticos y sus consecuencias sobre el funcionamiento y la estructura de los ecosistemas terrestres mediterráneos. In: Zamora R, Pugnaire FI (eds) Ecosistemas mediterráneos Análisis funcional. CSIC-AEET Press, Granada
- Peñuelas J, Boada M (2003) A global change-induced biome shift in the Montseny mountains (NE Spain). *Glob Chang Biol* 9:131–140
- Peñuelas J, Filella I (2001) Responses to a warming world. *Science* 294:793–795
- Peñuelas J, Filella I, Comas P (2002) Changed plant and animal life cycles from 1952 to 2000 in the Mediterranean region. *Glob Chang Biol* 8:532–544
- Peñuelas J, Filella I, Zhang X, Llorens L, Ogaya R, Lloret F, Comas P, Estiarte M, Terradas J (2004) Complex spatiotemporal phenological shifts as a response to rainfall changes. *New Phytol* 161:837–846
- Peñuelas J, Prieto P, Beier C, Cesaraccio C, De Angelis P, De Dato G, Emmett BA, Estiarte M, Garadnai J, Gorissen A, Kovács-Láng E, Kröel-Dulay G, Llorens L, Pellizzaro G, Riis-Nielsen T, Schmidt IK, Sirca C, Sowerby A, Spano D, Tietema A (2007) Response of plant species richness and primary productivity in shrublands along a north–south gradient in Europe to seven years of experimental warming and drought. Reductions in primary productivity in the heat and drought year of 2003. *Glob Chang Biol* 13:2563–2581
- Peñuelas J, Lloret F, Montoya R (2001) Severe drought effects on mediterranean woody flora in Spain. *Forest Sci* 47:214–218
- Pereira JS, Beyschlag G, Lange OL, Beyschlag W, Tenhunen JD (1987) Comparative phenology of four Mediterranean shrub species growing in Portugal. In: Plant response to stress: functional analysis in Mediterranean ecosystems, NATO Adv Sci Inst Ser G Ecol Sci. Springer, Berlin/Heidelberg
- Pinto CA, Henriques MO, Figueiredo JP, David JS, Abreu FG, Pereira JS, Correia I, David TS (2011) Forest phenology and growth dynamics in Mediterranean evergreen oaks: effects of environmental conditions and water relations. *Ecol Manag* 262(3):500–508
- Prieto P (2007) Phenology, biomass and community composition changes in a Mediterranean shrubland submitted to experimental warming and drought. Dissertation, Universitat Autònoma de Barcelona, Barcelona
- Prieto P, Peñuelas J, Niinemets Ü, Ogaya R, Schmidt IK, Beier C, Tietema A, Sowerby A, Emmett BA, Kovács Láng E, Kröel-Dulay G, Lhotsky B, Cesaraccio C, Pellizzaro G, de Dato G, Sirca C, Estiarte M (2009) Changes in the onset of spring growth in shrubland species in response to experimental warming along a north–south gradient in Europe. *Glob Ecol Biogeogr* 18:473–484
- Quezel P (1977) Forests of the Mediterranean basin. In: Mediterranean forests and maquis: ecology conservation and management. UNESCO, Paris
- Rambal S, Ourcival JM, Joffre R, Mouillot F, Nouvellon Y, Reichstein M, Rocheteau A (2003) Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: scaling from leaf to canopy. *Glob Chang Biol* 9:1813–1824
- Ramos MC, Martínez-Casasnovas JA (2004) Nutrient losses from a vineyard soil in North-eastern Spain caused by an extraordinary rainfall event. *Catena* 55:79–90

- Reichstein M, Tenhunen JD, Rouspard O, Ourcival JM, Rambal S, Miglietta F, Peressotti A, Pecchiari M, Tirone G, Valentini R (2002) Severe drought effects on ecosystem CO₂ and H₂O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? *Glob Chang Biol* 8:999–1017
- Rodrigo FS (2002) Changes in climate variability and seasonal rainfall extremes: a case study from San Fernando (Spain), 1821–2000. *Theor Appl Climatol* 72:193–207
- Rossiter RC, Ozanne PG (1970) South-western temperate forests, woodlands and heaths. In: Moore RM (ed) *Australian grassland*. Australian National University Press, Canberra
- Rundel PW (1981) The matorral zone of central Chile. In: di Castri F, Goodall DW, Specht RL (eds) *Ecosystems of the world: Mediterranean-type shrublands*. Elsevier Scientific Publishing Company, Amsterdam
- Rundel PW (1983) Impact of fire on nutrient cycles in Mediterranean-type ecosystems, with reference to chaparral. In: Kruger FJ, Mitchell DT, Jarvis JUM (eds) *Mediterranean-type ecosystems: the role of nutrients*. Springer, Berlin/Heidelberg
- Rundel PW (1995) Adaptive significance of some morphological and physiological characteristics in Mediterranean plants: facts and fallacies. In: Roy J, Aronson J, di Castri F (eds) *Time scales of biological responses to water constraints: the case of Mediterranean biota*. SPB Academic Publishers, Amsterdam
