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METHODS

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A rainout shelter design for intercepting different amounts of rainfall

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Abstract Field manipulative experiments represent a straightforward way to explore temporal relationships between annual precipitation and productivity. Water exclusion usually involves the use of rainout shelters, which are in general formed by a complete roof that intercepts 100% of the rainfall and require complicated mechanisms to move the shelter into place. The rainout-shelter design described here is a fixed-location shelter with a roof consisting of bands of transparent acrylic that blocks different amounts of rainfall while minimally affecting other environmental variables. We constructed thirty 3.76-m^2 shelters in an arid steppe near Río Mayo, Argentina (at 45°41′S, 70°16′W), to impose 30%, 55%, and 80% of rainfall interception. We tested the effectiveness of the design by collecting all the intercepted water in storage tanks and we evaluated changes in soil water content with the time domain reflectometry technique. We also measured soil water content in regular grids to assess the magnitude of the edge effect. We analysed the microclimate impact of the shelters by measuring photosynthetically active radiation and air and soil temperature inside and outside shelters. We did not detect significant differences between the observed and the expected rainfall interception for the 30% and 55% interception treatments but the 80% shelters intercepted 71% of incoming rainfall, which was significantly ($P<0.05$) lower than the expected value. Soil water content was significantly ($P<0.05$) higher in the control plots than in the plots with rainout shelter at all dates, except in January (summer). Radiation was not affected by the 30% interception treatment, but the roof with the largest number of acrylics bands (80% interception treatment) reduced incident radiation throughout the day by 10%. Air and soil temperatures were lower under than outside the shelters during the period of highest radiation but the opposite occurred with low radiation but with smaller differences. The two characteristics of the shelter, fixed design and low cost, allow for proper replication in space, which is required in ecological field experiments.

Keywords Arid ecosystems · Manipulative experiments · Rainfall manipulations · Soil moisture

Introduction

Water limitation constrains net primary productivity in grasslands, in both temperate and tropical regions (Noy-Meir 1973; Lieth and Whittaker 1975; Boutton et al. 1988; Le Houerou et al. 1988; Sala et al. 1988; Briggs and Knapp 1995). A robust assessment of the degree that water availability limits ecological processes under present climatic conditions is required before making predictions about responses to future climatic scenarios (Knapp et al. 2001). From an applied perspective, productivity responses to altered precipitation regimes are also important because they influence the capacity of grasslands to support livestock production and to sequester carbon.

There has been significant progress towards the understanding of controls of primary production of grasslands at a regional scale. Aboveground net primary productivity (ANPP) increases linearly along spatial precipitation gradients within the range of 200–1,300 mm/year in North American, South American, and African grasslands (Webb et al. 1978; Lauenroth 1979; Sala et al. 1988; McNaughton et al. 1993; Paruelo et al. 1998). Much less is known about the controls of the temporal, interannual variation of productivity at a given site. The temporal models relating time series of ANPP and annual precipitation for single sites showed lower slopes and regression coefficients than the spatial models (Smoliak 1986; Le Houerou et al. 1988; Lauenroth and Sala 1992; Briggs and Knapp 1995; Jobbágy et al. 2002). Lauenroth and Sala (1992) explored the relationship between annual ANPP and precipitation across a 52-year series in a single shortgrass steppe site and showed that the disper-

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sion of the data around the temporal model was larger than the dispersion of data around the regional model (precipitation accounted for 39% of the variability in ANPP among years, contrasting with 90% for the regional model). Such long-term data sets are scarce and most other temporal models have been based on shorter data sets (Jobbágy and Sala 2000).

Instead of waiting for the completion of long-term data sets, manipulative experiments are an alternative way to explore the relationships of interannual variation of productivity and precipitation. They can also play a significant role in clarifying the potential impacts of a range of climate change scenarios on ecosystems. Water-relation studies conducted in greenhouse environments may not relate accurately to natural conditions, so field water manipulations represent a good choice for addressing scientific questions demanding an understanding of integrated ecosystem responses to changes in water availability.

Experimental approaches to study precipitation impacts on ecosystems often involve irrigation experiments. However, Knapp and Smith (2001) showed that the response to high and low water availability is not symmetric. When grasslands experience unusually high precipitation, they showed a large production response but this pattern was not mirrored by a proportional decrease in ANPP during drought years (Knapp and Smith 2001). As a consequence of this asymmetric response, experiments designed to analyse ecosystems' response to water variability should involve not only water addition but water exclusion experiments too.

