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Automated rainfall manipulation system: a reliable and inexpensive tool for ecologists

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Abstract. Water availability is the major limiting factor of the functioning of deserts and grasslands and is going to be severely modified by climate change. Field manipulative experiments of precipitation represent the best way to explore cause-effect relationships between water availability and ecosystem functioning. However, there is a limited number of that type of studies because of logistic and cost limitations. Here, we report on a new system that alters precipitation for experimental plots from 80% reduction to 80% increase relative to ambient, that is low cost, and is fully solar powered. This two-part system consists of a rainout shelter that intercepts water and sends it to a temporary storage tank, from where a solar-powered pump then sends the water to sprinklers located in opposite corners of an irrigated plot. We tested this automated system for 5 levels of rainfall, reduction-irrigation (50–80%) and controls with $N = 3$. The system showed high reduction/irrigation accuracy and small effect on temperature and photosynthetically active radiation. System average cost was $228 USD per module of 2.5 m by 2.5 m and required low maintenance.

Key words: automated rainfall manipulation system (ARMS); irrigation system; manipulative experiment; methods; precipitation manipulation; rainout shelter.

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INTRODUCTION

Manipulative experiments are unique tools for studying causality of potential ecosystem responses to climate change (Sala et al. 2000) and constitute the basis for assessment and modeling of the response of ecosystem functioning to global climate change (Leuzinger et al. 2011). However, such experiments are relatively scarce because of expense and logistical constraints. Observational studies tend to be less costly and have effectively used time series within sites or cross-site comparisons and have generated an important body of knowledge (Huxman et al. 2004*a*, Sala et al. 2012). However, these studies are often limited in their ability to study causality because they cannot isolate variables under study from co-varying factors such as climate or soil properties. Thus, cost-effective manipulative experiments are a unique tool to study causality in ecological responses to changes in manipulated variables and to unravel the mechanisms behind observed response patterns.

Water availability constrains ecosystem functioning in arid to sub-humid ecosystems (Nemani et al. 2003), which occupy about one-third of the terrestrial surface of the Earth (Reynolds et al. 2007). Many ecosystem processes from microbial activity (Liu et al. 2009, Yahdjian and Sala 2010), to aboveground net primary production (Sala et al. 1988, Sala et al. 2012) are affected by water availability. And, climate change will affect water availability directly through changes in precipitation or indirectly through temperature and evaporative demand increases (Seager et al. 2007). Therefore, precipitation manipulation experiments become a key tool for scientists working towards a better understanding of the consequences of climate change on the functioning of ecosystems.

Methods for experimental rainfall manipulations can be divided in two main groups: active and passive (Hanson 2000). Active manipulations range from simple handheld sprinklers to fixed overhead sprinklers. Passive systems consist of partial interception rainout shelters or complete roofs that divert water from target plots. Yahdjian and Sala (2002) developed a rainout shelter design that has been replicated in many experiments around the world. Combinations of passive and active systems have been used in EXMAN projects in Europe for forest ecosystems (Beier et al. 1995) and by the RaMPs project in a grassland ecosystem in the United States (Fay et al. 2000). Experimental manipulations that include both rainfall exclusion and irrigation allow for testing responses to drought and increased water availability and their potential asymmetry. Most water manipulation experiments have used five replicates or less, and are usually limited to three (Liu et al. 2002, Huxman et al. 2004*b*, Harper et al. 2005, Dermody et al. 2007, Heisler-White et al. 2009, Carlyle et al. 2011) by high cost and logistical difficulties (Pangle et al. 2012). A water manipulation system that combines rainfall exclusion and water addition that is of low cost and relatively easy implementation would allow a greater number of experiments aiming to understand ecosystem responses to changes in water availability.

The objectives of the present study were: (1) to design a system that provides broad changes in precipitation in experimental plots at low cost and that requires low maintenance and no connection to the electrical grid, (2) to test the accuracy of the rainfall manipulation system and its impact on other environmental variables. The low cost requirement is essential to achieve adequate experimental replication, and the low maintenance and grid independence are necessary to implement treatments in remote locations.

