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Methodology and performance of a rainfall manipulation experiment in a piñon–juniper woodland

Robert E. Pangle,[1,†] Judson P. Hill,[1] Jennifer A. Plaut,[1] Enrico A. Yepez,[2] James R. Elliot,[1] Nathan Gehres,[1] Nate G. McDowell,[3] and William T. Pockman[1]

[1]*Department of Biology, MSC03 2020, 1 University of New Mexico, Albuquerque, New Mexico 87131-0001 USA*
[2]*Departamento de Ciencias del Agua y del Medio Ambiente, Instituto Tecnológico de Sonora, Ciudad Obregón México 85000 Mexico*
[3]*Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA*

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Abstract. Climate models predict that water limited regions around the world will become drier and warmer in the near future, including southwestern North America. We developed a large-scale experimental system that allows testing of stand level impacts of precipitation changes. Four treatments were applied to 1600 m^2 plots (40 m $\times$ 40 m), each with three replicates in a piñon pine (*Pinus edulis*) and juniper (*Juniper monosperma*) ecosystem. These species have extensive root systems, requiring large-scale manipulation to effectively alter soil water availability. Treatments consisted of: (1) irrigation plots that receive supplemental water additions, (2) drought plots that receive 55% of ambient rainfall, (3) cover-control plots that receive ambient precipitation, but allow determination of treatment infrastructure artifacts, and (4) ambient control plots. Our drought structures effectively reduced soil water potential and volumetric water content compared to the ambient, cover-control, and water addition plots. Drought and cover-control plots experienced an average increase in maximum soil and ground-level air temperature of 1–4°C during the growing season compared to ambient plots, and concurrent short-term diurnal increases in maximum air temperature were also observed directly above and below plastic structures. Our drought and irrigation treatments significantly influenced tree predawn water potential and canopy transpiration, with drought treatment trees exhibiting significant decreases in physiological function compared to ambient and irrigated trees. Supplemental irrigation resulted in a significant increase in both plant water potential and canopy transpiration compared to trees in the other treatments. This experimental design allows manipulation of plant water stress at the tree/stand scale, permits a wide range of drought conditions, and provides prolonged drought conditions comparable to historical droughts in the past—drought events for which wide-spread mortality in both these species was observed.

Key words: experimental rainfall manipulation; global climate change experiments; irrigation; *Juniperus monosperma*; mechanisms of tree mortality; piñon–juniper woodland; *Pinus edulis*; plant drought stress; through-fall exclusion; treatment artifacts.

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† **E-mail:** rpangle@unm.edu

Introduction

The mortality of forests and woodlands in response to extreme climate events can result in rapid and large-scale shifts in ecosystem structure and function (Condit et al. 1995, Allen and Breshears 1998, Hanson and Weltzin 2000, Breshears et al. 2005, Shaw et al. 2005, Berg et al. 2006, Gitlin et al. 2006, McDowell et al. 2008, Allen et al. 2010, Clifford et al. 2011). Extended drought in the southwestern United States has resulted in extensive forest and woodland tree mortality (Breshears et al. 2005, Floyd et al. 2009, Allen et al. 2010). During a regional drought that occurred from 2000–2003, widespread mortality occurred in populations of piñon pine (*Pinus edulis*); a species which dominates piñon–juniper woodlands—one of the most extensive vegetation types in western North America (Gottfried et al. 1995, Mueller et al. 2005, Breshears et al. 2009, Floyd et al. 2009, Clifford et al. 2011). Global climate change associated with continued, high fossil fuel emissions and subsequent increase in atmospheric [CO_2] is expected to exacerbate the frequency and severity of future droughts in many areas (Houghton et al. 1996, Easterling et al. 2000, IPCC 2001, IPCC 2007, Seager et al. 2007, Allison et al. 2009). Many regions are anticipated to experience greater inter-annual variability in rainfall and consequently in soil water availability, a scenario likely to push many forest types across potential climate-mortality thresholds (Adams et al. 2009*a*, Seager et al. 2007, Allen et al. 2010).

Unfortunately, the difficulty of experimentally altering the abiotic environment of trees on a large-scale is a significant challenge for researchers investigating the exact physiological and causal mechanisms leading to tree mortality. This challenge is particularly important for mature trees that have extensive root systems, forcing scientists to use potted plants, which limits the inferences that can be drawn from experimental results (Adams et al. 2009*b*, Leuzinger et al. 2009). Juniper trees in particular are known to have root systems extending horizontally over three times their total height (Gottfried 1989). Experimental designs that manipulate precipitation at the tree and stand scale include the use of permanent and movable rain-out shelters, subcanopy/understory shelters and troughs, and above canopy irrigation systems to alter the amount and timing of precipitation inputs (Svejcar et al. 1999, Fay et al. 2000, Nepstad et al. 2002, Yahdjian and Sala 2002, Beier et al. 2004, English et al. 2005, Wullschleger and Hanson 2006). In forested systems with mature trees, large-scale through-fall exclusion structures have been employed in efforts to experimentally induce drought at the tree, stand, and/or ecosystem level (Nepstad et al. 2002, Wullschleger and Hanson 2006, Fisher et al. 2007, Nepstad et al. 2007, Lola da Costa et al. 2010, and reviewed by Hanson 2000 and Rustad 2008).

In the present study, we developed a stand scale precipitation manipulation system that combines above canopy irrigation and below canopy precipitation/through-fall exclusion in a semi-arid piñon–juniper woodland. This manipulation provided an experimental test of the effects of long-term changes in precipitation on tree growth, physiology, and drought-induced mortality. This ecosystem type is a challenging environment for such an experiment due to: (1) the extensive rooting systems of the dominant species which necessitate a large-scale manipulation infrastructure, and (2) potential temperature artifacts of such an infrastructure given the high solar radiation loads of these open-canopied woodland systems.

Here we present the design details and performance of our experimental treatments in relation to abiotic conditions and the preliminary plant physiological responses to altered soil water availability. Specifically, this paper describes the responses of the following abiotic and physiological parameters to experimentally altered precipitation regimes: (1) soil water availability, both temporally and by depth; (2) air and soil temperature; and (3) plant water status. Additionally, we discuss preliminary canopy level physiological responses to altered precipitation and some of the experimental artifacts and indirect effects related to our experimental manipulations.

Methods

Study site and experimental plots

This research was conducted at the Sevilleta Long Term Ecological Research (LTER) project at the Sevilleta National Wildlife Refuge in central New Mexico, USA. Our experimental plots were established on the eastern slope of the Los Piños Mountains (34°23′11″ N, 106°31′46″ W) in the northeastern corner of the wildlife refuge and are dispersed across approximately 25 ha at a mean elevation of 1911 m. Climate records (20-yr) from a nearby Sevilleta LTER meteorological station (Cerro Montoso #42; http://sev.lternet.edu/) indi-

Table 1. Biomass parameters for piñon and juniper trees across all plots and experimental treatments. Error estimates represent (±1 SE) of the mean.

Biomass parameter	Irrigation (n = 3)	Drought (n = 3)	Cover-control (n = 3)	Ambient (n = 3)	Site mean (n = 12)
Basal area (m^2/ha)					
Piñon	5.2 (0.8)	1.9 (0.4)	2.2 (0.6)	2.4 (0.3)	2.9 (0.5)
Juniper	19.1 (1.8)	15.7 (0.6)	15.8 (1.5)	17.7 (1.4)	17.1 (0.7)
Total	24.3 (2.1)	17.6 (0.2)	18.0 (0.9)	20.0 (1.7)	20.0 (1.0)
Density (>5cm, stems/ha)					
Piñon	173 (20)	69 (13)	94 (27)	77 (15)	103 (15)
Juniper	394 (30)	285 (74)	194 (44)	273 (35)	287 (30)
Total	567 (46)	354 (85)	288 (69)	350 (22)	390(41)
Woody canopy coverage (%)†	47.5 (1.9)	32.3 (4.1)	30.6 (1.4)	36.6 (3.0)	36.7 (2.3)

Notes: Basal area estimates are based on diameter measured at 30 cm stem height. For individuals with multiple stems at 30 cm height, a single equivalent diameter was calculated. Stem density represents biomass conditions as observed at the beginning of the experiment in 2007 for all stems >5 cm, and total number of stems represents the sum of piñon and juniper density in each plot.

† Woody canopy coverage was estimated from aerial photos of the study site and included all woody shrubs and trees.

cate a mean annual precipitation total of 362.7 mm/yr. The region is strongly influenced by the North American Monsoon, with a large fraction of annual precipitation occurring in July, August, and September when monsoon circulation is active. Mean annual temperature (20-yr) at this nearby LTER site was 12.7°C, with a mean July maximum of 31.0°C and a mean December minimum of −3.3°C.

