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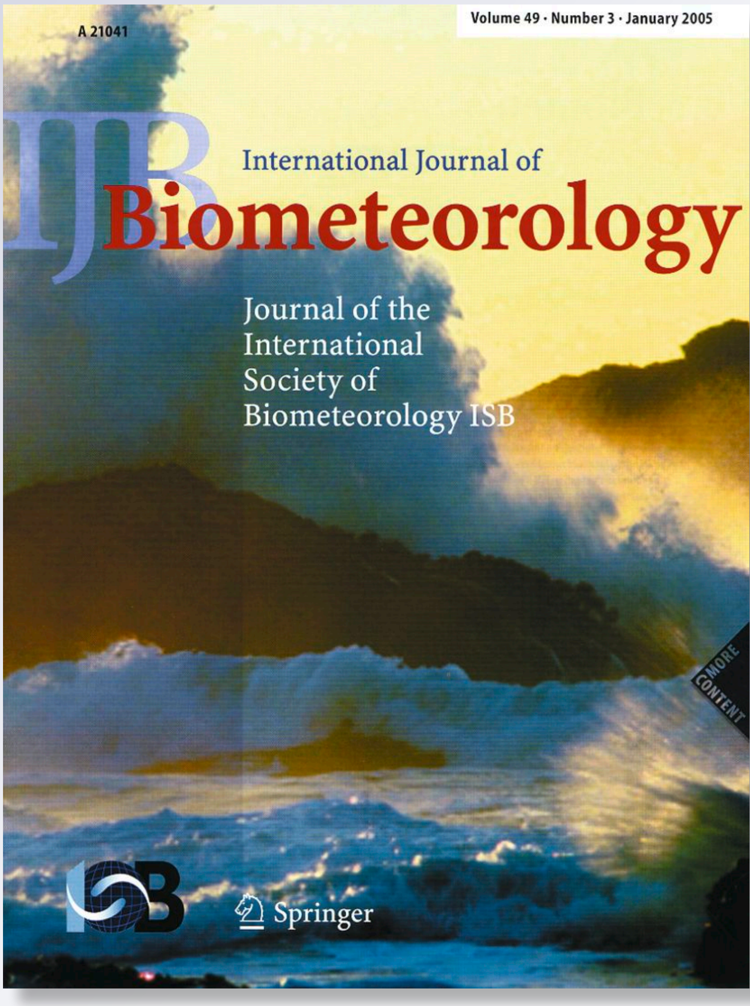

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ORIGINAL PAPER

Modifying rainfall patterns in a Mediterranean shrubland: system design, plant responses, and experimental burning

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Abstract Global warming is projected to increase the frequency and intensity of droughts in the Mediterranean region, as well as the occurrence of large fires. Understanding the interactions between drought, fire and plant responses is therefore important. In this study, we present an experiment in which rainfall patterns were modified to simulate various levels of drought in a Mediterranean shrubland of central Spain dominated by *Cistus ladanifer*, *Erica arborea* and *Phillyrea angustifolia*. A system composed of automatic rainout shelters with an irrigation facility was used. It was designed to be applied in vegetation 2 m tall, treat relatively large areas (36 m^2), and be quickly dismantled to perform experimental burning and reassembled back again. Twenty plots were subjected to four rainfall treatments from early spring: natural rainfall, long-term average rainfall (2 months drought), moderate drought (25% reduction from long-term rainfall, 5 months drought) and severe drought (45% reduction, 7 months drought). The plots were burned in late summer, without interfering with rainfall manipulations. Results indicated that rainfall manipulations caused differences in soil moisture among treatments, leading to reduced water availability and growth of *C. ladanifer* and *E. arborea* in the drought treatments. However, *P. angustifolia* was not affected by the manipulations. Rainout shelters had a negligible impact on plot microenvironment. Experimental burns were of high fire intensity, without differences among treatments. Our system provides a tool to study the combined effects of drought and fire on vegetation, which is important to assess the threats posed by climate change in Mediterranean environments.

Keywords Climate change · Drought · Fire · Plant growth · Rainout shelter · Water availability

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Introduction

Global warming is anticipated to alter the hydrological cycle in the Mediterranean region (Mariotti et al. 2008). Climate change models project a reduction in total precipitation and in the number of rainy days per year, with rainfall concentrating in fewer, but more intense events towards the winter months (Christensen et al. 2007). Therefore, the duration and intensity of the dry season is expected to increase. In addition, droughts are recurrent in the region (Lana et al. 2008), and are also expected to increase (Giorgi and Lionello 2008). Reduced water availability in combination with higher temperatures will result in increased length and severity of the fire season (Moreno et al. 2010; Moriondo et al. 2006). In fact, when the combination of water scarcity

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and high temperatures occurs at extreme values, multiple large fire episodes can be triggered, burning extensive areas at country level, as it happened in Spain in 1994 (Moreno et al. 1998), Portugal in 2003 (Trigo et al. 2006), or Greece in 2007 (Founda and Giannakopoulos 2009). Therefore, the potential impacts of the interactions between drought and fire can be substantial. Understanding these interactions is vital for assessing the impacts of climate change on Mediterranean ecosystems.

In fire-prone areas, drought, fire and plant regeneration strategy are closely interlinked. Plant regeneration after fire occurs by vegetative regrowth (resprouters) or seed germination (seeders) (Bond and van Wilgen 1996). The two plant functional groups exhibit varied responses to drought, either as established individuals or while establishing after fire. Drought can cause adult plant mortality and its impacts are usually higher in seeder species, which have shallower root systems than resprouter species (Bell et al. 1996; Keeley 1986; Silva et al. 2002). Following fire, seedling emergence and recruitment in seeders are also closely tied to rainfall, particularly during the first post-fire year (Quintana et al. 2004; Moreno et al. 2011). By contrary, the post-fire regeneration of resprouter species is not so closely tied to rainfall, due to their capacity to access deep-water sources by deep root systems, and reduced transpiration during the early stages after fire (Cruz 1996). Consequently, coexisting seeder and resprouter species can be differentially affected by drought and fire. However, the response of these functional plant groups to the combined effect of both factors remains poorly understood.