The automated rainfall manipulation system (ARMS) described here is a combination of a fixed location rainout shelter and an active system that diverts water from rainfall exclusion plots to irrigation plots. The experimental design to test the system had 5 levels of precipitation, 3 replicates and used 2.5 m $\times$ 2.5 m plots located in the Chihuahuan Desert in New Mexico. We measured rainfall manipulation accuracy, soil water content, air temperature, and photosynthetically active solar radiation (PAR) under the rainout shelters.

Methods

The automated rainfall manipulation system (ARMS) consists of coupled interception and irrigation plots (Figs. 1 and 2). Rainout shelters, in our case, intercepted either 50% or 80% of incoming precipitation, although the interception amount can be adjusted by changing the shingle density. Water from the shelters was stored temporarily in tanks and from there transferred to the irrigation system that increases precipitation by 50% and 80% relative to ambient (Figs. 1 and 2). Rainout shelters were based on the design reported by Yahdjian and Sala (2002). This type of shelter has been constructed and tested for field conditions at the Jornada LTER for 2006–2012 and they are currently being used in many experiments from Alaska to Patagonia (Yahdjian and Sala 2002, Yahdjian et al. 2006, Cipriotti et al. 2008, Heisler-White et al. 2008, Fiala et al. 2009, Chimner et al. 2010, Throop et al. 2012; Archer, *personal communication* AZ; Collins, *personal communication* NM; Knapp, *personal communication* CO; Schwinning, *personal communication* TX; Belnap, *personal communication* UT; Shaver, *personal communication* AK). The shelter design consists of a metal structure that supports V-shaped clear acrylic bands or shingles with high light transmission and low yellowness index (Yahdjian and Sala 2002). To construct the shingles, we bought acrylic sheets (from Regal Piedmont Plastics, LLC, El Paso, TX) that were cut in 254 cm length by 12.7 cm wide stripes. Then, we heated them using a Straight Line Bender, placed the heated shingle on top of a wood mold and put some weight on top of it. After cooling down, the shingle keeps the shape

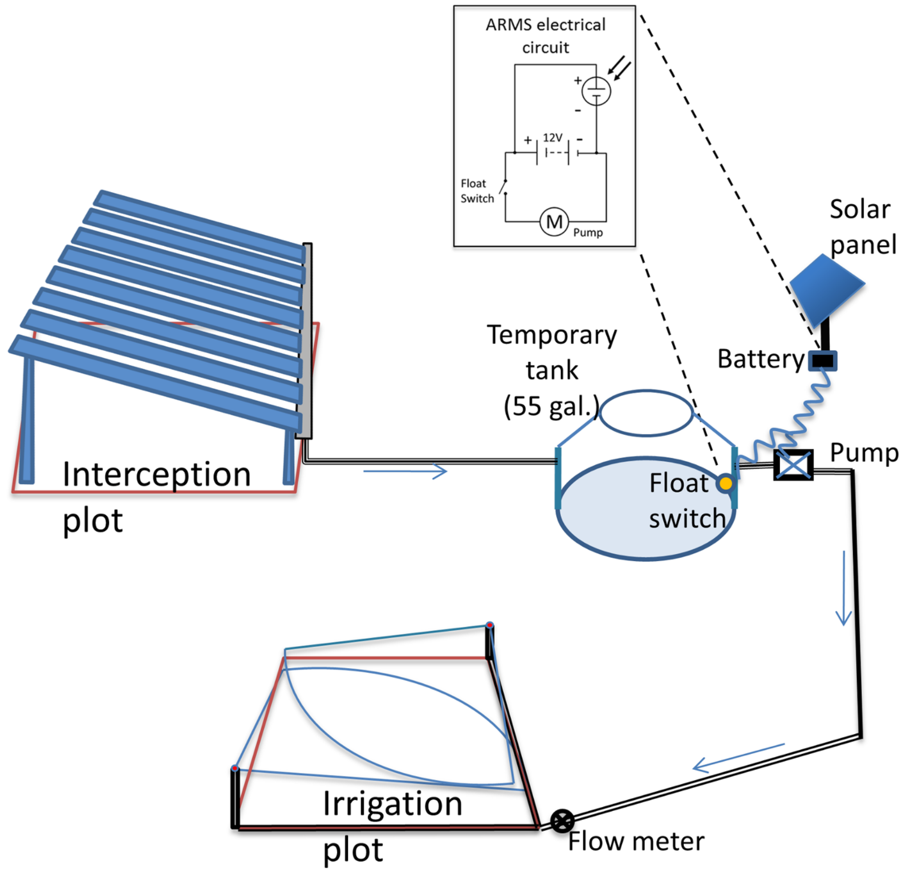

Fig. 1. Automatic rainfall manipulation system (ARMS) design showing the interception and irrigation components. Inset shows electrical circuit details.