Water exclusion usually involves the use of rainout shelters to reduce natural precipitation. Use of rainout shelters has facilitated studies to evaluate drought resistance of crop species (Stansell and Sparrow 1963; Arkin et al. 1976; Clawson et al. 1986; Starfield and Chapin 1996), water relations of rangeland shrubs (Jacoby et al. 1988), the impact of drought on desert shrubs (Reynolds et al. 1999), the relation between water and N availability (Fischer and Whitford 1995), and the impact of rainfall chemistry on growth and nutrient cycling of plantation conifers (Hultberg et al. 1995; Moldan et al. 1995). Simple shelters can provide control over the timing of drought. More elaborate shelters can include irrigation systems that allow for control over the daily, weekly, or seasonal timing and extent of wet and dry periods, independent of patterns of ambient rainfall (Fay et al. 2000). In all cases, the goal is to exclude rain from plots while allowing other aspects of the environment to remain largely unchanged.

Shelters are of two types, subcanopy and complete roofs. The understorey, subcanopy roof are models adapted for large woody plants, intercept rainfall without covering the canopy and have as a primary disadvantage the relatively poor access to the subshelter area after the wire mesh is installed (Jacoby et al. 1988). The complete roof employs a ceiling to intercept rainfall for diversion away from treatment plots (Hatfield et al. 1990; Beier et al. 1995; Fischer and Whitford 1995; Lamersdorf et al. 1995; Pilon et al. 1996; Hanson 2000). The scale of manipulation is variable, and ranges from small structures intended to exclude rainfall from the root zones (Beier et al. 1995) to large structures covering 100 m^2 at the watershed scale (Hultberg et al. 1995; Moldan et al. 1995). The main problem of the complete roof is that it must be functional only during periods of precipitation because it greatly modifies the microclimate under it, so it usually requires complicated mechanisms to move the shelter into place in order to shield the vegetation from the rain, which results in a large cost and potential experimental error in the case of malfunction (Stansell and Sparrow 1963; Upchurch et al. 1983; Dugas and Upchurch 1984; Foale et al. 1986).

Alternatives to these mobile rainout shelters are fixed designs. The simplicity and lower construction costs of fixed-location shelters allow for affordable replication in experiments on native ecosystems, which are more variable than cropping systems in soils and vegetation (Svejcar et al. 1999). However, the major tradeoff is the presence of chronic microclimate impacts (e.g. increased air temperature, decreased solar radiation, and decreased wind and vapour pressure deficit) (Dugas and Upchurch 1984; Jacoby et al. 1988). Fixed shelters can be designed to minimize these effects but they must be accompanied by unsheltered control plots to evaluate the impacts of the shelter (Fay et al. 2000).

The rainout shelter described here is a fixed-location shelter with a roof formed by bands, which can block different amounts of rainfall. It was used and tested in a field experiment in a shrub steppe in Río Mayo, Chubut (Argentina). The rainout-shelter design included the results of a careful study of the best band material, angle of inclination of the roof, and azimuth of the installation in order to minimize microclimate impacts. This paper describes the design of the shelter, the evaluation of the drought treatments obtained, and the impacts on the microclimate.

Materials and methods

Design of the rainout shelter

The rainout shelter had a metal frame supporting V-shaped clear acrylic (Acrilicopaolini®) bands, without a UV filter, covering an area of 3.76 m^2 (2×1.88 m). The mean height of the shelter was 0.50 m, which was selected taking into account the mean height of the shrubs in the study site (Fig. 1). The roof had a 20° inclination, and on the lowest side, it had a gutter that channelled the intercepted water into a flexible storage tank, made of white canvas covered with PVC, and with a capacity of 170 l (1 m diameter and 0.5 m height). The tank was completely closed, except for the sleeve connected to the gutter, to avoid water losses by evaporation (Fig. 1).

Each band or panel of transparent acrylic was 2 m long, 0.13 m wide and 2.4 mm thick, and was constructed with a longitudinal plait of 120°. We chose a clear acrylic material for the roof because it intercepted a small portion of direct solar radiation and it was elastic enough to withstand windy conditions at our study site. We placed the shelter oriented due north-south, with the tallest side to the north, which allowed the majority of the solar radiation to directly penetrate the plot area and only a small portion of the