The site is a piñon pine (*Pinus edulis*, Engelm.) and juniper (*Juniperus monosperma* (Engelm.) Sarg.) woodland, with several other commonly observed woody shrub species present, notably; *Mahonia* spp. (algerita), *Falugia paradoxa* (Apache plume), *Quercus turbinella* (shrub live oak), and *Rhus* spp. (sumac). Multiple species of cacti and agave (*Cylindropuntia* spp., *Opuntia* spp., and *Yucca* spp.) are present, along with numerous species of perennial grasses and forbs; including an extensive inter-canopy coverage by grasses of the genus *Bouteloua*. Piñon and juniper basal area (at 30 cm stem height) average 20.0 m^2/ha across the study site, with piñon basal area comprising 2.9 m^2/ha of this total (Table 1). Stem diameters in our experimental plots range up to 40.9 cm for piñon and 74.8 cm for juniper, with total woody canopy coverage across the site averaging 36.7% based on aerial photo estimates (Table 1). Data presented in Table 1 reflect stem density and canopy coverage conditions as they existed at the time of treatment implementation in 2007, and are not indicative of any treatment level effect.

In total, our study site consisted of 12 experimental plots located in three replicate blocks that varied in slope %, aspect, and soil depth. Slope varied from 0–2% in experimental plots situated in level portions of the site, with steeper grades ranging from 6–18% for plots established on hill-slopes. Soil texture analysis across the site (both hill-slope and flat/level topography) revealed that surface soils were predominately silt loam with; (1) a transition to sandy loam texture at depth, and (2) a significant percentage of coarse fragments present both at the soil surface and throughout the profile. Soil depth across the site ranged from 20 to ≥100 cm, with shallower soil depths occurring on hill-slopes where depth to caliche and/or bed-rock was only 20–30 cm in some instances. In one of our hill-slope replicates (south aspect block), soil data obtained during soil sensor installation and soil texture analysis revealed that average soil depth in this replicate (by plot) ranged from 43 to 64 cm, with soil depth in the drought treatment plot in this particular replicate/block averaging 52 cm. While depth to bedrock or caliche on hill-slope plots was often <1 m, piñon and juniper roots were observed growing at depths up to 1.5 m deep in exposed fractured bedrock adjacent to the hill-slope plots (the south and north aspect replicate blocks), and up to 2–2.5 m deep in exposed soil profiles located adjacent to plots on level terrain (the flat aspect replicate). Rooting depths were observed in exposed soil/bedrock profiles located at the edge of an arroyo that paralleled both the hill-slope and flat replicate plots. This suggests that effective rooting depth in this semi-arid woodland system was certainly

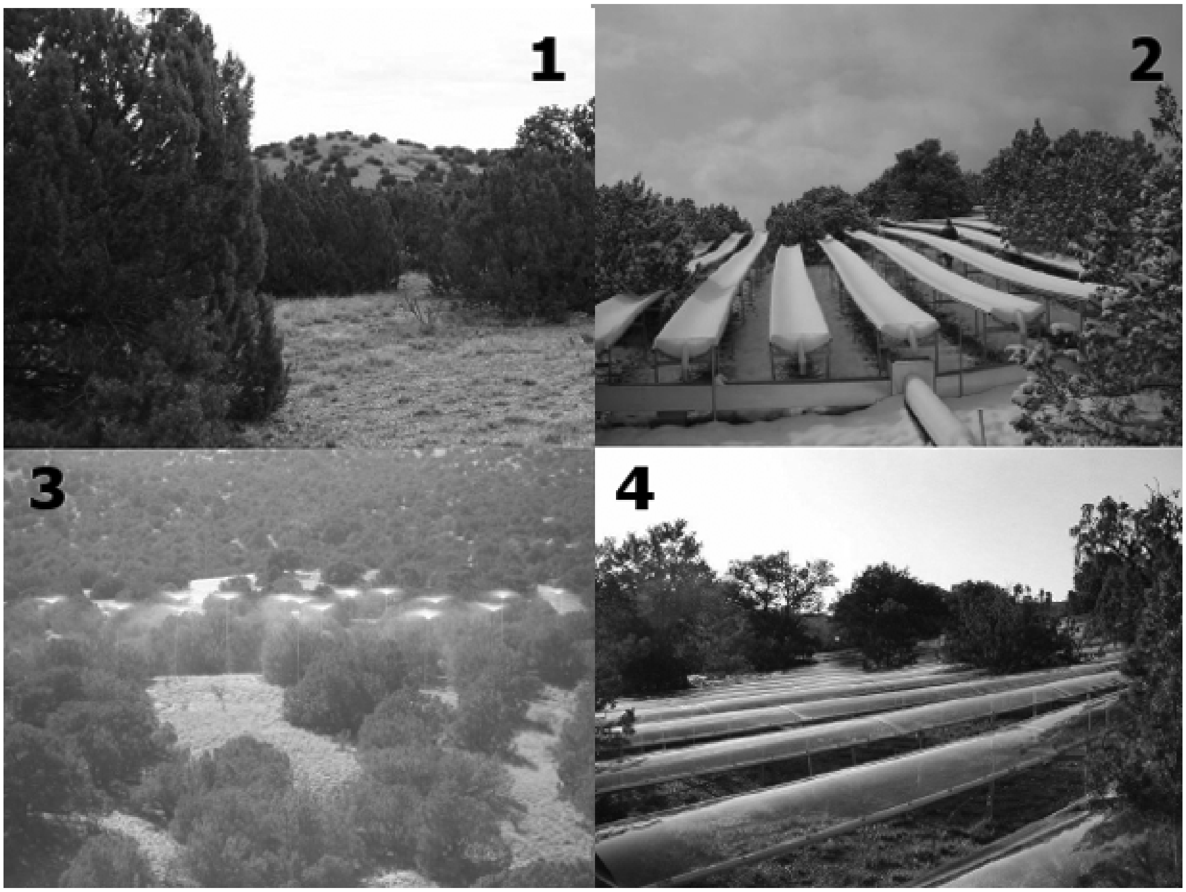

Fig. 1. Representative pictures of each experimental treatment (40 m $\times$ 40 m plot size). Experimental treatments include: (1) ambient control, (2) drought, (3) supplemental irrigation, and (4) cover-control. Each treatment is replicated in three different blocks that differ in their slope and aspect.

greater than depths we recorded during soil sensor installation (Schwinning 2010).

The study utilized four different experimental treatments applied in three replicate blocks. The four experimental treatments included (1) unmanipulated, ambient control plots, (2) drought plots, (3) supplemental irrigation plots, and (4) cover-control plots that have a similar infrastructure to the drought plots, but remove no precipitation (Fig. 1). The three replicated blocks differed in their slope and aspect. One block of four plots was located on south facing slopes, one on north facing slopes, and one in a flat area of the landscape.

Experimental treatment design

To effectively reduce water availability to trees, we installed treatments of sufficient size to minimize tree water uptake from outside of the plot. Piñon pine and juniper are reported to have root lengths of two and three times their height, respectively (Gottfried et al. 1995, Breshears et al. 1997). Because the average tree height was 4.2 and 3.4 m for mature target piñon and juniper respectively, we estimated the target trees at the center of each plot required at least 10 m distance from the stem to the outer edge of the plot. Thus, we constructed three replicated drought structures that were 40 m $\times$ 40 m (1600 m^2). Precipitation during the 2000–2003 drought that caused widespread piñon pine mortality in the southwest was approximately 48% of the 30 year mean (Breshears et al. 2005). Thus, we targeted a 50% reduction in ambient precipitation through water removal troughs that covered $\sim$50% of the land surface area (Fig. 1). Drought plot infrastructure was positioned to ensure that targeted piñon pine and juniper were centrally located within each drought plot to provide the maximum distance between tree stems and the nearest plot boundary. The mean distance between the stems of target trees and the nearest drought plot boundary (edge of infrastructure) averaged 12.1 ($\pm$0.7), 13.9 ($\pm$0.9), and 14.5 ($\pm$1.5) m for each drought plot replicate respectively. Thus, target trees were located well away from the edge of drought infrastructure which allowed us to effectively exclude rainfall over a large spatial area (and rooting radius) around targeted trees.

Each drought and cover-control plot consists of 29 parallel troughs or domes running across the 40 m plot. In the drought plots, each trough was constructed with overlapping 3 ft $\times$ 10 ft (0.91 m $\times$ 3.05 m) pieces of thermoplastic polymer sheets (Makloron SL Polycarbonate Sheet, Sheffield Plastics, Sheffield, MA) fixed with self-tapping metal screws to horizontal rails that are approximately waist height and are supported by vertical posts every 2.5–3.5 m (Fig. 1). The waist height ($\sim$1 m) of the troughs varied by $\sim$0.20 m due to local topography, a compromise between staying below the tree crowns while allowing airflow near the soil surface. The plastic sheets were bent into a concave shape to collect and divert the precipitation off plot. The bending and spacing of the plastic resulted in 0.81 m (32 in) troughs separated by 0.56 m (22 in) walkways.