Understanding plant responses to changes in rainfall patterns and drought is of primary interest for ecologists. Numerous observation-based studies (e.g. Bendix et al. 2006; Bullock 1997) have been traditionally conducted, but they rest on the occurrence of a phenomenon that is not controlled by the experimenter. Hence, an increasing number of studies address this problem by experimentally manipulating water availability under laboratory, greenhouse (e.g. Briede and McKell 1992; Fernandez and Reynolds 2000), or field conditions (e.g. Fay et al. 2000; Yahdjian and Sala 2002).

Rainfall manipulations in the field are carried out by using rainout shelters, which are structures that exclude rain when it is undesired. Shelter design has evolved over time to improve effectiveness in excluding rain and reduce the influence on microenvironmental variables, such as light, temperature, humidity, and wind. Rainout shelters can be classified as fixed or mobile, depending on whether the shelter is permanent or not, respectively, in the latter case being displayed when desired. Fixed rainout shelters are designed to completely cover a study area with plastic roofs (e.g. Borken et al. 2006; Gilgen and Buchmann 2009; Weltzin and McPherson 2000), or partially with plastic strips (e.g. Cleveland et al. 2010; Limousin et al. 2008; Yahdjian and Sala 2002). The completely covered systems allow total exclusion of rainfall, but they exert the largest microenvironmental effects. The partially covered systems reduce microenvironmental alterations, but they can only achieve partial rainfall exclusion. Mobile rainout shelters (e.g. Bates et al. 2005; Beier et al. 2004; Peñuelas et al. 2004) allow a complete exclusion of rainfall, covering the study plots only during undesired rain events, thus minimizing microenvironmental effects. However, mobile systems are usually more expensive and complex to operate than fixed systems, since they commonly require electricity to move the shelters, with the difficulties it entails for its use in remote locations. Furthermore, this type of system, except in Misson et al. (2011), has usually been applied to small plots (up to 20 m^2), suitable only for grasslands and short stature scrubs.

To better control the timing and magnitude of dry and wet periods, independently from natural rainfall patterns, some rainout systems incorporate an irrigation system (e.g. English et al. 2005; Fay et al. 2000; Fiala et al. 2009). These irrigation systems can be an advantage to solve the fact that control treatments (i.e., natural rain during a given period) can be difficult to interpret if the period under investigation deviates substantially from the long-term average rainfall. This can be common in ecosystems where the inter-annual variability of rainfall is very high, such as the Mediterranean and other semiarid regions (Lionello et al. 2006). Despite the sizeable number of experimental studies addressing drought impacts on vegetation, manipulative field studies that combine drought and subsequent burning have not yet been performed, neither in the Mediterranean nor in other fire-driven ecosystems. Indeed, the logistics of manipulating in the field these two factors together are challenging.

In this study, we describe a manipulative experiment in which rainfall patterns were modified before and after conducting an experimental burning in a Mediterranean shrubland of Central Spain. Rainfall manipulation was carried out with a set of mobile rainout shelters that, when desired, automatically unfolded over the study plots in response to rain. In addition, an irrigation system was incorporated, which allowed a finer control of the water falling onto the plots, plus establishing a treatment that simulated long-term average precipitation in the area. The structure was designed to treat vegetation up to 2 m in height, plots of 36 m^2, and be quickly dismantled for experimental burning and reassembled back again. The aims of this work were: to analyze the effectiveness of the rainfall manipulation system and its effects on plot soil moisture and microenvironment, to study some relevant responses of different functional groups of plants (seeders and resprouters) to drought before burning, and to report the fire characteristics of the burnings

conducted at the end of summer, subsequent to six months of drought implementation.

Materials and methods

Study site and experimental design

The study was conducted at the Coto Nacional de Quintos de Mora (Los Yébenes, Toledo; 39º25' N, 4º04' W) in Central Spain. The study area is located on a NW-facing 20% slope, at an altitude of 900 m. The region is characterized by a continental Mediterranean climate, with long, dry, and warm summers. Mean annual temperature is 14.9°C, with large daily and seasonal fluctuations. Mean annual rainfall is 622 mm (7% in summer, 31% in autumn, 29% in spring, and 33% in winter), with high inter-annual variability but usually with two or three months of summer drought (1948-2006 "Los Cortijos" meteorological station; 39º19' N, 4º04' W; AEMET, Ministerio de Medio Ambiente, Medio Rural y Marino, Spain).

The study area is covered by a Mediterranean shrubland. Mean vegetative cover is 72%; *Cistus ladanifer* L. (Cistaceae, 36% cover) dominates the plant community. Other important woody species include *Erica arborea* L. (Ericaceae, 17% cover), *Phillyrea angustifolia* L. (Oleaceae, 14%), *Erica scoparia* L. (Ericaceae, 12%), and *Rosmarinus officinalis* L. (Lamiaceae, 11%). Soil texture is sandy loam (68, 18, and 14% sand, silt and clay, respectively), with a high proportion of rock (40%), 5.8% organic matter, 6.5 pH, and 11.5 C:N ratio (Laboratorio Agroalimentario Regional de Albacete; Consejería de Agricultura y Medio Ambiente de Castilla-La Mancha, Spain).

The stand (100 m×75 m) was initially fenced to prevent large ungulate damage, and twenty 6 m x 6 m plots were selected. The plots were assigned to five treatments (four plots per treatment), following a randomized, complete block design, with four blocks arranged parallel to the slope (Fig. 1). Plots were subjected to rainfall manipulations as described below from early spring (late March, 2009), and were burned at the end of summer (late September). One plot per block was left as unmanipulated and unburned control (Fig. 1), and was not considered in this study.