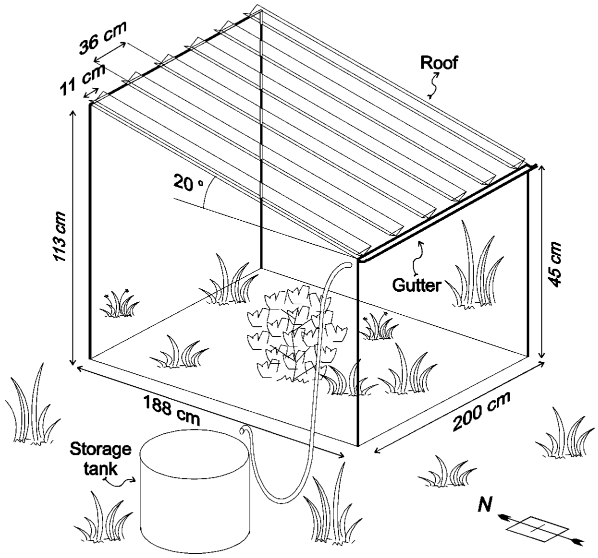

Fig. 1 Design of the rainout shelter that intercepts 30% of incoming precipitation

direct radiation to pass through the roof. At the latitude of our study site (45°41′S), the maximum angle of solar altitude with respect to the horizontal in summer is 68°.

We used three kinds of shelters for passively intercepting 30%, 55%, and 80% of the precipitation. In order to attain these different treatments, we used six, ten, and 14 bands of acrylic in the roof, at a distance from each other of 36, 20, and 14 cm. For example, the 30% rainfall interception treatment had six acrylic bands located regularly at a distance of 36 cm (Fig. 1).

Study site

This study was conducted in the Patagonian region of Argentina, in a site located near Río Mayo, Chubut (45°41′S, 70°16′W), elevation of 500 m. Mean monthly temperatures ranged from 1°C in July to 15°C in January, mean annual rainfall recorded over 37 years was 136 mm and ranged between 47 and 230 mm. Precipitation is mainly rainfall concentrated during autumn and winter periods (March–September). The soil is coarse textured, with pebbles, which account for 47% of its weight and it has a cemented calcareous layer at a depth of about 0.4 m (Paruelo et al. 1988). The vegetation is chiefly composed of grasses and shrubs. Tussock grasses have a basal cover of 25% and are represented principally by *Stipa speciosa* Trin et Ruprecht, *S. humilis* Cav., and *Poa ligularis* Nees ap. Steud. Shrubs have a cover of 12% and are represented mainly by *Mulinum spinosum* (Cav.) Pers., *Adesmia campestris* (Rendle) Rowlee, and *Senecio filaginoides* DC (Golluscio et al. 1982).

Evaluation of water interception and edge effect

We located 40 plots and randomly assigned them to one of three drought treatments (30%, 55%, and 80% precipitation interception) or control with ten replicates for each treatment. In order to test the drought treatments and to find out the real percentage of rainfall intercepted by each model, every 3 months we collected and measured all the intercepted water channelled by the gutters into the storage tanks. Rainfall was monitored during the study with an automatic weather station equipped with a datalogger Campbell SCI 21X located near the experimental area.

We evaluated the effectiveness of the shelters in inducing changes in soil water by measuring soil water content at two depths with the time domain reflectometry (TDR) technique (Reeves and Smith 1992) employing a Tektronix 1502C. At the initiation of the study in May 1999, we buried two pairs of TDR probes of 15 and 30 cm height in each plot and determined the initial soil water content. We left the probes in place to monitor this variable in each plot during the course of the study at various intervals. Additionally, in order to quantify the edge effect, we measured soil water content at 20-cm intervals along perpendicular transects located E–W and N–S under four 80% shelter plots. We measured soil water content at 0–20 cm depth with TDR after a rain event. Transects were 2.40 m long in the E–W direction and 2.20 m long in the N–S direction, which included 20 cm outside the shelter at each end.

Shelter microenvironment

We examined the magnitude of potential shelter effects on the microenvironment, independent of rain interception, such as changes in temperature and radiation. We made an spectrophotometer analysis of light transmittance between 250 and 700 nm wavelength through the acrylic material employed to construct the rainout shelters with a Spectronic Genesys 2. In the field, we examined shelter effects by a series of paired measurements inside and outside the shelters every 20 min during full days. We performed these measurements in two contrasting moments of the year with relatively high and low solar radiance and temperature (24 October and 8 May, respectively). We measured photosynthetically active radiation (PAR) using a 1-m linear quantum sensor LiCor (LI-190SZ; LiCor, Lincoln, Neb.) placed on bare soil, in a horizontal position and perpendicular to the acrylic bands. We also registered air temperature at 20 cm above the ground with an air thermometer and soil temperature at 5 cm depth with a soil thermometer.