Individual troughs often intersected the canopy of trees because of their height. The troughs were installed as close to the bole of the tree as possible without damaging branches in order to maximize the area covered by the plastic across the entire plot. An end-cap was attached to the downstream edge of the trough to prevent water from falling onto the base of the tree. The end-caps were 81 cm $\times$ 30 cm and made with the same plastic as the troughs. Each end-cap was fixed to the trough with a 75 cm piece of 20 gauge angle iron cut to match the curve of the bottom of the trough and held in place with self-tapping screws. The plastic junctures were then sealed with acrylic cement (Weld-On #3 epoxy, IPS, Compton, CA). The middle of the end-cap was fitted with a 3 in (7.62 cm) PVC collar to allow water to flow through. A piece of 3 in (7.62 cm) PVC pipe or suction hose (used when the bole of a tree was directly below a trough) was then attached to the downstream side of the end-cap, enabling water to flow into the trough on the other side of a tree. End-caps were also placed at the downhill end of the troughs on the edge of the plot and fitted with 90° fittings to divert water down into a 30 cm wide gutter (open on top) that ran perpendicular to the plot (Fig. 1). Collected water was then channeled from the gutter into storage tanks for use on irrigation plots, or into adjacent arroyos for drainage away from the study area.

We built cover-control infrastructures to investigate the impact of the plastic drought structures independent of changes in precipitation. This was necessary because of the high radiation environment in central New Mexico, in which the clear plastic troughs can effectively act as a greenhouse structure. The cover-control treatment had the same dimensions as the drought plots with one key difference. The plastic was attached to the rails in a convex orientation so precipitation would fall on top of the plastic and then drain directly down onto the plot (Fig. 1). The cover-control plots were designed to receive the same amount of precipitation as un-manipulated ambient plots, with the precipitation falling and draining into the walkways between the rows of troughs. Cover-control plots were constructed between 21 June 2007 and 24 July 2007; drought plots were constructed between 09 August 2007 and 27 August 2007.

The total plastic coverage in each plot is 45% ($\pm$1%) of the 1600 m^2 plot area due to the variable terrain and canopy cover. A direct test of the amount of precipitation excluded via the plastic troughs was performed over a 2-week period during the summer monsoon season of 2008. Two rainfall collection gutters (7.6 cm width, 6.1 m length) were installed perpendicular to four plastic drought structures and four intervening open walkways. One gutter was located below the troughs ($\sim$0.6 m above ground), and the other was located just above ($\sim$1.35 m) and offset, to determine the interception of rainfall by the troughs. Rainfall totals collected via the perpendicular gutters were measured using Series 525 tipping bucket rain gauges (Texas Electronics, Dallas, TX).

Our irrigation system consisted of above-canopy sprinkler nozzles configured to deliver supplemental rainstorm event(s) at a rate of 19 mm/hr. Our irrigation system is a modified design of the above-canopy irrigation system outlined by Munster et al. (2006). Each of the three irrigation plots has three 2750 gal (10.41 m^3) water storage tanks connected in parallel. These tanks were filled with either collected rainwater or filtered reverse osmosis (RO) water brought to the site with multiple tractor-trailer trucks, depending on the season. Due to technical difficulties related to collecting and storing adequate rainwater at the site, the overwhelming majority of our irrigation water has been supplied in the form of RO water trucked to the site. During irrigation events, water is pumped from the tanks through a series of hoses that decrease from 7.62 cm (3 in) main lines out of the tank to 2.54 cm (1 in) hoses attached to 16 equally-spaced sprinklers within the plot. Each sprinkler is 6.1 m (20 ft) tall (2–3 m higher than mean tree height), and fitted with a sprinkler nozzle that creates an even circular distribution of water with a radius of 5 m on the ground (Fig. 1). Due to the varying topography, sprinklers located downslope (if unregulated) would receive more pressure than those at the top of a hill and thus spray more water. To mitigate this problem, each sprinkler line was fitted with a pressure gauge and variable globe valve (inline water spigot with precise regulation) equidistant from the top of the sprinkler. Each sprinkler line was then set so that the pressure gauges were equal, thus ensuring equal distribution of water throughout the plot, regardless of elevation differences. The irrigation systems were tested in October 2007 (2 mm supplemental), and full applications (19 mm) were applied in 2008 on 24 June, 15 July, and 26 August. During the 24 June event, we deployed six $\sim$1 m^2 circular trays across one of the irrigation plots to test the spatial variation of the wetting. Data from this test indicated that on average, collection trays received 19.5 ($\pm$2.5) mm of water.

The cost of building ecosystem scale infrastructure will vary with the quality of the materials used, vendors, and economic variation. Briefly, the cost of installing one 1600 m^2 drought plot was approximately US $73,500. The cost of plastic (US $21,000) was 56% of total material cost. Contractor installation costs were high (US $36,000), but greatly reduced the time required to initiate treatment compared to our early in-house installation efforts. The cover-control infrastructure cost slightly less (US $70,000), since plumbing for tree breaks and gutters to move water off-plot were not required. The materials cost to install the irrigation system on one 1600 m^2 plot was approximately US $15,800, which included all hoses, piping/plumbing, masts/nozzles, water storage tanks, and a portable gas powered water pump needed to pressurize the system. The labor needed to construct the irrigation system was provided by personnel working on the project.

Site abiotic monitoring

We used Campbell Scientific dataloggers to continuously monitor and record abiotic conditions and physiological measurements across the site. All systems were connected to a solar-powered wireless network with NL100 relays (Campbell Scientific, Logan, UT). Plots were instrumented with CR-1000, CR-7, and CR-10X dataloggers (Campbell Scientific, Logan, UT). Each CR-1000 datalogger was accompanied by AM25T and AM 16/32 multiplexers to expand sensor measurement capacity (Campbell Scientific, Logan, UT). The south facing block of experimental plots (the intensive physiology block) was extensively instrumented with sensors to measure both abiotic and plant physiological parameters. The non-intensive experimental plots in the north facing and flat blocks were initially only instrumented to monitor abiotic conditions. In the non-intensive plots, abiotic conditions were measured at three locations under each cover type: under piñon, juniper, and in intercanopy areas between trees. These measurements included; (1) soil temperature (T_S) at -5 cm depth and shielded air temperature (T_A) at 10 cm (above soil surface), both measured with 24 gauge Type–T thermocouples (Omega, Stamford, CT), and (2) volumetric water content (VWC) at -5 cm measured using EC-20 ECH_2O probes (Decagon, Pullman, WA). South aspect intensive physiology plots were instrumented with the same sensors listed above, with an increased sampling size of $n = 4$ temperature measurements, and $n = 5$ VWC measurements per cover type. Additionally, south aspect intensive physiology plots were instrumented with a CR-7 datalogger measuring soil water potential (Ψ_S) at three depths at 15 locations throughout each plot using PST-55 psychrometers

(Wescor, Logan, UT); one profile under each target tree as well as five intercanopy locations throughout the plot. Each profile had psychrometers at −15 cm, −20 cm, and as deep as possible (down to −100 cm, depending on soil conditions). The temperature and soil moisture sensors measuring the abiotic conditions were placed in the plots before the construction of plastic drought and cover-control structures. This resulted in a random distribution of sensors relative to the location of the plastic troughs. Similar to target trees, temperature and soil moisture sensors in drought plots were located away from plot boundaries to ensure that interior plot conditions near target trees were well characterized (i.e., paired temperature and soil moisture sensors located in the piñon and juniper cover types were positioned beneath the canopies of target trees). The random spatial positioning of temperature and soil moisture sensors beneath plastic troughs/infrastructure varied as follows; (1) drought plots: directly under plastic, 50%; open walkways, 30.8%; edge of plastic or partially covered, 19.2%; and (2) cover-control plots: directly under plastic, 33.3%; open walkways, 55.6%; plastic edge or drip-line, 11.2%.

Periodic measurements of relative humidity (RH%) and air temperature (T_A) directly below and above the plastic drought structures in each of the three replicate blocks were performed during 2008. These measurements were made using six Vaisala HMP45C sensors (Campbell Scientific, Logan, UT); one mounted 0.8 m above each plastic drought structure (1.9 m above ground), and a second mounted 0.4 m below each plastic drought structure (0.8 m above ground).

An additional CR-10X datalogger was used to record data from a micrometeorological tower centrally located in an open intercanopy area of the study site. This tower (hereafter, the site met-station) recorded precipitation with a Series 525 rain gauge (Texas Electronics, Dallas, TX), VWC, net radiation with a Kipp and Zonen NK-LITE net radiometer (Campbell Scientific, Logan, UT), photosynthetically active radiation (PAR) with a LI-190SA sensor (Li-Cor, Lincoln, NE), windspeed and direction with a 05103-L R.M. Young wind monitor (Campbell Scientific, Logan, UT), and air temperature and RH% with a Vaisala HMP45C sensor. During winter months the rain gauge was fitted with a snow adaptor to thaw snow and record the total amount in mm rain. All met-station measurements were made at a height of 1–3 m above ground depending on the sensor array in question.

Plant physiological response

Multiple physiological characteristics of ten target trees (five piñon and five juniper) within each of the intensive measurement plots were continually monitored by automated sensors and periodic manual measurements. While the long term physiological responses of the trees are beyond the scope of this paper, several components are included here to describe the responses associated with the different treatments; specifically plant water potential and canopy transpiration measured via stem sap-flow sensors. The examination of canopy transpiration in cover-control versus ambient plots provides an integrative physiological assessment of any unintended experimental artifacts (due to plastic structures) that may have affected canopy and whole tree physiological function.