of the mold, resulting in a shingle 11-cm wide bent in a 120° angle. In order to windproof our shelters, we buried a 150-cm long rebar 75 cm into the soil; the aboveground part of the rebar in each corner of the plot fitted in the metal structure of the shelter. Finally, we tightened the legs of the shelter to the rebar using wire.

Intercepted water was channeled through a gutter and discharge pipe to a 55-gallon generic plastic tank. When water in the storage tank reached a certain level, a float switch turned on a water pump that drove the water to an irrigated plot through a 3/4-inch PVC pipe line. We used an Atwood Marine Automatic float switch to turn on the electric pump. The float switch was carefully located to match the level of the tank outlet so the switch would turn off the pump before the tank was empty, preventing pump damage. The Pacific Hydrostar 12-volt utility pump has a maximum pumping rate of 200 gallons per hour at approximately 10 PSI. To power the pump we used a 12-volt, 15-amp/hour generic battery recharged by a 5-watt Solartech SPM005P solar panel. Two Rain Bird 8-VAN adjustable spray nozzles located at opposite corners of irrigated plots distributed water on top of the canopy. We calibrated the angle and radius of each nozzle on site before each rainy season so water fell uniformly within irrigated plots (Fig. 1).

Description of the experiment and measurements

Our experimental design consisted of 5 treatments; 4 levels of precipitation manipulation −80%, −50%, +50%, +80% relative to ambient precipitation plus a control. We used three replicates per treatment, totaling 15 plots of 2.54 m by 2.54 m size. Plot size is adequate to