Rainout shelters and watering system design

A 6 m×6 m aluminum frame (0.1 m width) was installed in all rainfall manipulation plots 2 m above ground. Four aluminum posts (2.0 m×0.1 m×0.05 m) supported the frame, each inserted 0.4 m into the soil within a cement foundation. Two aluminum beams (2.0 m×0.1 m×0.05 m) were placed at the top of the frame every 2 m, to increase frame stability, allow movement of the shelter, and support the irrigation system (Supplementary Fig. 1). The irrigation system was comprised of four sprayers (90º range) located at the corners of the frame, and one (360º range) at the center of the plot. Analogical counters measured the incoming water in each plot (Supplementary Fig. 1). Water for irrigation was pumped through a pipeline system by a hydraulic pressure bomb from four containers (10,000 L of total storage) located on one side of the stand (Fig. 1).

A 6 m×6 m single transparent PVC sheet (2 mm thick) without UV filter was installed on top of each base structure. The PVC shelters unfold and fold by sliding through rails along the aluminum beams, driven by an electric motor placed on the north side of the frame (Supplementary Fig. 1). Complete shelter unfolding occurred automatically after a few raindrops moistened a stainless steel sensor (Regenfühler; SOMFY S.A.S., Cluses, France) that activated the motor. Since the rainfall sensor could make the shelters open and close intermittently in case of variable weather, and therefore cause system failures, we decided to keep the shelters unfolded during 6 hours after each rainfall event, as in other similar studies (Misson et al. 2011). Following this fixed period of time, the shelters entered again into an automatic operation mode. Energy was supplied by solar panels, with a gasoline motor for back-up (Fig. 1). The correct functioning of the system was verified by a lap counter in the motors, which allowed us to know if the shelters had unfolded in response to a given rainfall event. All the information was available online, so that at any time it was possible to check the correct functioning of the system.

A gutter (0.2 m wide×0.1 m deep) installed on the down slope side of each structure drained the rain collected by the shelter, and channeled the water out of the plot by means of the corresponding tubing system (Supplementary Fig. 1). Surface run-off water flowing towards the plot was diverted by forming an arch with three galvanized iron sheets (2 m× 0.50 m each), which were buried 20 cm deep on the upslope side of the structure (Supplementary Fig. 1). The large rock content of the site prevented us from digging deeper. Thus, down slope, subsurface run-off could not be ruled out completely. However, temporal monitoring of soil moisture indicated that this was not a problem. Edge effects were limited in the study by considering only the central 5 m×5 m area within the 6 m×6 m area covered by the shelters.

Rainfall manipulation

Rainfall manipulation treatments were established based on the long-term (1948–2006) precipitation records from the meteorological station at "Los Cortijos". First, we calculated the long-term average precipitation for each two-week period during the year, excluding extreme values (99th percentile) of the data series. Second, we designed a biweekly

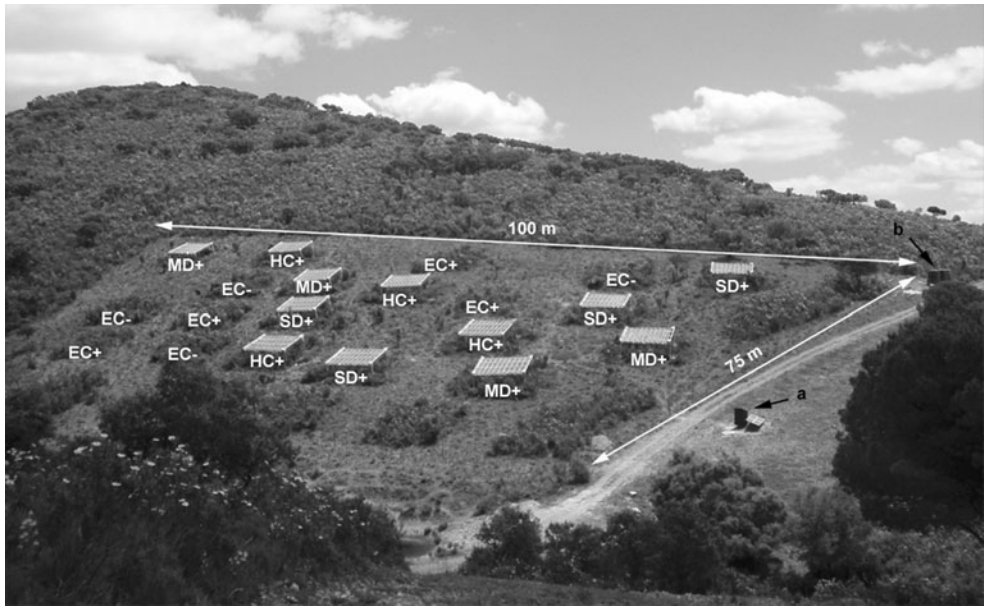

Fig. 1 Stand view showing the experimental setup. The plots were subjected to the following treatments: environmental control (EC), historical control (HC), moderate drought (MD), and severe drought (SD). The areas between plots were cleared prior to the experimental fire in September 2009. Symbols+and – represent burned and unburned plots, respectively. **a** Solar panel connected to an electric accumulator. **b** Water containers for irrigation

rainfall schedule for each treatment by modifying the historical long-term rainfall pattern as follows (Fig. 2): (i) environmental control (EC)—no change in the natural rainfall pattern (426 mm fell during 2009); (ii) historical control (HC)—simulate the long-term rainfall pattern (600 mm/year was the target set), with two months of rainfall exclusion during July and August (62 days of drought); (iii) moderate drought (MD)—25% decrease in rainfall relative to HC treatment (450 mm/year), five months of drought from May to September (153 days); (iv) severe drought (SD)—45% decrease in rainfall relative to HC treatment (325 mm/year), seven months of drought from April to October (214 days).