Predawn (Ψ_{PD}) and mid-day (Ψ_{MD}) plant water potentials were measured with multiple Scholander-type pressure chambers (PMS Instrument, Albany, OR) on all target trees. When possible, Ψ_{PD} was measured both before and after supplemental irrigation events.

Stem sap-flow (J_S) was measured using Granier heat dissipation sap flow sensors installed in 2007 in each intensive physiology plot within the south aspect block. Trees in north facing (plots 5–8) and flat blocks (plots 1–4) were not instrumented with sap-flow sensors during the 2007 or 2008 seasons. All target trees had two 10 mm Granier sap-flow sensors installed in the outermost sapwood (Granier 1987). Each sensor used the traditional two probe heated and unheated reference design (Granier 1987), with two additional probes located 5 cm to the right side of the primary probes to correct for axial temperature gradients in the stem (Goulden and Field 1994). We found that this compensation for axial temperature gradients is critical to reduce measurement noise resulting from the open-canopy and high radiation environment of this ecosystem. In addition, stems were wrapped with reflective insulation (Reflectix, Markleville, IN) in an effort to shield sap-flow probes from short term ambient temperature fluctuations and direct solar irradiance. Sap-flow (J_S) was calculated according to the methods outlined in Granier (1987) and Goulden and Field (1994). Sapwood depth was greater than 10 mm on the majority of instrumented trees, thus only a small % of measurements required a correction due to sensor installation in non-functional stem heartwood (see Clearwater et al. 1999). All data from sap-flow sensors was recorded using Campbell Scientific AM16/32 multiplexers and CR1000 dataloggers (Campbell Scientific, Logan, UT).

Statistics

Significance tests for treatment differences in soil VWC and soil water potential (Ψ_S) were performed using one way ANOVA (SAS Software, SAS v9.2: SAS Institute, Cary NC). Statistical tests for treatment differences in air temperature (T_A), soil temperature (T_S), and stem sap-flow (J_S) were analyzed using a linear-effects mixed model with repeated measures. For the repeated measures analysis, an autoregressive first order [AR(1)] covariance structure was utilized. Finally, treatment differences in predawn water potential (Ψ_{PD}) were evaluated using two-tailed t-tests. Differences between groups and/or treatment means were deemed significant at a threshold α value of $p = 0.05$. All mean values are reported with ± 1 SE.

Results

Precipitation and soil moisture

During 2007 and 2008, 679.7 mm of precipitation fell on the site, with the drought plots receiving 467 mm after interception by the plastic infrastructure. The irrigation plots received three supplemental irrigations totaling 57 mm in 2008 and a 2 mm addition to test the system in 2007, increasing the total precipitation input on the irrigated plots over the two year period to 739 mm (Fig. 2A). An examination of the ratio of rainfall collected below/above plastic drought structures during a two-week period of the 2008 monsoon season indicated that approximately 57.9% of the precipitation falling on the gauged drought plot reached the soil surface below plastic troughs. During this test, rain fell on five days and yielded a total of 61.2 mm of rainfall, with daily totals ranging from 1.78 to 29.7 mm. Over those five days of rainfall, the ratio of daily total rainfall collected below the plastic to rainfall collected above plastic ranged from 0.47 to 0.69.

Drought plots had the lowest VWC throughout the year, with little variation between the ambient, cover-control, and irrigation plots (Fig. 2B). VWC at 5 cm soil depth (−5 cm) was significantly different among the experimental treatments ($p < 0.001$), and additional analyses show that there was no difference between the VWC of the irrigation (7.6 ± 0.1%), cover-control (7.8 ± 0.2%), or ambient plots (7.7 ± 0.2%) during this time, but all were significantly ($p < 0.001$) wetter than the drought plots (4.2 ± 0.1%).

Similar to the VWC measurements, Ψ_S in the drought plot at depths greater than −5 cm was lower than in the other treatments (Fig. 2C, D). There was little variation observed in Ψ_S between the ambient, supplemental irrigation, and cover-control plots (south aspect block) at greater depths than VWC measurements in the soil profile (Fig. 2C, D).

Supplemental irrigation

Three watering events added a total of 57 mm of precipitation to the supplemental irrigation plots during the summer of 2008 (Fig. 2A). While there was no variation in the VWC between the irrigation, cover-control, and ambient plots averaged over April–September, there was a distinctive pulse response in VWC following the irrigation events (Fig. 2B). Combining the daily observations for the first week following the three water additions, the VWC of the irrigation plots (10.4%) was significantly greater ($p < 0.001$) than the drought (5.7%), cover-control (8.4%), and ambient (8.4%) plots. Despite several large natural rainfall events following the first and second supplemental irrigations (Fig. 2A), the VWC of the irrigation plots was still significantly greater ($p < 0.001$) than the other treatments two weeks after watering. There were no significant differences between the irrigation, cover-control, and ambient plots three weeks after irrigation ($p > 0.05$).

Temperature

Air temperature 10 cm above the soil surface (T_A) and soil temperature −5 cm below the surface (T_S) exhibited significant variations throughout the year, as well as between treat-

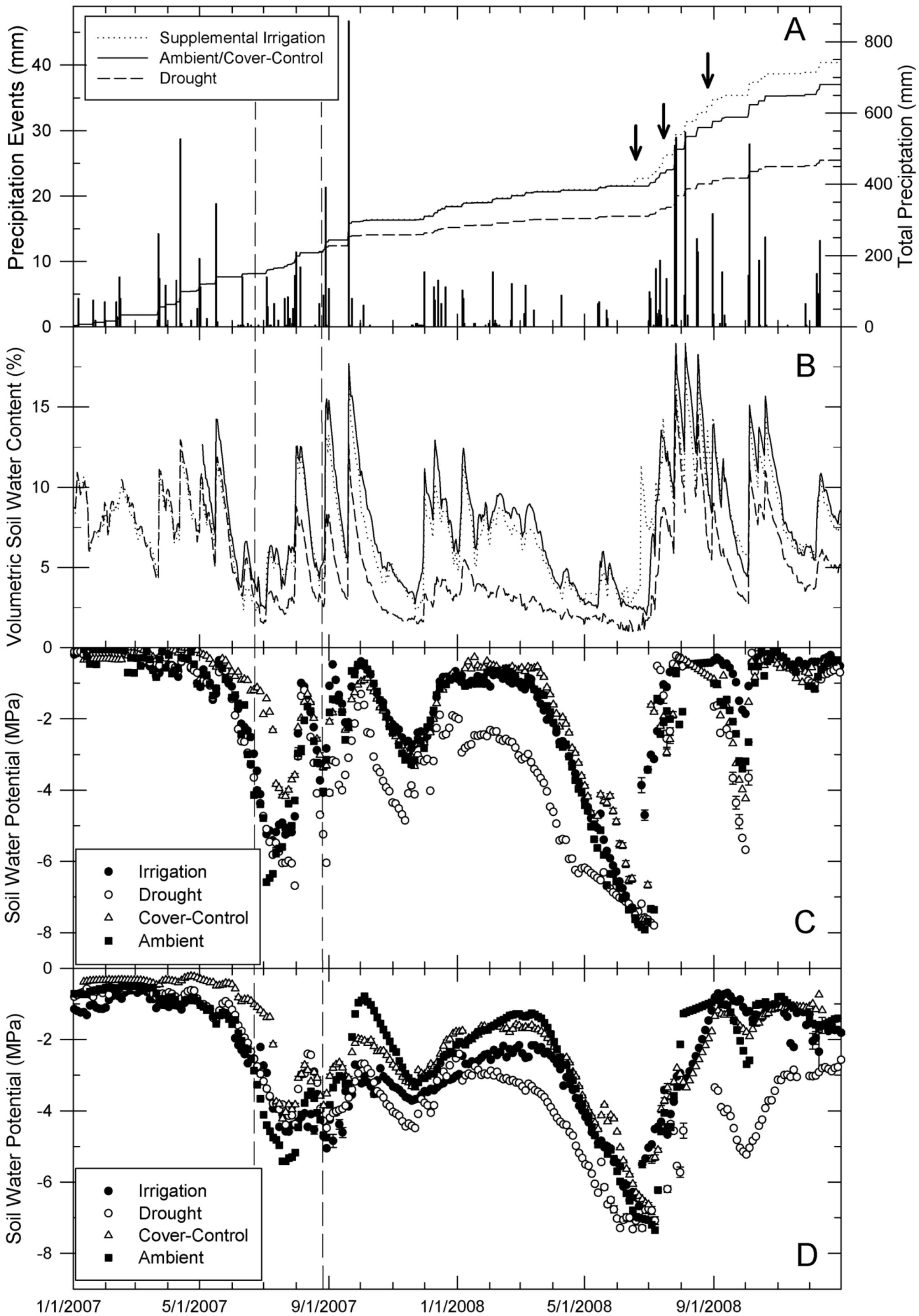

Fig. 2. (A) Total cumulative precipitation across different treatments and natural precipitation events (arrows indicate supplemental irrigation events); (B) mean soil volumetric water content at 5cm depth; (C) soil water potential (MPa) at 20 cm soil depth in south facing block plots; and (D) deepest measurements of soil water potential (up to 80 cm soil depth) in south facing block plots. Vertical dashed lines indicate period of drought and cover-control infrastructure installation. Key in panel A pertains also to panel B.