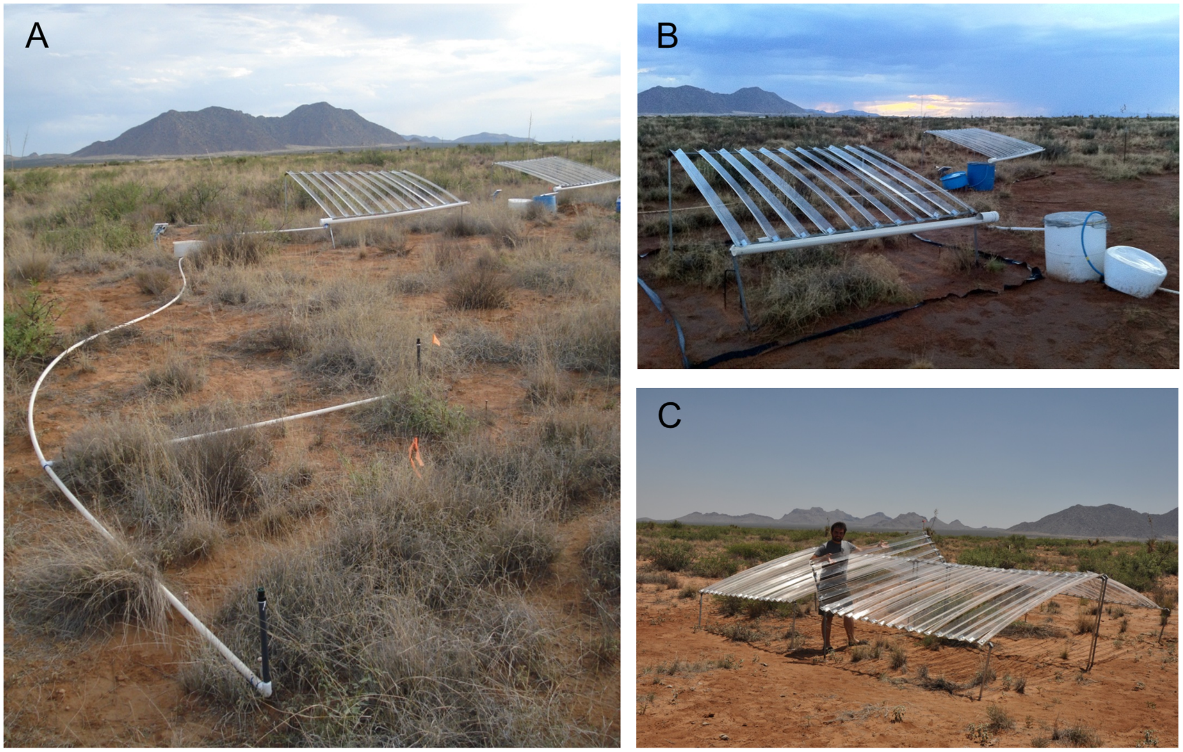

Fig. 2. Automated rainfall manipulation system (ARMS) photos showing, (A) interception and irrigated plots, (B) a view of the interception component and its connection to the storage tank, (C) four modules of rainout shelters put together including a removable panel with hinges that allows walking access to the center of the plot.

modify the water supply to Chihuahuan Desert plants based on data regarding size of individuals (Drewa et al. 2006) and magnitude of the edge effect (Yahdjian and Sala 2002). We trenched all plots down to 60 cm depth or to caliche layer depth using 6 mil PVC film in order to avoid horizontal water exchange between plots and surrounding non-manipulated areas.

Expected and observed precipitation measurements assessed the accuracy of the system to capture water and transfer it to irrigated plots. Soil water, air temperature and photosynthetically active radiation (PAR) estimated environmental effects of the ARMS. We calculated expected precipitation received underneath rainout shelters as the product of plot area, water column height for the growing season and a target manipulation coefficient (i.e., 1.8 for the +80% treatment or 0.5 for the −50% treatment). Actual water excluded from sheltered plots and added to irrigated plots was estimated using flow meters located in the PVC pipeline right before irrigated plots (Fig. 1). We measured soil water content in the top 30 cm of the profile hourly using Campbell Scientific CS625 probes and logged onto Campbell Scientific CR200X data loggers. We measured air temperature every 30 minutes at canopy height using iButtons DS1921c and PAR with a LI-COR line quantum sensor model LI-191 along three parallel and evenly spaced permanent lines per plot, each of 250 cm length. We placed the radiation sensor above the canopy; and six readings distributed through each plot were taken at 10:00, 12:00 and 17:00 hours under clear sky conditions during the growing season.

We carried out statistical analyses using R version 2.14.2 (R Development Core Team 2012) and used a linear regression model blocked by year to analyze expected and observed precipitation relationships. Repeated-measures ANOVA analyses were used for soil moisture and air temperature testing for treatment, time and interaction effects. We tested effects on PAR using single-factor ANOVA analysis performed for each time during the day with treatment as main effect. The six readings taken on each plot were treated as subsamples.

Results and Discussion

Observed versus expected precipitation results across treatments fulfilled our objective of designing a system that modified a broad range of incoming precipitation (Fig. 3). We successfully manipulated rainfall from 80% exclusion to 80% addition relative to ambient precipitation. The slope of a fitted model of observed precipitation regressed to expected precipitation across all treatments (Fig. 3; $PPT_{obs} = 2.11 + 1.004\ PPT_{exp}$, $F_{1,22} = 280$, $P < 0.0001$) was not significantly different from a 1:1 model for two growing seasons (Fig. 3; $t = 0.0006$, $P > 0.05$). The intercept of the fitted model was not significantly different from zero (Fig. 3; $t = 0.35$, $P = 0.72$). Flow meter readings are a reliable metric of irrigation effectiveness because there is no other source of water than the rainout shelter, and all of the water running through the flow meter is ensured to get into the irrigated plot. Although the two monitored growing seasons were contrasting in terms of precipitation amount, ARMS successfully manipulated rainfall to the desired levels in both cases.

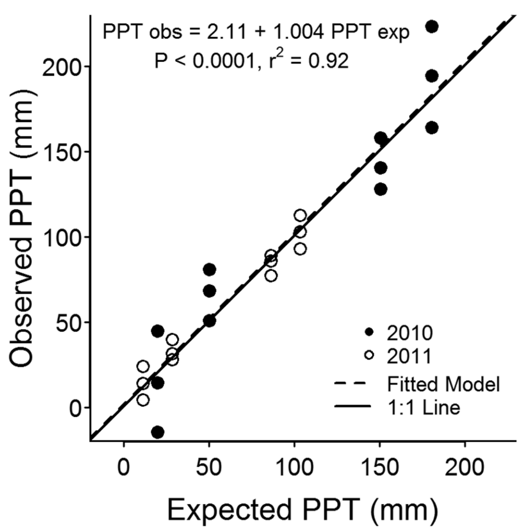

Fig. 3. Observed versus expected precipitation for 4 precipitation manipulation treatments and a control during two growing seasons; full circles 2010 and empty circles 2011. Fitted model (dashed) and 1:1 (solid) lines are plotted. Precipitation in mm was estimated from flow meter readings located in the pipe line prior to irrigated plots.