The simulated rainfall patterns were consistent with projections for the Mediterranean region (Christensen et al. 2007), i.e., lengthened summer drought and precipitation concentrated in winter (Fig. 2). We reached the target rainfall for each treatment by excluding rainfall from the plots (once natural rainfall had reached the established level) or watering them (if natural rainfall was lower than established) in the last days of each biweekly period. This approach was chosen to maximize the input of natural rainfall, and minimize rainout shelter effects on the microenvironment of the plots.

Microenvironment and soil water content

The effect of the rainout shelters on the plot microenvironment was tested by measuring photosynthetic photon flux density (PPFD), air temperature (T), air relative humidity (RH), and air vapor pressure deficit (VPD) during one complete day in winter and spring. The measurements were conducted at these two periods of the year because it is

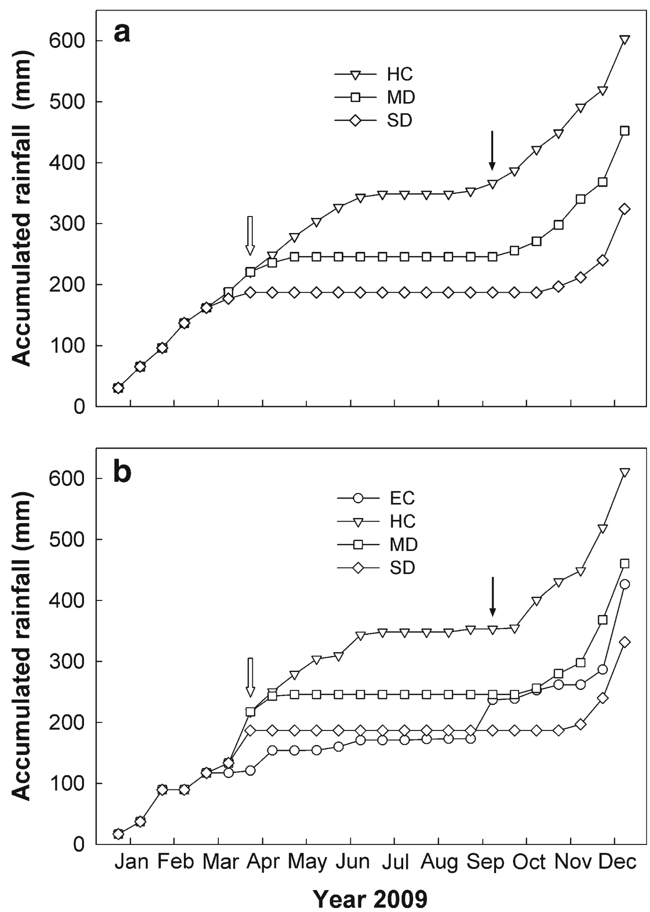

Fig. 2 Biweekly programmed accumulated rainfall (**a**) and biweekly actual accumulated rainfall (**b**) during 2009 for the various treatments: environmental control (EC), historical control (HC), moderate drought (MD), and severe drought (SD). The *white arrow* indicates the beginning of the experimental manipulation, and the *black arrow* indicates the date of the experimental burning

when rainfall is most frequent in the study area (62% of annual rainfall), i.e. when the shelters more often come into operation and present contrasting values of temperature and solar radiation. PPFD was measured with a quantum flux sensor (HD 9021 RAD/PAR; Delta OHM S.R.L., Padova, Italy) at three equidistant positions above and underneath each shelter (12 plots) at midday solar time. T and RH were measured each hour with sensors connected to a data logger (HOBO Pro v2 Temp/RH Data Logger (U23-001); Onset Computer Corporation, Bourne, MA, USA) at the center of each plot, and 1 m above ground (mean canopy vegetation height). Mean day and night T and VPD (estimated from T and RH values; Monteith and Unsworth 2008) were compared in folded (or not sheltered) and unfolded (sheltered) conditions (eight plots per condition).

Volumetric soil water content (θ) was measured using a time-domain reflectometer (TDR 100; Campbell Scientific Inc., Logan, UT, USA). Four 0.15-m long probes were installed at the corners and center of each plot. The dielectric constant was converted to θ using Topp's equation (Topp et al. 1980). TDR measurements had previously been calibrated in the laboratory using the gravimetric water content of 12 soil blocks from the study site (0.10 m diameter x 0.20 m long) at different stages of a dryness cycle ($y=1.34x+2.35$; $r^2=0.99$). θ was measured monthly from April 2009 to December 2009 for all study plots.

Plant water availability and growth

Predawn, shoot water potential (Ψ_{pd}) was measured in one labeled individual per plot for each of the three dominant species (*Cistus ladanifer*, *Erica arborea*, and *Phillyrea angustifolia*) using a Scholander-type pressure chamber (Model 1000; PMS Instrument Company, Albany, OR, USA). The measurements were conducted on April 1st and August 14th, 2009, coinciding with the peak of water availability and scarcity, respectively. We used Ψ_{pd} as an indicator of water availability in the rhizosphere, assuming absence of nighttime transpiration (Larcher 2003).

Shoot growth was measured in the two tallest individuals per plot per species during the spring and summer of 2009. On April 1st, at the beginning of the growing season, we labeled three apical shoots on the south side of each plant. On July 15th, these shoots were harvested, dried (70°C for 48 hours) and weighed. We collected the shoots at this time of the year since previous observations in the study area indicated that beyond early July vegetative growth stops during summer, and even some plants (e.g., the malacophyllous *Cistus ladanifer*) begin to lose their leaves. We estimated the absolute growth rate (AGR), following Causton and Venus (1981), as the mean biomass grown per unit time in each plant:

$$AGR = \Delta W / \Delta t$$

Where ΔW is the biomass dry weight generated by the apical shoots during the growing season (April 1st - July 15th), and Δt is the number of days.