ments (Figs. 3, 4). There was no significant difference in daily mean, maximum, or minimum T_A at 10 cm (Fig. 3) between irrigation and ambient plots ($p > 0.05$, all contrasts), or between drought and cover-control plots ($p > 0.05$, all contrasts) once plastic infrastructure was installed (summer 2007). The drought and cover-control plots experienced warmer T_A at 10 cm than the irrigation and ambient plots (Fig. 3D–F, $p < 0.05$; all contrasts) throughout the year. The greatest differences in maximum daily T_A at 10 cm were observed between April and September 2008, when temperatures for the irrigation, drought, cover-control, and ambient plots were 29.1 (±0.6), 31.9 (±0.9), 31.2 (±0.6), and 29.1 (±0.9)°C, respectively. Depending on the month, mean daily maximum T_A at 10 cm ranged from 1 to 4°C warmer under the plastic drought and cover-control structures (Fig. 3E). Daily minimum T_A at 10 cm exhibited similar trends across the four treatments (Fig. 3C, F), as did daily mean (Fig. 4A, D), maximum (Fig. 4B, E) and minimum (Fig. 4C, F) soil temperature (T_S). Monthly mean daily maximum and minimum T_S ranged from 1 to 3°C warmer under the plastic drought and cover-control structures compared to ambient plots (Fig. 4E, F). Notably, irrigated plots had significantly lower T_S temperatures ($p < 0.05$, all contrasts) compared to drought and cover-control plots (Fig. 4D–F).

Relative humidity

Relative humidity (RH%) observations at the site met-station ranged from a daily maximum high of 96.7% down to a daily minimum low of 3.4% during 2008 (Fig. 5). Days with very low RH% were commonly observed during late spring/early summer prior to the onset of the North American monsoon (Fig. 5A–C). On a monthly basis, our measurements of RH% made directly below and above plastic drought structures indicated that daily average RH% ranged up to approximately 4% higher for sensors positioned either below or above plastic structures compared to values observed at the site met-station (Fig. 5D), and daily maximum RH% was observed to average up to approximately 6% higher for sensors positioned below and above structures (Fig. 5E). Minimum daily RH% was observed to differ between sensors after the onset of the summer monsoon season, when below-plastic sensors exhibited lower minimum RH% values of 5–6% compared to the site met-station (Fig. 5F). Similar to temperature effects near the soil, air temperature deviations (T_A, from ambient conditions) adjacent to plastic structures were most pronounced during periods of high solar irradiance. Specifically, mean maximum daily T_A ranged up to 6°C higher for sensors positioned directly under the plastic infrastructure compared to the site met-station, and up to 2°C higher for probes positioned directly above the infrastructure (Fig. 5H). In contrast, deviations from ambient in daily mean T_A and daily minimum T_A were much less pronounced (Fig. 5G, I).

Plant water status

Pre-irrigation (10 June 2008) predawn water potentials (Ψ_{PD}) for piñon trees in early June 2008 ranged from a mean of −2.16 (±0.12) MPa in the cover-control treatment to −2.55 (±0.13) MPa in the drought treatment, and there were no significant differences between treatments for piñon trees (Fig. 6). Pre-irrigation (Ψ_{PD}) for juniper trees in early June 2008 ranged from a mean of −5.10 (±0.60) MPa in the ambient control treatment to −7.56 (±0.24) MPa in the drought treatment (Fig. 6), and trees in the drought treatment were significantly more water stressed compared to trees in the other treatments ($p < 0.01$, all contrasts). Pre-irrigation, there were no significant differences in Ψ_{PD} between irrigated, cover-control and ambient juniper trees.

Both species exhibited an increase in Ψ_{PD} following an irrigation event on 24 June 2008 (day 176) prior to the onset of monsoon rains (Figs. 2A–D, 6), a period when Ψ_{PD} was quite negative across all treatments (Fig. 6). Following irrigation, irrigated piñon Ψ_{PD} increased to −1.65 (±0.05) MPa (Fig. 6), significantly differing from piñon trees in other treatments, which continued to exhibit declining Ψ_{PD} values ($p < 0.02$, across contrasts). Likewise, irrigated juniper Ψ_{PD} increased to −2.23 (±0.16) MPa (Fig. 6), which significantly differed from juniper trees in the other non-irrigated treatments ($p < 0.0001$, all contrasts). For both the pre- (10 June 2008) and post- (26 June 2008) irrigation measurements, the most negative mean Ψ_{PD} values for both species were observed in the drought treatment plot (Fig. 6).

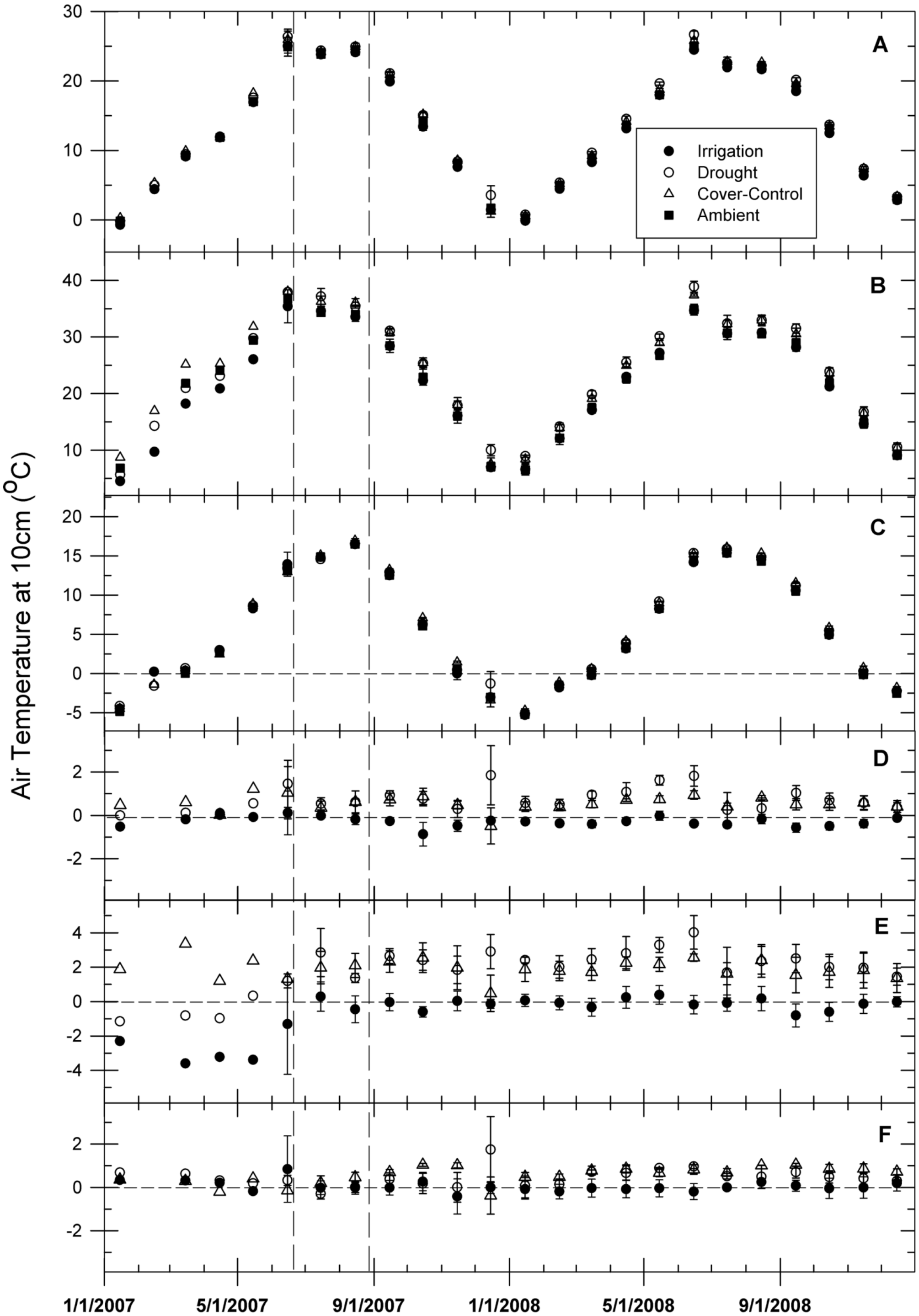

Fig. 3. Monthly mean values (±1 SE) for (A) average daily air temperature (at 10 cm), (B) maximum daily air temperature, and (C) minimum daily air temperature across four experimental treatments. Vertical dashed lines indicate period of drought and cover-control infrastructure installation. Mean treatment differences (treatment − ambient control) presented as follows; (D) average daily air temperature difference, (E) maximum daily air temperature difference, and (F) minimum daily air temperature difference.