We performed *t*-tests for comparing observed and expected values of water interception and we analysed differences among treatments in the amount of water in storage tanks with a one-way ANOVA. We analysed soil water contents in treatment plots using repeated measurements ANOVA (RM-ANOVA) with rainout treatments as the main effect and date as the repeated factor. We performed a post-hoc Tukey test for multiple comparisons when the ANOVA was significant ($P<0.05$). We analysed soil water content data, which were measured to detect the edge effect, by a one-way ANOVA. All analyses were performed using the statistical package Statistica (StatSoft, Tulsa, Okla.).

Results

Water interception, soil water content, and the edge effect

The 30% and 55% interception treatments were effective in intercepting the expected amount of water, with no significant differences between the observed and the expected water interception for those treatments. In contrast, water interception in the 80% shelters was significantly lower than the expected value ($P<0.05$) and accounted for 71% of incoming rainfall (Table 1). The water collected by each rainout shelter type (30%, 55%, and 80% rainfall interception) was significantly different ($P<0.001$) (Table 1). During the experiment, observed precipitation was near the mean of the site (141 mm) and was distributed throughout the year with the typical seasonality with rainfall concentrated during autumn and winter.

Soil water content at 0–15 and 0–30 cm depth was significantly lower ($P<0.05$) in the treatments plots than

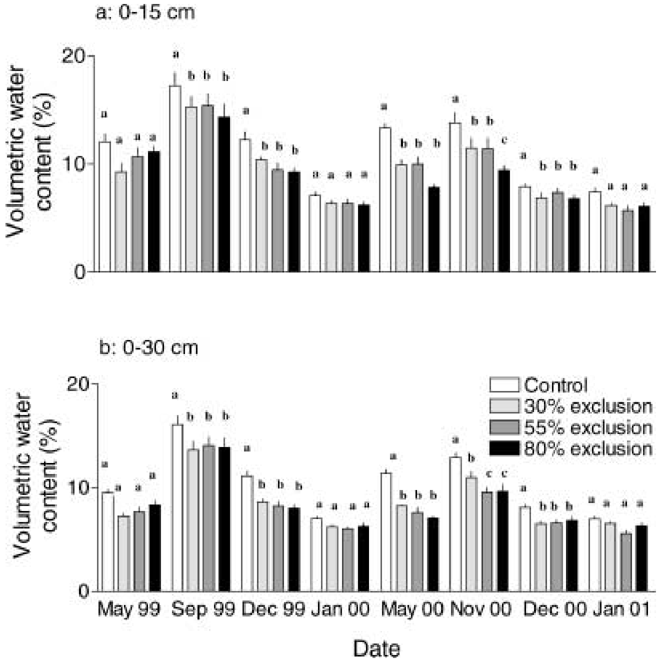

Fig. 2a, b Rainout-shelter effects on soil water content at **a** 0–15 cm depth and **b** 0–30 cm depth (mean±1 SE) for eight dates. The rainfall interception levels are 0% (control), 30%, 55%, and 80% of rainfall exclusion. *Different letters* represent significant differences for a given date ($P<0.05$). *Sep* September, *Dec* December, *Jan* January, *Nov* November

Table 1 Rainfall interception of three drought treatments and comparison with expected values for the period 25 January–22 May 2000. Rainfall recorded in the weather station during the same period was 48.6 mm. The *last column* shows the result of the post-hoc Tukey test of the one-way ANOVA of water collected in the storage tanks. *Different letters* in the *last column* indicate significant differences among treatments ($P<0.001$)

Expected interception		Observed interception		Expected vs. observed	
(%)	(l)	Water in storage tanks±SD (l)[a]	(%)		
30	55	53±9	29	NS	a
55	101	86±16	47	NS	b
80	146	130±10	71	$P<0.05$	c

[a] Each value represents the average amount of water intercepted in nine plots

in the controls except in January (peak of the growing season and minimum of precipitation), but we did not detect significant differences among the three levels of interception treatments for six of the seven dates (Fig. 2). Only in November 2000 was the soil moisture under the 30% treatment significantly higher than the soil moisture under the 50% and the 80% drought treatments.

The edge effect, as evaluated by soil water content measurements in a regular grid, was approximately 20 cm wide. The soil water content beyond 20 cm was significantly ($P<0.05$) lower and different from the soil water content outside the shelters (Fig. 3). Edge effects were more apparent on the north and west sides probably because roofs were slanted towards the south, and predominant winds in our study site are from the west (Fig. 3).