- Rundel PW (1998) Landscape disturbance in Mediterranean-type ecosystems: an overview. In: Rundel PW, Montenegro G, Jaksic FM (eds) *Ecological studies: landscape degradation and biodiversity in Mediterranean-type ecosystems*. Springer, Berlin/Heidelberg
- Rundel PW (2007) Mediterranean-climate ecosystems. In: Levin S (ed) *Encyclopedia of biodiversity*. Academic, Elsevier
- Rundel PW, Vankat JL (1989) Chaparral communities and ecosystems. In: Keeley S (ed) *The California chaparral: paradigms reexamined*. Los Angeles County Museum of Natural History, Los Angeles
- Sala OE, Chapin IFS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DH, Mooney HA, Oesterheld M, Leroy Poff N, Sykes MT, Walker BH, Walker M, Wall DH (2000) Global biodiversity scenarios for the year 2100. *Science* 287:1770–1774
- Sanz-Pérez V, Castro-Díez P, Valladares F (2009) Differential and interactive effects of temperature and photoperiod on budburst and carbon reserves in two co-occurring Mediterranean oaks. *Plant Biol* 11(2):142–151
- Sardans J, Penuelas J (2004) Increasing drought decreases phosphorus availability in an evergreen Mediterranean forest. *Plant Soil* 267:367–377
- Sardans J, Penuelas J (2007) Drought changes phosphorus and potassium accumulation patterns in an evergreen Mediterranean forest. *Funct Ecol* 21:191–201
- Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim Dyn* 31:79–105
- Simões MP, Madeira M, Gazarini L (2008) The role of phenology, growth and nutrient re-tention during leaf fall in the competitive potential of two species of Mediterranean shrubs in the context of global climate changes. *Flora* 203:578–589
- Somot S, Sevault F, Deque M, Crepon M (2008) 21st century climate change scenario for the Mediterranean using a couple atmosphere ocean regional climate model. *Glob Planet Chang* 63:112–126
- Spano D, Cesaraccio C, Duce P, Snyder RL (1999) Phenological stages of natural species and their use as climate indicators. *Int J Biometeorol* 42:124–133
- Specht RL (1973) Structure and functional response of ecosystems in the Mediterranean climate of Australia. In: di Castri F, Mooney HA (eds) *Mediterranean-type ecosystems, origin and structure*. Springer, Berlin/Heidelberg
- Specht RL (1979) *Ecosystems of the world: heathlands and related shrublands*. Elsevier, Amsterdam

- Specht RL (1981) Mallee ecosystem in southern Australia. In: Castri F, Goodall DW, Specht RL (eds) *Mediterranean-type shrublands*. Elsevier, Amsterdam
- Tenhunen JD, Catarino FM, Lange OL, Oechel WC (1987) Plant response to stress: functional analysis in Mediterranean ecosystems. NATO Adv Sci Inst Ser G Ecol Sci. Springer, Berlin/Heidelberg
- Thomas CD, Williams SE, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Philipps OL (2004) Biodiversity conservation: uncertainty in predictions of extinction risk/effects of changes in climate and land use/climate change and extinction risk (reply). *Nature* 430:34
- Thrower NJW, Bradbury DE (1973) The physiography of the Mediterranean lands with special emphasis on California and Chile. In: di Castri F, Mooney HA (eds) *Mediterranean-type ecosystems, origin and structure*. Springer, Berlin/Heidelberg
- Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC (2005) Climate change threats to plant diversity in Europe. *Proc Natl Acad Sci U S A* 102:8245–8250
- Trabaud L, Prodon R (1993) Fire in Mediterranean ecosystems. Commission of European Communities, Brussels
- Tryjanowski P, Panek M, Sparks TH (2006) Phenological response of plants to temperature varies at the same latitude: case study of dog violet and horse chestnut in England and Poland. *Clim Res* 32:89–93
- Valladares F, Vilagrosa A, Peñuelas J, Ogaya R, Camarero JJ, Corcuera L, Siso S, Gil Pelegrin E (2004) Estres hídrico: ecofisiología y escalas de la sequía. In: Valladares F (ed) *Ecología del bosque mediterráneo en un mundo cambiante*. Ministerio de Medio Ambiente, EGRAF, S.A, Madrid
- Viegas DX, Viegas MT, Ferreira AD (1992) Moisture content of fine forest fuels and fire occurrence in central Portugal. *Int J Wildland Fire* 2:69–86
- Viegas DX, Piñol J, Viegas MT, Ogaya R (2001) Estimating live fine fuels moisture content using meteorologically-based indexes. *Int J Wildland Fire* 10:223–240
- Zinke PJ (1973) Analogies between the soil and vegetation types in Italy, Greece and California. In: di Castri F, Mooney HA (eds) *Mediterranean-type ecosystems, origin and structure*. Springer, Berlin/Heidelberg