Rainfall manipulations translated into significant differences in volumetric soil water content among treatments ($F_{4,10} = 11.08$, $P = 0.001$). Irrigated plots showed higher soil moisture than rainfall interception plots; and control plots showed intermediate values (Fig. 4). The passive interception and the active irrigation components of the ARMS had perfect timing therefore both passive interception and active irrigation treatments showed simultaneous peaks of soil moisture (Fig. 4). The small differences between +50 and +80% treatments may be due to the fact that pulses generated by the 50% rainfall addition may have saturated the 0–30 cm layer percolating to deeper layers. Water percolation to deep layers (>80 cm) in response to rain was observed for three different soil types in the Jornada LTER (Duniway et al. 2010). Our automated irrigation system had the advantage over manual systems that it did not modify number of rain events nor irrigate the day after a rain event when other climatic conditions (i.e., temperature, radiation) could be substantially different than conditions during the rainy day.

Side effects of ARMS on PAR and temperature were very small. Incoming PAR was slightly reduced underneath rainout shelters in the morning ($F_{2,6} = 5.291$, $P = 0.04$) and at noon ($F_{2,6} = 33.05$, $P < 0.0001$) but was similar across treatments in the afternoon (Fig. 5; $F_{2,6} = 0.717$, $P = 0.52$). Mean overall incoming radiation as a percent of control plots was 94.1% for the 80% PPT reduction treatment and 97.2% for the 50% PPT reduction treatment. An explanation for such low effect is that the tall end of rainout shelters faces south allowing a large fraction of the plot to receive direct sunlight.

Temperature was also minimally affected by the presence of rainout shelters. There were no significant differences among treatments in mean daily temperature in any of the two monitored growing seasons (Fig. 6 A, B; $F_{2,6} = 0.254$, $P = 0.78$, $F_{2,6} = 0.5$, $P = 0.63$). However, there was a significant increase in mean night-time temperature of 0.8°C and 0.55°C for the 80% and 50% PPT interception treatments respectively (Fig. 6 C, D;

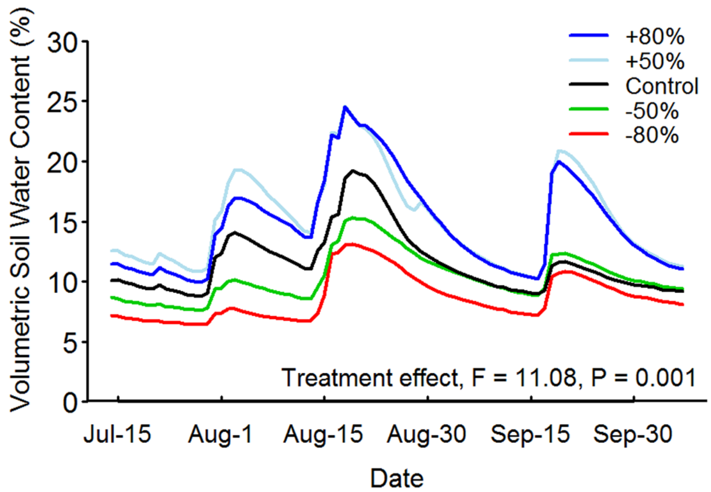

Fig. 4. Precipitation manipulation effect on soil water content 0–30 cm depth during 2011 growing season. Lines represent mean daily values of hourly recorded data. Manipulation treatments range from 80% and 50% interception to 50% and 80% addition relative to ambient precipitation, and a control.

$F_{2,6} = 16.56$, $P = 0.003$, $F_{2,6} = 10.46$, $P = 0.01$). Rainout shelters may absorb, re-radiate and reflect long-wave radiation emitted by the soil surface at night, slightly increasing canopy temperature in experimental plots. This effect is probably offset during the day by a small reduction in short wave radiation. Even though we found significant differences among treatments, radiation and temperature results showed that ARMS had small average side effects.