Experimental fire

The study plots were burned at the end of summer 2009 (September 23rd). All rainout shelter structures and the irrigation and tubing systems were dismantled and moved to a safe zone prior to burning. Furthermore, the unburned plots were surrounded with 2 m×1 m galvanized steel plates to avoid radiating heat damage from the adjacent burning plots. The fire was conducted under safe conditions, with clear sky and wind gusts not exceeding 6.5 $m s^{-1}$. Meteorological data were measured with a weather station (Model MTD-3016; GEONICA S.A., Madrid, Spain) placed at the field site. A total of 16 plots were burned, one by one, down-wind. Soil surface temperatures were continuously measured during fire with thermocouples (n=3–4) placed 1 cm above ground (HOBO Type K Thermocouple; Onset Computer Corporation, Bourne, MA, USA). The rainout shelters and irrigation system was reinstalled in the following days after fire and was fully operational within one week. No rainfall fell during this period.

Statistical analysis

One-way block ANOVA and *post-hoc* SHD Tukey tests were conducted to assess responses of AGR, Ψ_{pd} (in April and August), monthly θ among rainfall manipulation treatments, and fire intensity measurements (n=4 plots per treatment). The effects of rainout shelters on PPFD (n=12), T, and VPD (n=8) were assessed by one-way ANOVA. Actual rainfall was compared with scheduled rainfall for each treatment by a χ^2 test. All statistical analyses were carried out using SPSS 17.0 version software for Windows (SPSS, Chicago, IL, USA).

Results

Rainfall manipulation and soil water content

The rainout shelters and irrigation system operated satisfactorily since complete installation in March 2009, modifying amount and timing of rainfall as desired (Fig. 2). The actual patterns of simulated rainfall from the beginning of the manipulation until the end of the year closely matched those

initially programmed for the three rainfall manipulation treatments (historical control [HC], χ_{17}^2=9.6, P>0.5; moderate drought [MD], χ_{17}^2=8.0, P>0.5; severe drought [SD], χ_{17}^2=1.7, P>0.5) (Fig. 2). The study year was very dry (426 mm/year, 31.5% below the long-term average), especially during spring and most of the summer. The accumulated natural rainfall was even lower than the SD treatment until early September (Fig. 2). Thus, the shelters operated only during a limited number of days (13, 33 and 39 days/year) and large amounts of water (299, 187, and 94 mm/year) had to be added to the HC, MD, and SD plots, respectively, to achieve the programmed rainfall.

Volumetric soil water content (θ) in April was significantly lower ($F_{3,9}$=14.4, P<0.01) in EC plots (14.3%) than in HC, MD, and SD plots (all values above 23%) (Fig. 3). During May, we also found significant differences ($F_{3,9}$=28.7, P<0.01) among treatments. SD plots exhibited a rapid decrease in θ (from 27.0% in April to 9.6% in May) due to the imposed rainfall exclusion, while θ remained unchanged in EC (14.3% to 13.3%), or decreased slightly in HC (23.7% to 16.9%) and MD (26.0% to 17.4%) treatments (Fig. 3). In June, we detected θ values below 5.5% in all treatments, with the lowest θ values in SD plots ($F_{3,9}$=6.2, P<0.05). Following the summer dry period, soil moisture significantly increased in EC plots to 13.4% in October, due to the first autumn rains, while the rest of the treatments remained at values below 7.5% ($F_{3,9}$=56.8, P<0.01). In November, we observed significant differences ($F_{3,9}$=63.9, P<0.01) among all treatments with values of 14.3%, 11.6%, 8.6%, and 5.8% for EC, HC, MD, and SD, respectively, due to different amounts of water fallen onto the various treatments (Fig. 3).

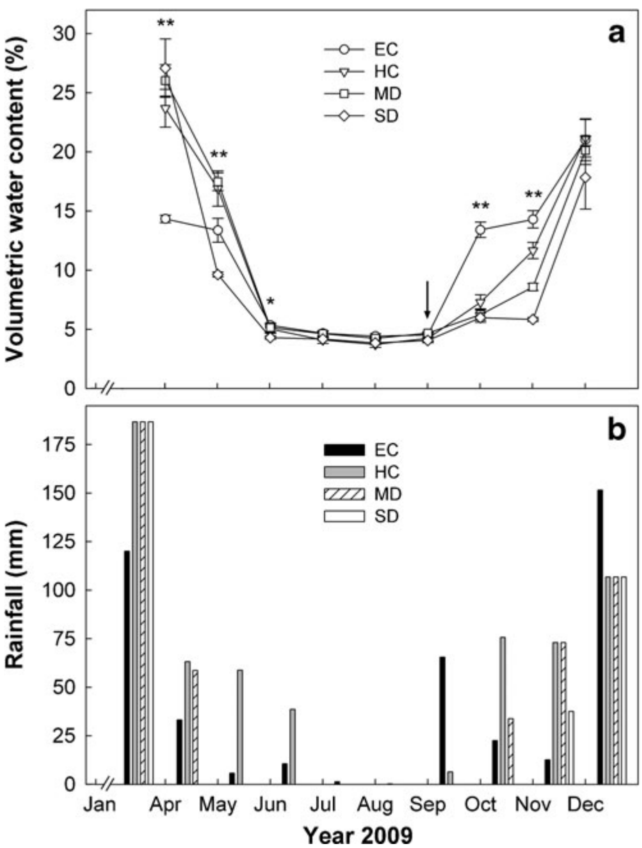

Fig. 3 **a** Monthly mean volumetric soil water content (θ) at 15-cm depth for the environmental control (EC), historical control (HC), moderate drought (MD), and severe drought (SD) treatments. Significant differences among treatments are shown by asterisks: (*) $P \le 0.05$; (**) $P \le 0.01$. *Error bars* represent standard errors and the *black arrow* indicates the date of the experimental burning. **b** Actual rainfall falling onto each experimental treatment between the different soil moisture measurements shown above