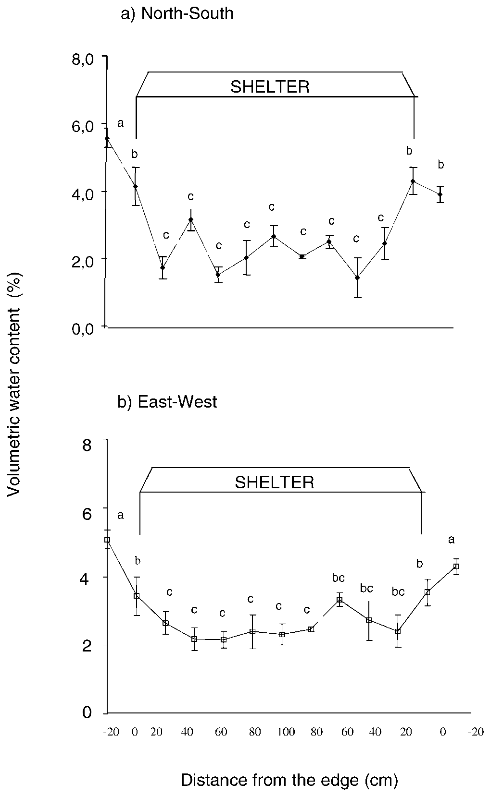

Fig. 3a, b Assessment of the edge effect under the shelters. Soil water content at 0–20 cm depth along transects under 80% interception shelter ($n=4$), located **a** north–south and **b** east–west. *Different letters* represent significant differences among points in each transect ($P<0.05$)

Microclimate environment

The percentage of light transmittance through the acrylic material used in the roofs showed that the acrylic was almost transparent in the visible region of the solar spectrum (the transmittance between 400 and 700 nm was 92%) (Fig. 4). In the UV-A region of the spectrum (400–315 nm), the transmittance fell to 70% and in the UV-B part (315–280 nm) it was ca. 50% (Fig. 4). In the field, PAR radiation had the same pattern for the two contrasting dates. Under the 30% interception shelter, it differed little from that under ambient conditions, i.e. the percentage of PAR under the shelter was close to 100% of the ambient PAR (Fig. 5a, b). Under the 80% treatment, radiation showed a mean decrease of about 10% of ambient PAR under the shelter (Fig. 5c, d), with a maximum difference of 25% at midday when the incident radiation was highest (Fig. 5c).

Air temperature showed little difference in the 30% interception treatment in relation with the ambient tem-

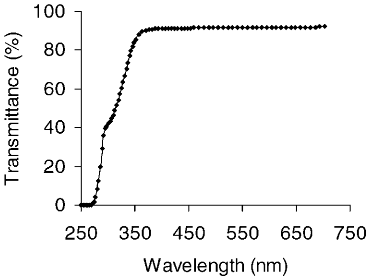

Fig. 4 Effect of roof-shelter material on light quality. Percentage of light transmittance through the acrylic between 250 and 700 nm

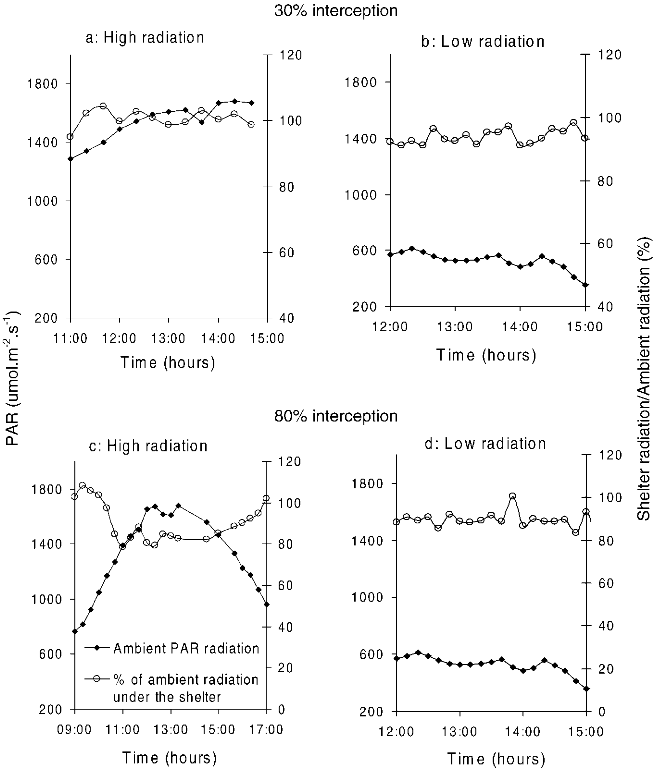

Fig. 5a–d Microenvironmental effects of rainout shelters. Percentage of photosynthetically active radiation measured under shelters and outside (ambient radiation) in **a** 30% interception shelter under high radiation conditions, **b** 30% interception shelter under low radiation conditions, **c** 80% interception shelter under high radiation conditions, and **d** 80% interception shelter under low radiation conditions