The ARMS design has been very resistant to extreme climatic conditions. For example, ARMS withstood windy and high irradiance conditions of the Chihuahuan Desert with average wind speed of 12 km h^{-1}, maxima of 80 km h^{-1} and solar radiation as high as 671.1 MJ m^{-2} (Wainwright 2006). Rainout shelters also contended well under high wind conditions of the Patagonian Steppe with wind maximum values of 70 km h^{-1} (Beltran 1997). Performance of the

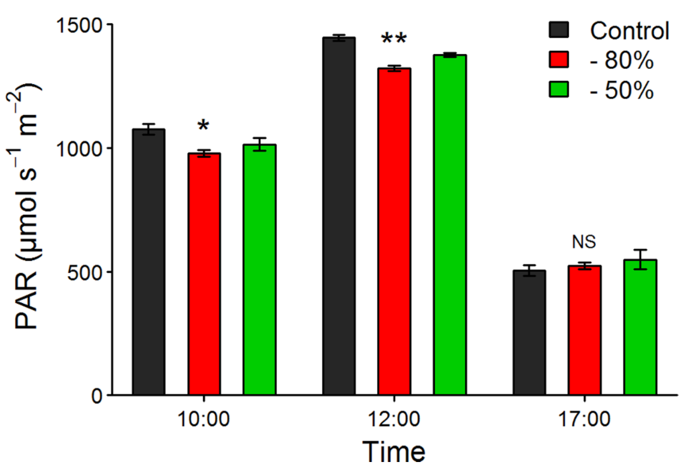

Fig. 5. Rainout shelter effect on photosynthetically active radiation (PAR), 6 subsamples evenly located per plot measured on top of the canopy. Bars indicate mean ± 1 SE for interception and control treatments at three different times, under clear sky conditions. One star indicates p-value < 0.05, double star indicates p-value < 0.01 and NS indicates non-significant differences among treatments for a particular time.

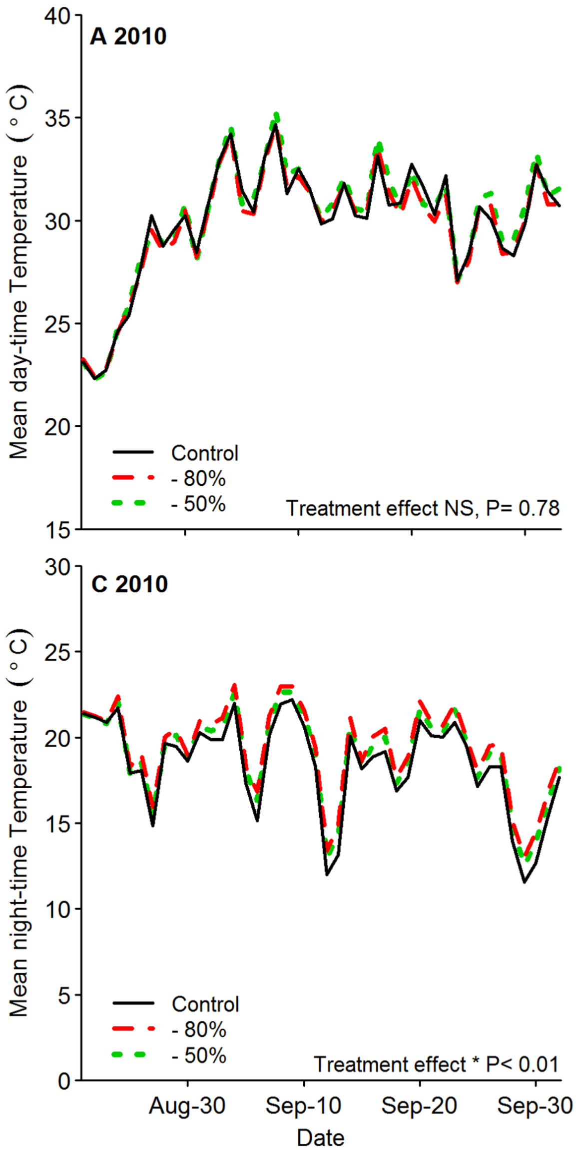

Fig. 6. Rainout shelters effect on air temperature at the canopy level. Lines represent mean day-time temperature (panels A and B) and mean night-time temperature (panels C and D) of data recorded every 30 minutes for two growing seasons.