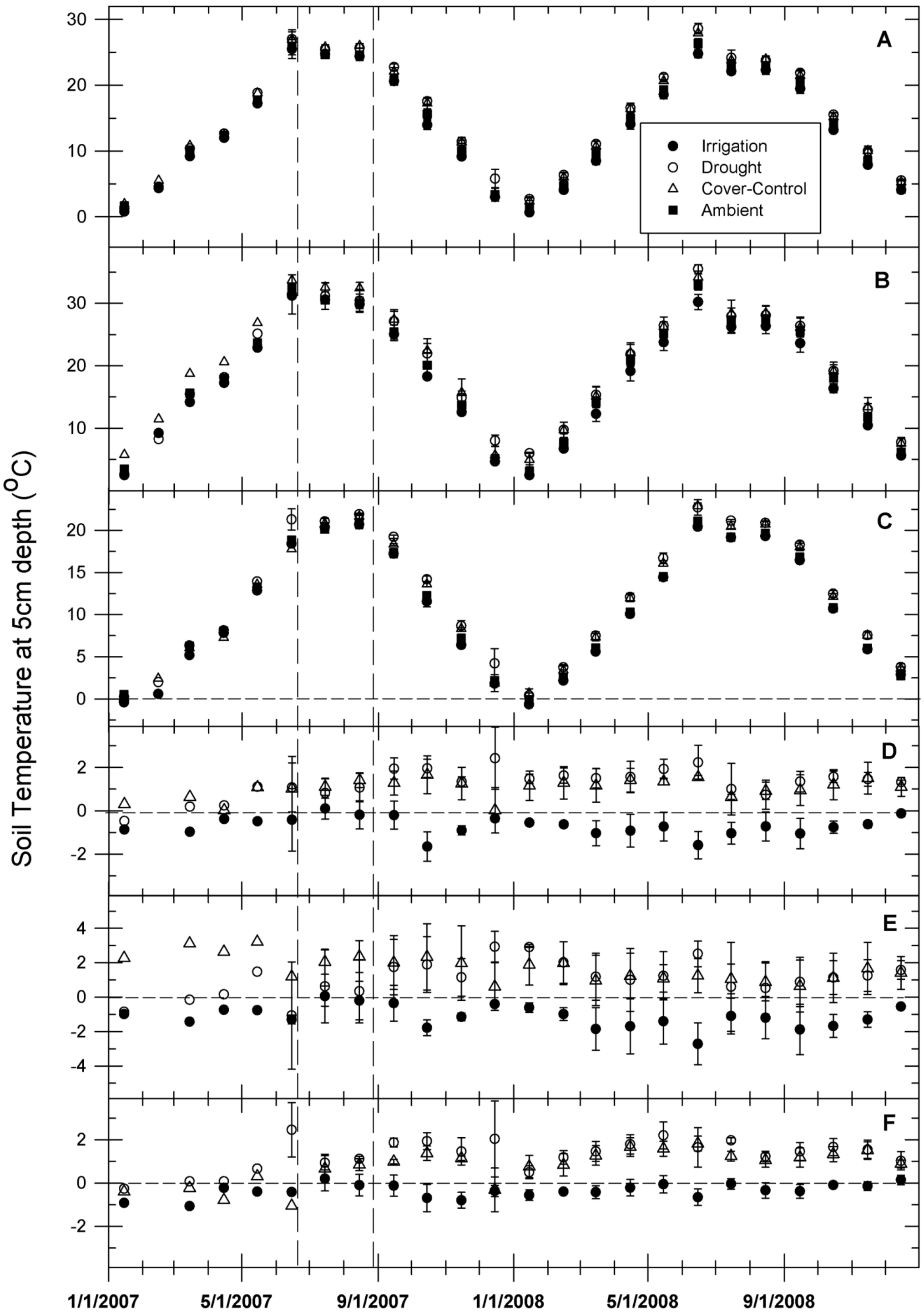

Fig. 4. Monthly mean values (±1 SE) for (A) average daily soil temperature (at −5 cm depth), (B) maximum daily soil temperature, and (C) minimum daily soil temperature across four experimental treatments. Vertical dashed lines indicate period of drought and cover-control infrastructure installation. Mean treatment differences (treatment − ambient control) presented as follows; (D) average daily soil temperature difference, (E) maximum daily soil temperature difference, and (F) minimum daily soil temperature difference.

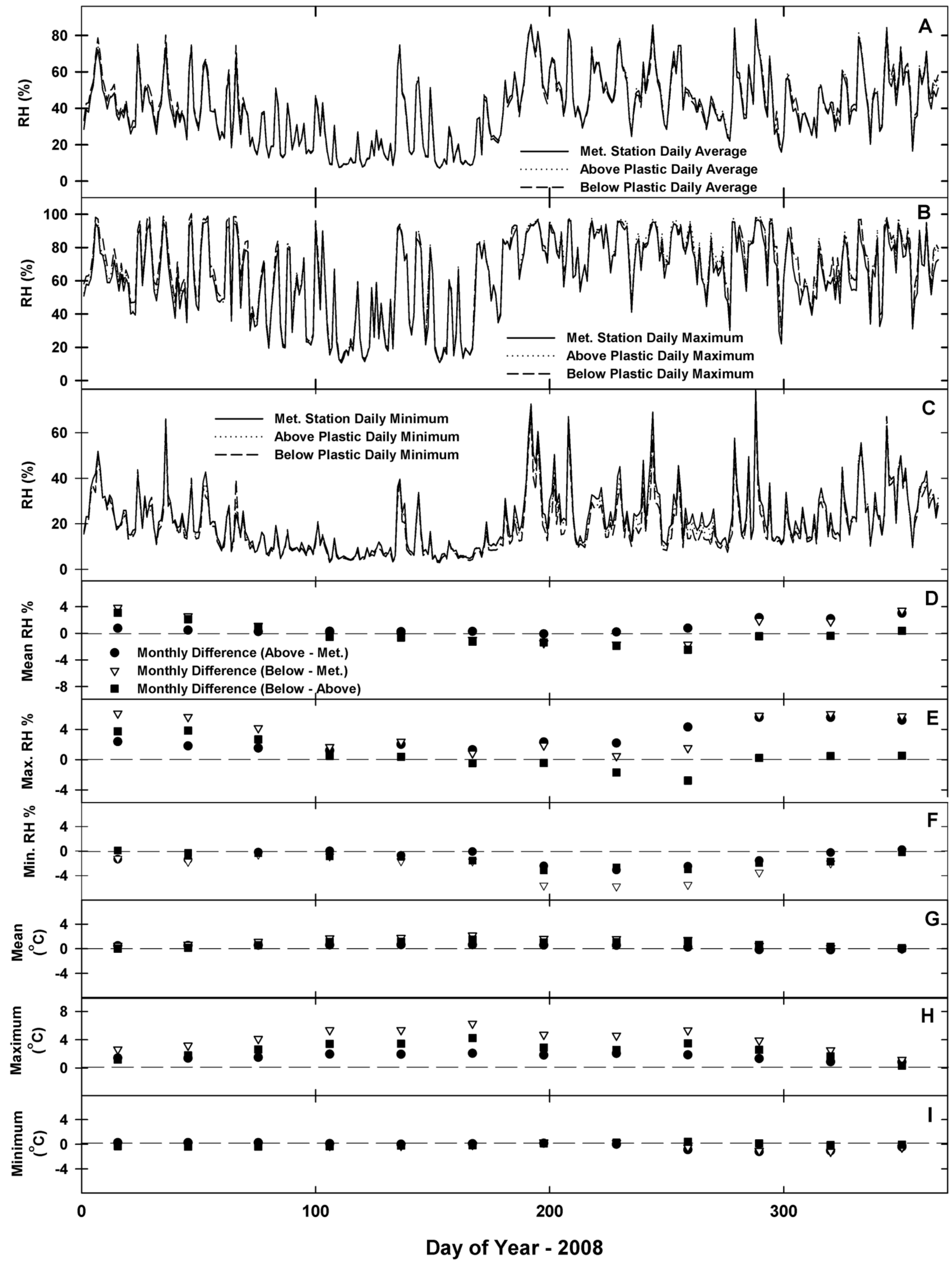

Fig. 5. Relative humidity (RH%) and air temperature measured directly above and below plastic drought structures during 2008. Specific sensor comparisons include (A) Daily average RH%, (B) daily maximum RH%, and (C) daily minimum RH% measured at the site meteorological station and above and below plastic structures. Corresponding differences in RH% and temperature measurements for the aforementioned sensors are presented in panels D–I.