Effects of rainout shelters on plot microenvironment

Photosynthetic photon flux density (PPFD) was 25.6% and 23.6% lower underneath the shelters than above them in winter ($F_{1,22}$=49.9, P<0.01) and spring ($F_{1,22}$=6.7, P<0.05), respectively (Table 1). No significant effect of the shelters was observed on daytime air temperature (T), and vapor pressure deficit (VPD). However, the shelters significantly increased nighttime T by 0.8°C ($F_{1,14}$=110.6, P<0.01) and 1.1°C ($F_{1,14}$=113.2, P<0.01) in winter and spring, respectively. Similarly, nighttime VPD was significantly increased by 0.03 kPa ($F_{1,14}$=51.8, P<0.01) and 0.08 kPa ($F_{1,14}$=105.9, P<0.01) in winter and spring, respectively (Table 1).

Effects of rainfall manipulation on plant responses

Differences in predawn shoot water potential (Ψ_{pd}) across species were clearly observed at the onset of the manipulation, while differences among treatments were not detected (Table 2, Fig. 4). Ψ_{pd} (mean±SE) in April was −0.8±0.04 MPa, −0.8±0.06 MPa, and −0.4±0.04 MPa for *C. ladanifer*, *P. angustifolia*, and *E. arborea,* respectively. In August, after six months of rainfall manipulation, we found higher inter-specific differences in Ψ_{pd}, and a significant treatment effect depending on the species. *C. ladanifer* showed marginally significant differences among treatments, with a higher Ψ_{pd} in HC plots (−2.6±0.3 MPa) than in the other treatments (all values approximately −4.0 MPa) (Table 2, Fig. 4). In contrast, no differences were detected in *P. angustifolia,* in which Ψ_{pd} values were at approximately −2.5 MPa for all treatments (Table 2, Fig. 4). *E. arborea* was most affected by rainfall manipulations, showing significantly lower Ψ_{pd} in SD plots (−6.2±0.4 MPa) than in the other treatments, with all values above −4.7 MPa (Table 2, Fig. 4). Regardless of species, Ψ_{pd} in SD was consistently lower than in any other treatment (Fig. 4).

Table 1 Microclimate characteristics in sheltered and non-sheltered plots. Values of photosynthetic photon flux density (PPFD) were taken at solar midday (mean±SE). Values of air temperature (*T*) and vapor pressure deficit (VPD) were based on daytime and nighttime mean values (mean±SE). All measurements were conducted for days with low (winter) and high (spring) temperature and solar radiation values

Microclimate parameter	Winter[a]			Spring[b]		
	No shelter	Shelter	P^c	No shelter	Shelter	P^c
PPFD (μmol m^{-2} s^{-1})	708.86±21.25	526.31±14.67	<0.001	2153.31±141.01	1667.06±123.78	0.017
T (°C)						
Day	4.72±0.11	5.00±0.13	0.115	22.38±0.21	21.92±0.28	0.207
Night	0.06±0.07	0.85±0.03	<0.001	10.15±0.08	11.28±0.07	<0.001
VPD (kPa)						
Day	0.56±0.007	0.57±0.007	0.365	1.87±0.032	1.77±0.045	0.102
Night	0.31±0.004	0.34±0.003	<0.001	0.38±0.006	0.46±0.005	<0.001

[a] Data collected on March 9–10, 2009

[b] Data collected on May 12–13, 2009

[c] Based on one-way ANOVA

Growth (AGR) showed a relatively similar pattern to water availability in August. We found significant differences among treatments in *C. ladanifer* and *E. arborea*, but not in *P. angustifolia* (Table 2, Fig. 4). *C. ladanifer* and *E. arborea* showed the highest AGR in HC (36.2±3.5 and 3.9±0.4 mg day^{-1}, respectively), and the lowest in SD (21.7±2.4 and 1.5±0.2 mg day^{-1}, respectively), with intermediate values in MD and EC treatments (Fig. 4). *C. ladanifer* exhibited the highest mean growth rate (28.8±2.0 mg day^{-1}), compared to the intermediate value of *P. angustifolia* (7.2±0.8 mg day^{-1}), and lowest of *E. arborea* (2.2±0.2 mg day^{-1}) (Fig. 4). No plant mortality was observed in any of the treatments.

Table 2 One-way block ANOVA (*F*- and *P*- values) of predawn shoot water potential (Ψ_{pd}) in April and August, and absolute growth rate (AGR) for *Cistus ladanifer*, *Phillyrea angustifolia,* and *Erica arborea*

Species/Effect	Ψ_{pd} April		Ψ_{pd} August		AGR	
	$F_{3,9}$	*P*	$F_{3,9}$	*P*	$F_{3,9}$	*P*
Cistus ladanifer						
Rainfall manipulation	0.66	0.596	3.23	0.075	4.56	0.033
Block	1.31	0.328	1.60	0.255	2.05	0.177
Phillyrea angustifolia						
Rainfall manipulation	3.76	0.053	1.07	0.406	1.70	0.236
Block	11.39	0.002	3.49	0.063	0.96	0.451
Erica arborea						
Rainfall manipulation	0.42	0.739	4.48	0.035	15.24	0.001
Block	0.42	0.739	1.61	0.254	0.30	0.824

Experimental fire

Experimental burning of the plots was conducted successfully during the morning of September 23, 2009. All plots were burned with high and similar fire intensity (Fig. 5). No significant differences were detected in the residence time of different temperature thresholds ($F_{3,9}$<2.0, P>0.1 for all temperatures tested: 50°C, 100°C, 150°C, and so on up to 700°C) among plots with different rainfall treatments. The mean residence time over 100°C was 13.7±1.7 min, and 1.8±0.2 min over 500°C (Fig. 5). Similarly, no significant differences were detected in the maximum temperatures reached at the soil surface ($F_{3,9}$=0.1, P>0.5) among different rainfall treatments. The mean maximum temperature of fire was 710.0±25.4°C (Fig. 5).