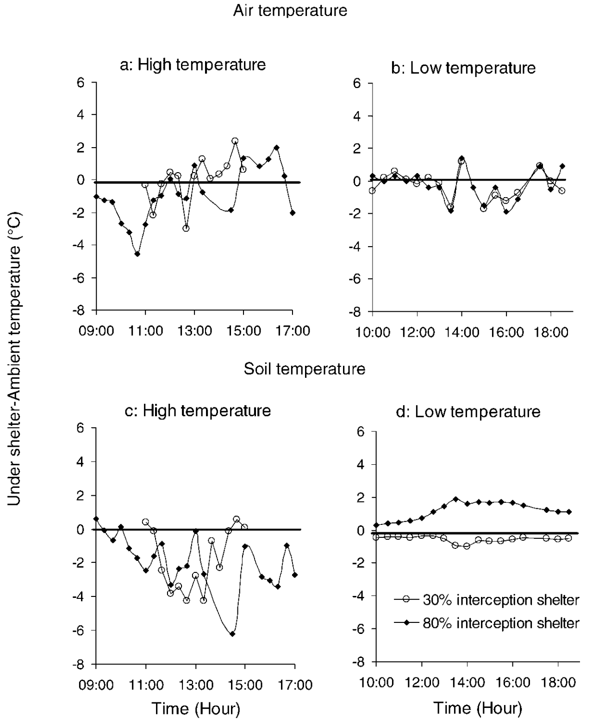

Fig. 6a–d Microenvironmental effects of rainout shelters. Air and soil temperature difference between sheltered treatments and the reference outside shelters for a 30% interception shelter and an 80% interception shelter. **a** Differences in air temperature under high temperature conditions, **b** differences in air temperature under low temperature conditions, **c** differences in soil temperature under high temperature conditions, and **d** differences in soil temperature under low temperature conditions. Mean air temperature outside shelters was 28°C and 7.5°C and mean soil temperature was 19°C and 6.9°C in the high and low temperature conditions, respectively

perature (maximum difference of 3.4°C lower under the shelter than outside the shelter at midday of the high air-temperature day) (Fig. 6a, b). In the 80% drought treatment, temperature differences between inside and outside the shelters were negligible at the time when temperature was low and, more importantly, when temperature was high, with a maximum of 5.6°C lower under the shelter than outside (Fig. 6a, b). We did not detect a greenhouse effect under the shelter, but we observed a small shadow effect. Soil temperature presented a different pattern depending on the time of the year analysed. When temperature was relatively high, the soil temperature was lower under the shelter than outside with a mean difference of 1.8°C and a maximum of 6°C under the 30% shelter and a mean difference of 2°C and a maximum of 6.5°C lower under the 80% shelter (Fig. 6c, d). In contrast, when temperature was low, the soil temperature was slightly lower under the 30% interception treatment but was higher under the 80% interception treatment, with a maximum of 2°C difference.

Discussion

The shelter performed to our expectations and accomplished our primary goals of intercepting different amounts of rainfall with a minimal effect on the environment. The three types of rainout shelter effectively intercepted different amounts of water indicating that we successfully generated three levels of rainfall interception by placing a different number of acrylic bands on the roof. Rainfall interception in the three kinds of shelter was very near the values that we had anticipated. We obtained slightly less rainfall interception than expected in the three treatments, which was statistically different only for the 80% interception shelter. Differences in soil-water content were statistically significant among shelter treatments for one date, November 2000, after the end of the rainy season and at the beginning of the growing season. For the other dates, we found significant differences between control and sheltered plots, but we did not find differences among the three shelters. During summer months (January), there were no differences in soil water content, probably because the soil was very dry even in the control plots. Summer is the season when precipitation is low and potential evapotranspiration is maximum.

Light transmittance through the acrylic is very high, except for the UV-B-region of the spectrum. Nevertheless, the observed 50% transmittance of the UV-B is high compared with other transparent materials like plastic or PVC, which block 100% of the UV-B. Both the reduction of PAR and the differences in temperature under the shelters were small. The incorporation of the bands in the shelter design eliminated possible greenhouse effects during the hottest months of the year because of the unconstrained air movement under the shelter. When incoming radiation was high, the temperature under shelters was even cooler, probably due to lower radiation at the soil surface induced by the protection offered by the roof. On the contrary, when radiation was relatively low, the roofs must have captured part of the long wave radiation emitted from the soil resulting in slightly higher temperatures under the shelters.