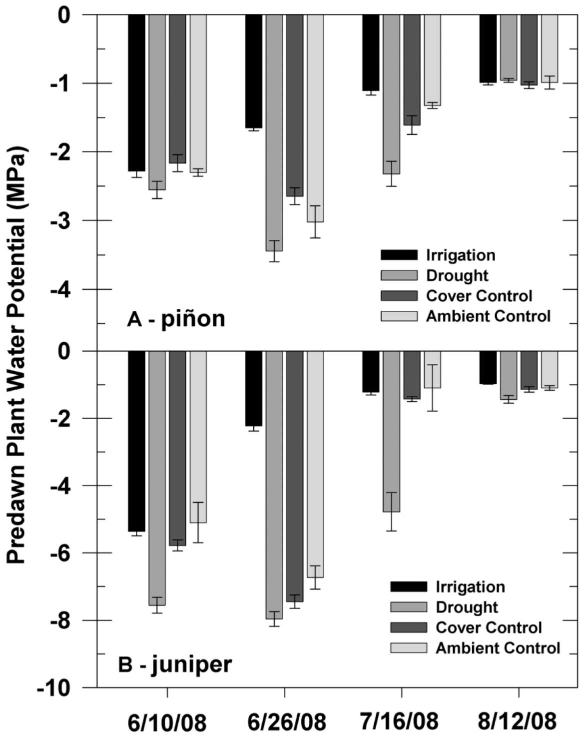

Fig. 6. Pre-dawn plant water potential (Ψ_{PD}) for piñon and juniper trees across four experimental treatments before and after the onset of the 2008 monsoon season. Error bars represent ±1 SE (n = 5).

Predawn water potential (Ψ_{PD}) exhibited an increase in all treatments following the official onset (4 July, day 186) of the 2008 North American monsoon season in New Mexico and Arizona (Figs. 2A, 6). For Ψ_{PD} measured in mid-July 2008, values ranged from a high of −1.11 (±0.06) MPa in irrigated piñon trees to a low of −4.78 (±0.57) MPa in droughted juniper (Fig. 6). The increase in Ψ_{PD} for droughted trees over this period was much less than the observed increase in ambient and cover-control treatments ($p < 0.02$, across contrasts). Irrigated piñon trees (mid-July, second irrigation) had significantly higher Ψ_{PD} values one day post-irrigation (Fig. 6), compared to trees in other treatments ($p < 0.04$, across contrasts). There were no significant differences ($p > 0.05$) in juniper Ψ_{PD} between irrigated and ambient and cover-control trees in mid-July (Fig. 6). By mid-August 2008, the absolute difference in Ψ_{PD} between treatments was much less apparent (Fig. 6), due to the cumulative effect of summer monsoon rains (Fig. 2A–D).

Discussion

Effectiveness of rainfall manipulation structures

In our study, we observed a growing season average VWC% (at 5 cm depth) of 4.2% (±0.1%) in the drought plots, a 45.5% reduction in upper soil VWC% compared to mean values in the ambient plots (7.7% ± 0.2%) during the April to September 2008 period (Fig. 2B). This percentage reduction in upper soil VWC% under our drought structures is in good agreement with our estimates for the percentage of plot area that was covered by plastic structures. On average across all plots with plastic structures (drought and cover-control), 45% (±0.1%) of the total plot area was covered by plastic sheeting. This is similar to the 42.1% reduction in ambient rainfall observed in our rainfall collection tests performed above and below the plastic troughs during summer 2008. Our measures of plot % coverage by plastic, reduced shallow soil VWC%, and the rainfall collection test all yield an average estimate of precipitation reduction in the range of 42–46%. In contrast, our supplemental irrigation events raised VWC for short term periods immediately following treatments (Figs. 2, 7E).

Plant responses to treatments

The drought and irrigation treatments successfully altered soil water availability and water stress of the target trees (Figs. 2, 6). The effects of irrigation were evident in increased plant predawn Ψ_{PD} and stem sap-flow following supplemental irrigation (Figs. 6, 7). The increase in soil water during the normally dry pre-monsoon season served to relieve water stress in irrigated trees, and provided for increased sap-flow and canopy transpiration compared to non-irrigated and drought treatment trees (Fig. 7A, B). Our drought treatment reduced predawn Ψ_{PD} (Fig. 6) and reduced maximum daily piñon and juniper sap-flow rates by 57% and 73% respectively (Fig. 7A, B), compared to peak J_S rates in ambient control trees during pre-monsoon measurements (days 171–181). Following the onset of the monsoon rains, we still observed reductions of maximum daily piñon and juniper J_S rates by 69% and 77% compared to ambient control trees (days 192–202, data not shown). Compared to peak J_S rates in ambient control trees, reductions

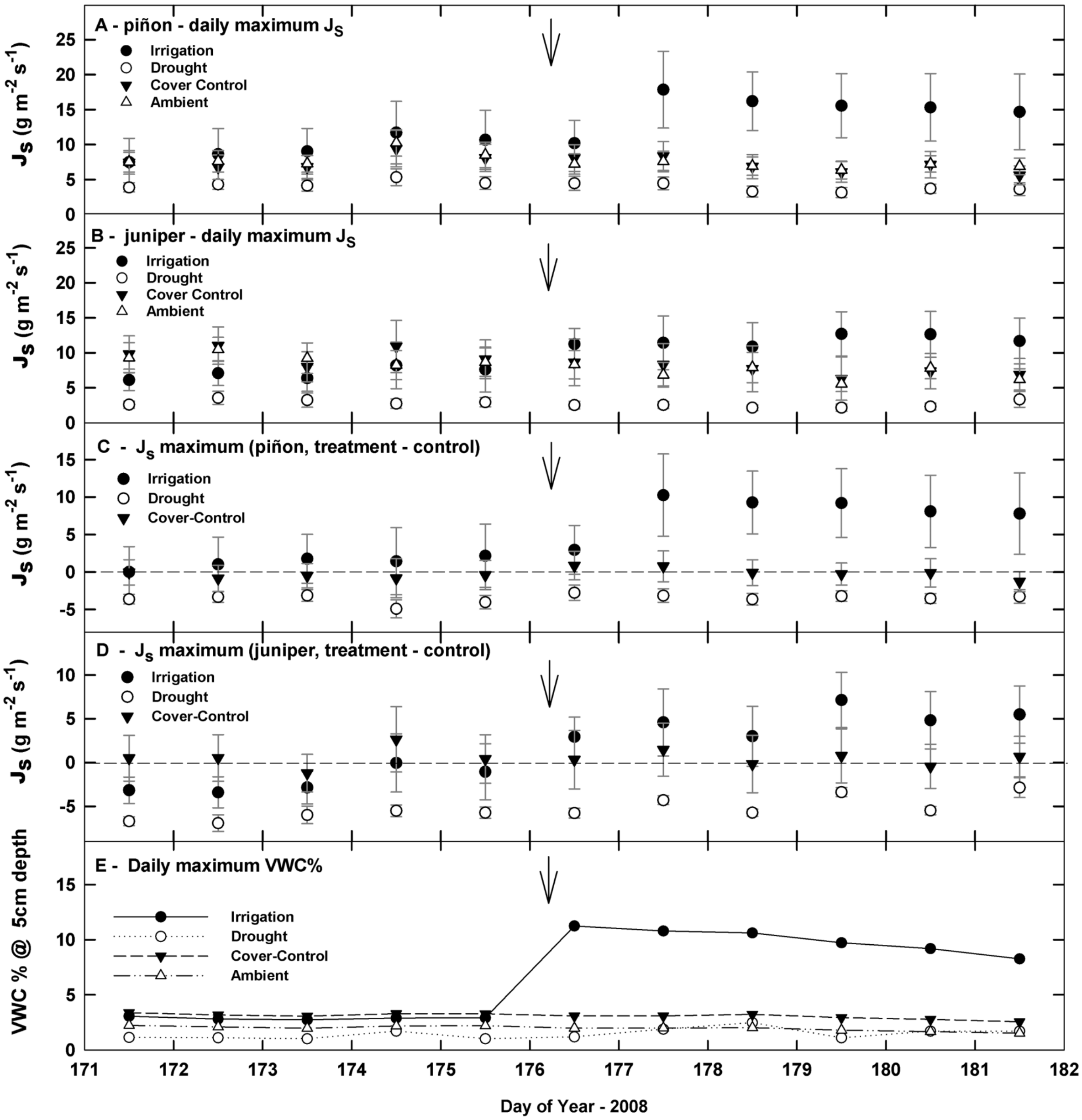

Fig. 7. (A) Piñon and (B) juniper sap-flow response (maximum J_S) to irrigation and drought treatments over days 171–181 prior to onset of the 2008 summer monsoon season. Supplemental irrigation was applied on day-176 at dawn (vertical arrow). Error bars represent ±1 SE of the maximum (J_S) across n = 3 trees per treatment. (C, D) Mean treatment differences in maximum daily sap-flux (J_S, treatment − ambient control). (E) Daily maximum VWC% across the period.

of 65% and 37% in droughted piñon and juniper, respectively, were still evident as late as early August 2008 (days 210–216), a period when cumulative summer rainfall totaled over 93 mm, and soil VWC% had increased significantly (Figs. 2, 6). Taken together, these long-term physiological responses to imposed drought are a good indication that tests of mortality mechanisms related to water stress and drought (McDowell and Sevanto 2010, Sala et al. 2010, McDowell

2011) are feasible with this design.