Discussion

In this study, we describe a system that allows modifying rainfall patterns in a Mediterranean shrubland. The system was designed to treat relatively large surfaces (36 m^2) and plants (2 m tall), and be quickly dismantled and set back again to allow burning of the study plots without interrupting the rainfall manipulations. The implemented drought treatments during one season were sufficient to produce significant effects on soil moisture, plant water availability and plant growth. This proves that our system is a valuable tool to study the effects of drought and fire, which is critically important to understand the projected impacts of climate change in the Mediterranean and other similar ecosystems of the world.

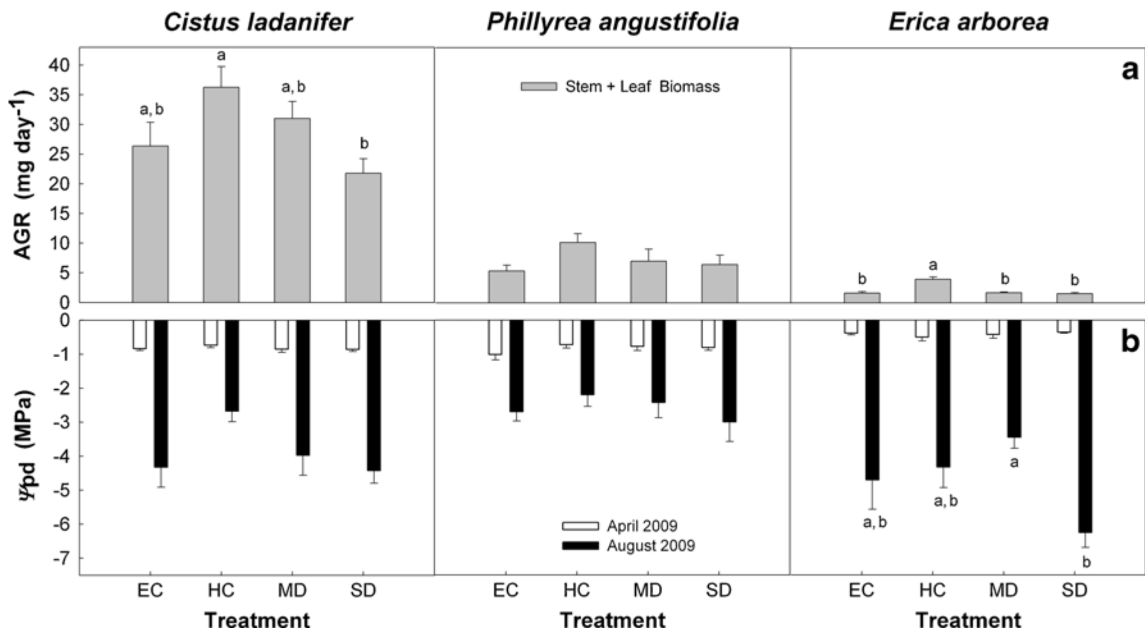

Fig. 4 Mean absolute growth rate (AGR) (**a**) and mean predawn shoot water potential (Ψ_{pd}) (**b**) measured during the growing season for *Cistus ladanifer*, *Phillyrea angustifolia*, and *Erica arborea* in environmental control (EC), historical control (HC), moderate drought (MD), and severe drought (SD) treatments. *Error bars* represent standard errors. The letters *a* and *b* represent statistically homogeneous subsets based *post-hoc* Tukey test

Approaches and limitations to manipulating rainfall

Excluding rainfall from a given piece of land is easy; however, the various techniques have advantages and limitations. Mobile rainout shelters, as the ones used here, provide a high effectiveness in rainfall exclusion. However, mobile systems, in contrast to completely-covered fixed systems, cannot achieve total rainfall exclusion due to a short delay in the full unfolding of the rainout shelter over the plots since the beginning of a rainfall event (Beier et al. 2004). This delay could be a problem in late spring and summer, when convective storms are dominant and rainfall intensity might be high (Lionello et al. 2006). In our case, complete shelter unfolding took a maximum of 2.5 min. During the period in which the shelters were operating, there were 39 rainfall events, of which only five exceeded an accumulated precipitation of 0.5 mm during the first 10 minutes. The maximum accumulated rainfall during 10 minutes was 2 mm. Therefore the time taken to unfold the shelters was insufficient to significantly alter the imposed drought treatments (Fig. 2).

Another main advantage of mobile systems is their lower impact on plot microenvironment compared to fixed systems. Our rainout shelters caused a PPFD reduction of 25% and 23% in winter and spring, respectively (Table 1), similar to those observed in other fixed and mobile rainout shelters (English et al. 2005; Misson et al. 2011; Yahdjian and Sala 2002). *T* and VPD were not affected by the shelters during the day, consistent with the results reported in Fay et al. (2000). However, *T* and VPD increased at night (Table 1).

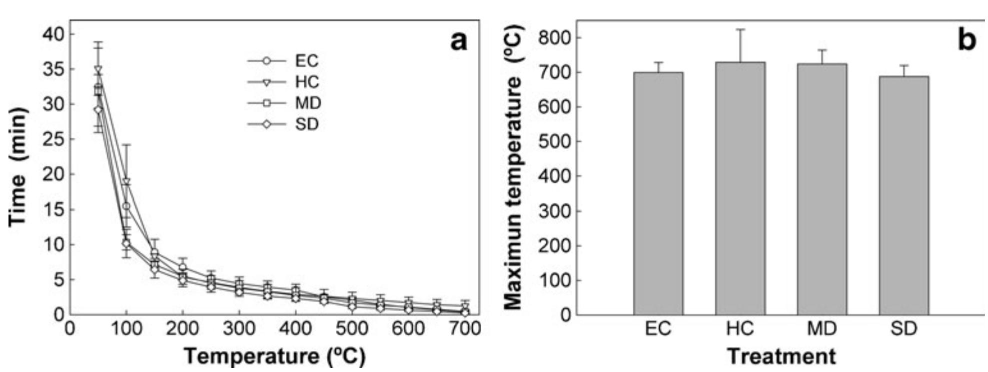

Fig. 5 **a** Temperature-residence time curves. **b** Mean maximum temperatures reached in soil surface during the fire for environmental control (EC), historical control (HC), moderate drought (MD), and severe drought (SD) treatments. *Error bars* represent standard errors