We detected a relatively small edge effect on the soil water content that was lower than at 20 cm from the edge. We did not install a soil barrier in the perimeter of plots because in our study site the soil is coarse textured and the topography is flat, so movement of water due to runoff is minimum (Paruelo and Sala 1995). Variations of our design could provide a bigger plot area especially if the vegetation under study included taller individuals that would require higher roofs with an unavoidable larger edge effect.

Another important issue is the fact that our rainout-shelter design alters the amount of each rainfall event. We did not manipulate the number of rainfall events, we only manipulated the amount of each event by intercepting different proportions of water; consequently, the structure of precipitation changed with more small rainfall events and fewer large rainfall events than under natural conditions. The average event size decreased from 1.6 mm in the control to 1.2 mm in the 30% interception treatment, 0.9 mm in the 55% treatment, and 0.5 mm in the 80% interception treatment, during the experiment.

The material of the roof is almost transparent to sun radiation and the loss of PAR intercepted was less than that for designs employed by other workers (Clawson et al. 1986). This characteristic allows the permanent installation of the roof with the benefit of avoiding the use of an automated retraction system, which is not only costly but also incorporates a new source of experimental error. With the fixed model, there is no possibility that a precipitation event occurs while the roof is not installed. Acrylic is an expensive material but its elasticity and resistance makes it more durable than plastic or glass. Our model was cheaper than more complicated shelters currently in use (Foale et al. 1986) and its low cost allows for a high number of replicates in space.

The time taken to construct each shelter was estimated at 10 h, which was 10 times less than for the construction of other types of shelter reported in the literature (Jacoby et al. 1988). Because the installation of the structure does not involve major and permanent modification of the experimental site, the vegetation response can be monitored after the structure is dismantled. In addition, the components removed at the conclusion of the experiment can be stored for use in other experiments.

We suggest that the most important contribution of this design is the permanent installation of the roof and the possibility of regulating the proportion of rainfall intercepted. These two characteristics allow for well-replicated experiments with minimal secondary microenvironmental effects.

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References

Arkin GF, Ritchie JT, Thompson M, Chaison R (1976) A rainout shelter installation for studying drought stress. Agron J 68: 429–431

Beier C, Gundersen P, Hansen K, Rasmussen L (1995) Experimental manipulations of water and nutrient input to a Norway spruce plantation at Klosterhede, Denmark. II. Effects on tree growth and nutrition. Plant Soil 168–169:613–622

Boutton TW, Tieszen LL, Imbamba SK (1988) Biomass dynamics of grassland vegetation in Kenya. Afr J Ecol 26:89–101

Briggs JM, Knapp AK (1995) Interannual variability in primary production in tallgrass prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. Am J Bot 82:1024–1030

Clawson KL, Blad BL, Specht JE (1986) Use of portable rainout shelters to induce water stress. Agron J 78:120–123

Dugas WAJ, Upchurch DR (1984) Microclimate of a rainfall shelter. Agron J 76:867–871

Fay PA, Carlisle JD, Knapp AK, Blair JM, Collins SL (2000) Altering rainfall timing and quantity in a mesic grassland ecosystem: design and performance of rainfall manipulations shelters. Ecosystems 3:308–319

Fischer FM, Whitford WG (1995) Field simulation of wet and dry years in the Chihuahuan desert: soil moisture, N mineralization and ion-exchange resin bags. Biol Fertil Soils 20:137–146

Foale MA, Davis R, Upchurch DR (1986) The design of rain shelters for field experimentation: a review. J Agric Eng Res 34:1–16

Golluscio RA, León RJC, Perelman SB (1982) Caracterización fitosociológica de la estepa del Oeste de Chubut; su relación con el gradiente ambiental. Bol Soc Arg Bot 21:299–324

Hanson PJ (2000) Large -scale water manipulations. In: Sala OE, Jackson RB, Mooney HA, Howarth RH (eds) Methods in ecosystem science. Springer, Berlin Heidelberg New York, pp 341–352

Hatfield PM, Wright GC, Tapsall WR (1990) A large, retractable, low cost and re-locatable rain out shelter design. Exp Agric 26:57–62

Hultberg HA, Andersson BI, Moldan F (1995) The covered catchment – an experimental approach to reversal of acidification in a forest ecosystem. In: Rasmussen L, Brydges T, Mathy P (eds) Experimental manipulations of biota and biochemical cycling in ecosystems. Ecosystem research report no. 4. Commission of the European Communities, Brussels, pp 46–54