interception component of ARMS was estimated as the edge effect to be just 20 cm (Yahdjian and Sala 2002). The irrigation component performed properly under weather conditions of the experimental period. Soil moisture was successfully manipulated to target values (Fig. 4). Other experiments looking at ecophysiological plant responses (Throop et al. 2012) and aboveground plant productivity (Reichmann et al., *in press a*) used similar irrigation systems under similar conditions and yielded significant irrigation effects.

ARMS is a flexible system in terms of ecosystem type where it can be implemented ranging from arid to sub-humid ecosystems. Studies carried out in humid or tree-dominated ecosystems need larger scale designs than ARMS in order to be able to handle large amounts of water across tall canopies (see Pangle et al. 2012). ARMS is also versatile in terms of target

Table 1. ARMS cost in U.S. dollars per experimental unit of 2.5 m by 2.5 m in 2011. Cost of the interception component is separated for the 50% and 80% interception treatments (Yahdjian and Sala 2002). The irrigation component has the same cost for both 50% and 80% water addition treatments. The average cost per plot of the 50 and 80% treatment is presented.

Component	Cost (US$)
Interception	
Structure	
Rebar	12
Electrical metal conduit	18
Elbows	18
Gutter	20
Bolts and nuts	10
Wire (2.5 m per shelter)	2
Shingles	
50% (11 acrylic stripes)	83
80% (18 acrylic stripes)	135
−50%	$162
−80%	$215
Irrigation	
Battery	33
Pump	35
Solar panel	38
Float switch	20
Tank	50
Pipe & fittings	65
Flow meter	45
Other	20
Irrigated	$306
Mean cost per plot	**$228**

manipulation because percentage of manipulated rainfall can be easily modified by changing shingle density and requires the same irrigation system. ARMS plot size can also be modified, modules of 2.5 m by 2.5 m can be put together to manipulate PPT over larger plots. For example, we built a 6 m by 5 m shelter in the Jornada LTER using four rainout shelter modules with a removable 1-m wide section that allowed walking access to a neutron probe tube located in the center of the plot (Fig. 2C). The removable section of the shelter had hinges that allowed easy opening and closing (Fig. 2C). The irrigation component for such a large plot could be handled by the exact same tank, pump and pipeline used for the design presented here for the 2.5 m by 2.5 m module. However, it may need different nozzles in order to cover a large irrigated plot but there is a wide range of nozzles commercially available. The cost of larger ARMS scales up linearly to the number of shingles for the interception component and stays almost constant for plots up to 8 m by 5 m for the irrigation component.

The flexibility of our design allows researchers to adapt it to a variety of sites and studies. A broad range of hypotheses from the population and community to ecosystem scale can be tested using ARMS. Examples of recent studies that used some sort of rainfall manipulation system include those that tested for the occurrence of precipitation legacies on primary production (Sala et al. 2012; Reichmann et al., *in press a*) and the effects of water availability on ecophysiological responses of grasses and shrubs (Throop et al. 2012), to those that assessed effects of precipitation change on the nitrogen cycle (Reichmann et al., *in press b*).

ARMS is a great tool for ecologists interested in manipulating precipitation and is available at a mean cost of $228 USD per module of 2.5 m by 2.5 m (Table 1). It is able to successfully manipulate incoming precipitation and translate it into different soil water contents and have small effects on temperature and incoming radiation. The low cost of ARMS has two advantages. First, it solves the limitation imposed on the number of replicates by previous expensive designs. Second, it allows for the implementation of precipitation manipulation experiments in countries where funding sources are limited and may ameliorate the concentration of experiments in the Northern Hemisphere. ARMS operates off the electrical grid since it is fully solar powered, allowing installation in remote locations and distribution of experimental units according to spatial environmental heterogeneity specific to each study site and independent of the location of power sources. ARMS maintenance is estimated at one month of work for two people per year to maintain 10 replicates of 5 levels of precipitation manipulation totaling 50 plots. This low work effort required is due to the automatic design, which also keeps the number of rain pulses and timing constant across treatments.

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