The global (day + night) increase of *T* values was 0.5°C and 0.3°C in winter and spring, respectively, which are also comparable to values reported in other studies (English et al. 2005; Svejcar et al. 1999). It is important to note that the shelters were unfolded only whenever rainfall was about to exceed the scheduled rain for a given biweekly period. Thus, we maximized the use of natural rain while minimizing the effects of the shelters on the plot microenvironment. In total, the shelters were unfolded 13, 33 and 39 days during the year for HC, MD and SD treatments, respectively, which permits arguing that the total impact they exerted over the course of the entire year was negligible.

Our system was effective in producing differences in soil moisture across treatments in spring and autumn, but not during the summer months (Fig. 3). This may appear as contradictory but is consistent with other rainfall manipulation experiments in seasonally contrasted climates (Yahdjian and Sala 2002). The water in the upper soil levels is usually depleted in summer, due to lack of rainfall at a time when evapotranspiration is maximum (Rambal 1984), although moisture can remain available at greater soil depths. Unfortunately, water availability at depths beyond 15 cm could not be reliably sampled, due to the high rock content of the soil.

Irrigation systems are a common tool in fixed rainout shelters, but not in mobile ones. We incorporated this facility to our system to produce a treatment that would simulate the long-term yearly precipitation pattern in the study area. This type of control treatment has been applied in a few manipulative field experiments (e.g. Jentsch et al. 2007; Svejcar et al. 1999; Weltzin and McPherson 2000), but can be crucial in Mediterranean climates where the probability of any year to be at one of the extremes of the long-term rainfall observations is very high (Lionello et al. 2006), rendering the control treatments difficult to interpret. In fact, this is what happened during the course of our experiment since, during a large portion of the year 2009, natural precipitation was well below the long-term average and even below our most severe drought treatment (Fig. 2). The HC treatment allowed us to have a reference for the actual effects of the imposed droughts relative to the long-term average conditions that plants typically endure. We argue that the approaches used here should be used in similar studies conducted in highly variable climates.

Rainfall manipulation effects on plant responses

Rainfall manipulation treatments resulted in differences in plant performance among species. *C. ladanifer* (seeder) exhibited a high coupling of water availability (as indicated by Ψ_{pd}) and growth to changes in experimental rainfall regimes (Fig. 4). This response was likely driven by the shallow root system characteristic of seeder species (Bell et al. 1996; Keeley 1986). In fact, maximum root depth recorded for other *Cistus* species in the Iberian Peninsula does not exceed 30 cm (Silva et al. 2002). At the other extreme, *P. angustifolia* (resprouter) showed a small Ψ_{pd} variation between the point of greatest (April) and lowest (August) water availability. Its growth was equally not affected by the rainfall treatments (Fig. 4). Alessio et al. (2004) characterized *P. angustifolia* as a deep-rooted species, with accessibility to deep-water sources, which could explain its response to the drought treatments. On the other hand, *E. arborea* (resprouter) showed the lowest Ψ_{pd} and AGR (Fig. 4). These results are incongruent with previous *E. arborea* classifications as a species able to explore deep soil resources (Gratani and Varone 2004). However, they are consistent with low Ψ_{pd} recorded for other closely related *Erica* species within our study area (Cruz 1996), and the substantial above-ground dieback observed in *Erica* in numerous areas of the central and southern Iberian Peninsula (Peñuelas et al. 2001) during the severe droughts that occurred in Spain in 1994 and 1995. Therefore, the capacity of *E. arborea* to withstand drought requires further investigation.

Experimental fire

Climate change projections include an increase in the severity and occurrence of droughts in the Mediterranean region (Giorgi and Lionello 2008), as well as a rise in the frequency, intensity, and duration of heat waves (Christensen et al. 2007). These changes in climate can increase the duration of the fire season and fire risk, particularly of large fires (Moreno et al. 2010; Moriondo et al. 2006). A problem with fire experimentation is that experimental burnings are usually carried out when conditions are not severe, and therefore fire intensity might not match the one expected for the worst drought and fire scenarios that are anticipated for the future. For this reason, it was important to conduct a high fire intensity burning. Our results show that we successfully achieved this since all plots burned with high fire intensity (mean residence time over 100°C was 13 min, and mean maximum temperature was 710°C) (Fig. 5). The fire intensity was higher than that recorded in other experimental burns performed with the same vegetation in late summer at this same location (mean residence time over 100°C was approximately 10 min and mean maximum temperature did not exceed 650°C; Moreno et al. 2011), and was within the upper range of the reported values for other Mediterranean shrubland fires (Céspedes et al. 2011; De Luis et al. 2004; Molina and Llinares 2001). Furthermore, fire intensity was homogeneous across treatments, which enabled us to conclude that future post-fire effects observed in this study will not be due to changes in fire intensity.

Concluding remarks

Manipulative experiments, where rainfall and fire can be jointly manipulated, represent a major logistical challenge, especially when the size of plants is relatively large, as is the case of Mediterranean shrublands. In this study, we demonstrate how these logistical problems can be overcome in order to permit evaluating vegetation response to drought and fire, two factors that likely will be severely affected by global warming. The study of both factors may be key to better understand climate change effects on the composition, structure and functioning of Mediterranean ecosystems.

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