Jacoby PW, Ansley RJ, Lawrence BK (1988) Design of rain shelters for studying water relations of rangeland shrubs. J Range Manage 41:83–85

Jobbágy EG, Sala OE (2000) Controls of grass and shrub aboveground production in the Patagonian steppe. Ecol Appl 10: 541–549

Jobbágy E, Sala OE, Paruelo JM (2002) Patterns and controls of primary production in the Patagonian steppe: a remote sensing approach. Ecology 83:307–319

Knapp AK, Smith MD (2001) Variation among biomes in temporal dynamics of aboveground primary production. Science 291:481–484

Knapp AK, Briggs JM, Koelliker JK (2001) Frequency and extent of water limitation to primary production in a mesic temperate grassland. Ecosystems 4:19–28

Lamersdorf NP, et al. (1995) Reactions of soil solution chemistry to drought: results of experiments within the EXAM projects. In: Jenkins A, Ferrier RC, Kirby C (eds) Ecosystem manipulation experiments: scientific approaches, experimental design and relevant results. Commission of the European Communities, ecosystem research report no. 20. Commission of the European Communities, Brussels, pp 86–95

Lauenroth WK (1979) Grassland primary production: North American Grasslands in perspective. In: French NR (ed) Perspectives in grassland ecology ecological studies, vol 32. Springer, Berlin Heidelberg New York, pp 3–24

Lauenroth WK, Sala OE (1992) Long-term forage production of North American shortgrass steppe. Ecol Appl 2:397–403

Le Houerou HN, Bingham RL, Skerbek W (1988) Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. J Arid Environ 15:1–8

Lieth H, Whittaker R (1975) Primary productivity of the biosphere. Springer, Berlin Heidelberg New York

McNaughton SJ, Sala OE, Oesterheld M (1993) Comparative ecology of African and South American arid to subhumid ecosystems. In: Goldblatt P (ed) Biological relationships between Africa and South America. Yale University Press, New Haven, N.J. pp 548–567

Moldan F, Hultberg H, Andersson A (1995) Gardsjon covered catchment experiment: changes in runoff after three years of throughfall exclusion. In: Jenkins A, Ferrier RC, Kirby C (eds) Ecosystem manipulation experiments: scientific approaches, experimental design and relevant results, Ecosystem research report no. 20. Commission of the European Communities, Brussels, pp 113–118

Noy-Meir I (1973) Desert ecosystems: environment and producers. Annu Rev Ecol Syst 4:25–52

Paruelo JM, Sala OE (1995) Water losses in the Patagonian steppe: a modeling approach. Ecology 76:510–520

Paruelo JM, Aguiar MR, Golluscio RA (1988) Soil water availability in the Patagonian arid steppe: gravel content effect. Arid Soil Res Rehabil 2:67–74

Paruelo JM, Jobbágy EG, Sala OE, Lauenroth WK, Burke IC (1998) Functional and structural convergence of temperate grassland and shrubland ecosystems. Ecol Appl 8:194–206

Pilon CE, Côté B, Fyles JW (1996) Effect of an artificially induced drought on leaf peroxidase activity, mineral nutrition and growth of sugar maple. Plant Soil 179:151–158

Reeves TL, Smith MA (1992) Time domain reflectometry for measuring soil water content in range surveys. J Range Manage 45:412–414

Reynolds FJ, Virginia RA, Kemp PR, Soyza AG, Tremmel DC (1999) Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. Ecol Monogr 69:69–106

Sala OE, Parton WJ, Lauenroth WK, Joyce LA (1988) Primary production of the central grassland region of the United States. Ecology 69:40–45

Smoliak S (1986) Influence of climatic conditions on production of Stipa-Bouteloua prairie over a 50-year period. J Range Manage 39:100–103

Stansell JR, Sparrow GN (1963) Rainfall controlled shelter for research plots. Agric Eng 44:318–319

Starfield AM, Chapin FS (1996) Model of transient changes in arctic and boreal vegetation in response to climate and land use change. Ecol App 6:842–864

Svejcar AJ, Angell R, Miller R (1999) Fixed location rain shelters for studying precipitation effects on rangelands. J Arid Environ 42:187–193

Upchurch DR, Richie JT, Foale MA (1983) Design of a large, dual-structure rainout shelter. Agron J 75:845–848

Webb W, Szarek S, Lauenroth WK, Kinerson R, Smith M (1978) Primary productivity and water use in native forest, grassland, and desert ecosystems. Ecology 59:1239–1247