Indirect treatment effects

Rainfall manipulation structures can have a number of indirect and unintended effects on the microclimate and soils of experimental plots including; (1) changes in temperature, humidity, and vapor pressure deficit (VPD), (2) changes in light quality and quantity, and (3) changes in the spatial pattern of soil water due to the positioning of rainfall exclusion troughs or panels (Fay et al. 2000, Hanson 2000). We observed higher maximum air (T_A) and soil (T_S) temperatures under the plastic drought and cover-control structures in our study, with maximum daily T_A near the soil surface averaging 2 to 4°C above the mean maximum T_A values observed in ambient plots across the April to September growing season of 2008 (Fig. 3E). Differences in minimum daily T_A between ambient and drought/cover-control plots were much less pronounced (Fig. 3F), but slightly higher nighttime minimum T_S values were observed in drought and cover-control plots (Fig. 4F). Differences in daily maximum T_S between treatments exhibited a pattern similar to daily air temperature at 10 cm (Fig. 4E), with the exception of slightly lower T_S values in the irrigation plots, possibly due to higher VWC in surface soils which served to dampen midday temperature increases. We also observed significant transient temperature deviations (T_A) from ambient conditions for sensors mounted adjacent to the plastic structures, with monthly maximum daily T_A ranging up to 2°C higher directly above the plastic infrastructure, and up to 6°C higher directly below structures compared to ambient conditions measured at the site met-station (Fig. 5H). On average, higher maximum air and/or soil temperatures under plastic rainout shelters on the order of 0.5 to 2.5°C have been observed in other rainfall manipulation studies performed in shrub-land, semi-arid desert, and grassland systems (Svejcar et al. 1999, Fay et al. 2000, English et al. 2005). Higher nighttime minimum soil temperatures under plastic rain-out structures have been attributed to reduced nighttime radiative heat loss (Fay et al. 2000).

We observed slight decreases in minimum midday RH% directly below plastic in warmer months, and consistent slight increases in nighttime maximum RH% both directly below and above plastic compared to RH% values measured at the site met-station (Fig. 5). Lower minimum RH% values below plastic structures can be partially attributed to higher daily maximum temperatures observed for sensors below plastic compared to site met-station observations (Fig. 5H). It should also be noted that differences in mean, maximum, and minimum RH% between the paired sensors mounted directly below and above plastic drought structures were often less pronounced than deviations from the site met-station (Fig. 5D–H). This suggests that some portion of the small RH% differences between plastic structures and the site met-station sensors may be due to small scale spatial differences relating to the topographical positioning of the site met-station in relation to the drought structures, especially as it relates to daytime ground/air heating and nocturnal cold air drainage patterns. In addition, the relative differences we observed in our RH% measurements should be interpreted after accounting for potential measurement errors in our sensors. The measurement error of Vaisala HMP45C sensors is $\pm 2\%$, which could account for some of the differences we observed between our plot level RH% sensors and the RH% sensor mounted at our site met-station.

The differences in RH% and temperature (Fig. 5D–H) directly under the plastic structures may impact the physiology of the sparse understory, but most likely had little effect on our target tree canopies, which are above the plastic structures. Periods with very low or zero wind speed are relatively uncommon at our site (mean wind speed across the 2008 growing season was 2.21 m/s), and should serve to increase boundary layer conductance, heat and water vapor transfer, and the efficient mixing of air above plastic infrastructure (Kelliher et al. 1993, Martin et al. 1999), thus preventing an excessive build-up or storage of heat within these canopies. In contrast, wind speeds below the plastic structures could have been much reduced, resulting in lower boundary layer conductance both for small statured plant canopies and at the soil surface. A reduction in boundary layer conductance and mixing of air below the plastic structures could exacerbate the greenhouse effect on leaf temperature (Martin et al. 1999). These peak temperature increases may impact shallow-soil processes below the plastic drought and cover-control structures. Thus, the cover-control treatments should be used as the control for comparison to drought plots when there is a possibility of artifacts impacting the processes of interest. We did not observe any significant changes in cover-control tree sap-flow compared to ambient control trees one year post treatment/plastic structure installation (Fig. 7A, B). Stem sap-flow provides an integrative measure of canopy physiological function, and the absence of significant variation in cover-control stem J_S (compared to ambient control) suggests that indirect experimental artifacts due to treatment infrastructure did not significantly affect canopy level processes (from a transpiration perspective).

Our structures also have the potential to change the spatial pattern of other variables such as soil moisture and light at ground level due to the absence or presence of plastic over a specific spot or location. The individual plastic structures in our design measured 0.81 m (32 in) in width, and rows were up to 40 m long in the absence of breaks for trees, etc. This created considerable ground area under plastic troughs where a percentage of the soil and ground level vegetation were visibly dry most of the time, even following some precipitation events. In cover-control plots, a similar pattern existed directly under plastic, along with the addition of high rainfall deposition (i.e., drip-lines) where water drained off the convex shaped plastic. While small scale spatial patterns in soil VWC most likely impacted soil processes and small statured vegetation (i.e., grasses) directly under structures, its effects were probably much more limited in relation to the target trees. Both piñon and juniper have been shown to utilize water from inter-canopy spaces (Breshears et al. 1997), and mature trees with such a relatively large horizontal rooting pattern should not be as strongly influenced by small scale spatial variations in VWC. However, the fine rooting pattern of target trees could be affected by changes in spatial VWC under plastic structures, and this is certainly a question worthy of further research. In future work, the width and spacing of plastic structures (troughs) could be modified to mitigate or reduce some of the inherent spatial variability of soil VWC that resulted from rainfall exclusion under plastic structures. As discussed earlier, due to the size and canopy height of our target trees, the particular configuration we employed allowed us to successfully drought the piñon and juniper trees at our site (Figs. 1, 2). Conversely, if smaller statured plants such as shrubs, forbs, and grasses were the focus of our study, a rain-out structure with substantially narrower plastic structures/troughs would be required (see Yahdjian and Sala 2002).

We also tested the effects of the plastic on PAR transmittance by performing diurnal measurements of PAR below plastic in both a drought and cover-control plot. Measurements were made from 0900 to 1600 hrs on a single day (day 299), when ambient PAR ranged from 700-1400 μmol m^{-2} s^{-1}. Measurements of PAR below the plastic (both treatment types) averaged 83.3% ($\pm$0.5%) of ambient levels, and PAR reductions ranged from 15% to 19% diurnally. Reductions in PAR ranging from 21% to 50% under rain-out structures have been previously reported (Svejcar et al. 1999, Fay et al. 2000, Yahdjian and Sala 2002). Our structures also reduce the transmittance of UV light below the plastic due to a UV protective coating that is necessary in this high-radiation environment to protect the structures for multiple years of experimental treatment. This may influence processes such as photo-degradation of surface litter, which could impact decomposition processes given the chronic drought conditions that persist directly under our plastic drought and cover-control structures (Austin and Vivanco 2006).

Future applications

A number of differing scenarios can be explored with the type of irrigation system we employed, including tests regarding the timing, frequency, and intensity of supplemental water additions. For example, this system could potentially apply numerous supplemental irrigations over a short period prior to the normal onset of summer monsoon rains. This strategy would have experimentally simulated a temporal shift in the timing and duration of the summer monsoon rains in this system. A wide range of scientific tests of value to hydrology, soil processes, and tree physiology can be employed with this type of a system. We did not attempt to simulate a temporal or quantitative shift in monsoon precipitation due to technical and logistical constraints related to water availability. We simply employed supplemental irrigations on a monthly basis to alleviate seasonal plant water stress across the growing season.

Finally, while rainfall manipulation experiments of the type we employed have been shown to successfully reduce ambient rainfall, these types of ecosystem level rainfall experiments generally do not incorporate treatment factors such as warming and changes in ambient RH% and VPD at the ecosystem scale due to logistical, technical, and monetary constraints. Under certain future climate scenarios, warmer temperatures will accompany future droughts (Allison et al. 2009), impacting physiological processes directly and through increased evaporative demand. In our study we manipulated the supply side of the soil plant air continuum model without any attempt at modifying canopy temperature or evaporative demand. The next generation of experimental manipulations to determine plant responses to future climate change should also include whole system warming treatments when possible.

Conclusion

The design and configuration of our rainfall manipulation structures effectively reduced soil water availability and increased the water stress experienced by targeted trees. In contrast, our irrigation treatments successfully served to elevate soil water availability and alleviate water stress in targeted trees, especially during prolonged seasonal dry periods at our site. The rainfall manipulation infrastructure produced small changes in the abiotic environment due to the high solar radiation load and low canopy coverage in this ecosystem. The successful manipulation of the severity of plant water stress allowed us to examine the physiological response of piñon (*P. edulis*) and juniper (*J. monosperma*) to a wide range of drought conditions—conditions that have been observed historically during severe droughts in the past, and conditions that could become more frequent in the future given recent climate model predictions for this region.

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