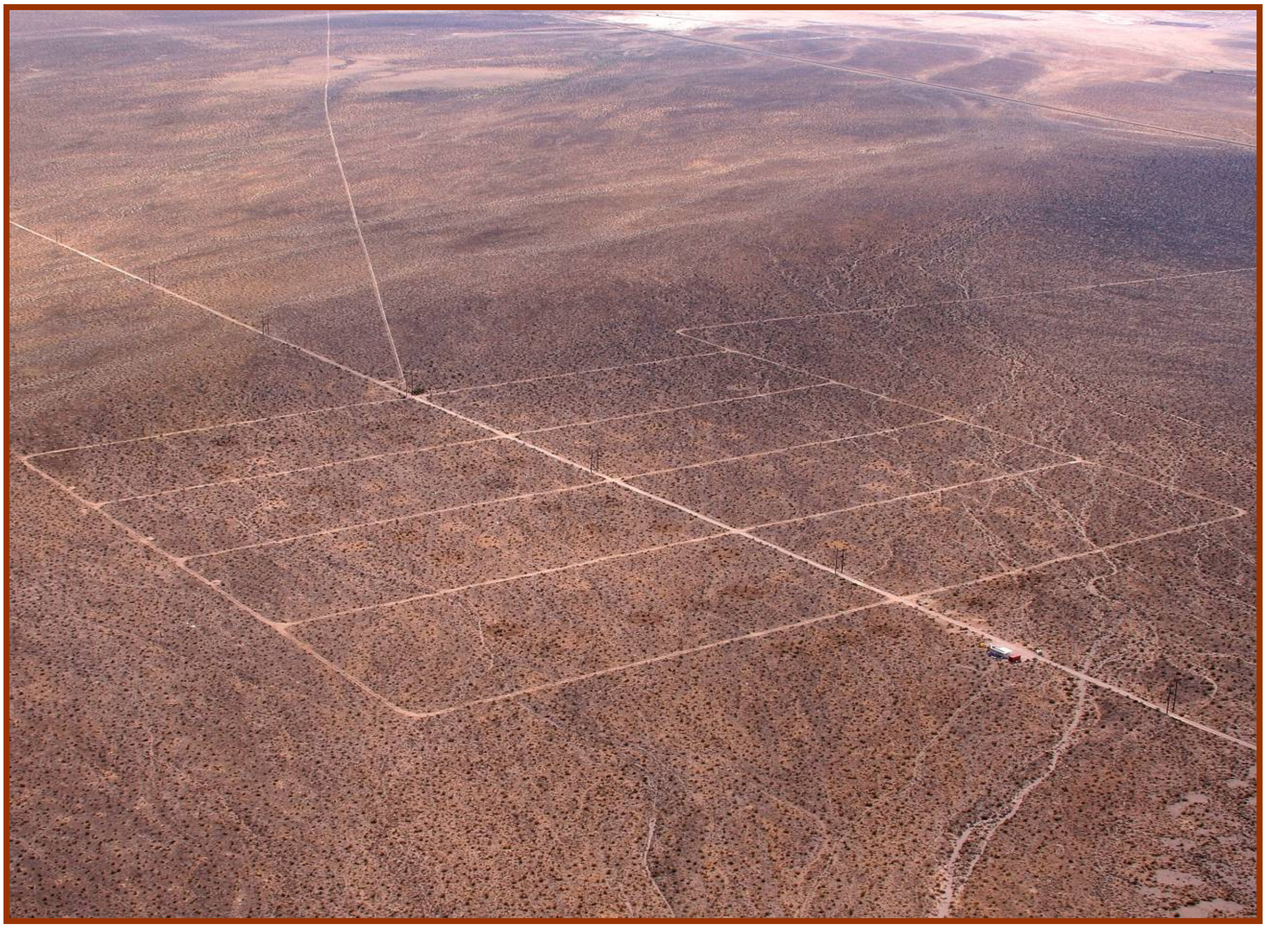


(Oblique aerial photograph of the Mojave Global Change Facility immediately after a summer irrigation treatment to the western half of the MGCF. Photo courtesy of Kent Ostler and Dennis Hansen, National Security Technologies, Las Vegas, NV)

FINAL REPORT

Effects of Changing Water and Nitrogen Inputs on a Mojave Desert Ecosystem

DOE# DE-FG03-02ER63361

Prepared By

Stanley D. Smith, University of Nevada Las Vegas
Robert S. Nowak, University of Nevada Reno
Lynn F. Fenstermaker, Desert Research Institute
Michael H. Young, Desert Research Institute

November 30, 2007

Effects of Changing Water and Nitrogen Inputs on a Mojave Desert Ecosystem
DOE# DE-FG03-02ER63361

Stanley D. Smith, University of Nevada, Las Vegas
Robert S. Nowak, University of Nevada, Reno
Lynn F. Fenstermaker, Desert Research Institute
Michael H. Young, Desert Research Institute
Principal Investigators

Final Technical Report
November 30, 2007

Questions addressed under this grant shared the common hypothesis that plant and ecosystem performance will positively respond to the augmentation of the most limiting resources to plant growth in the Mojave Desert, e.g., water and nitrogen. Specific hypotheses include (1) increased summer rainfall will significantly increase plant production through an alleviation of moisture stress in the dry summer months, (2) N-deposition will increase plant production in this N-limited system, particularly in wet years or in concert with added summer rain, and (3) biological crust disturbance will gradually decrease bio-available N, with concomitant long-term reductions in photosynthesis and ANPP. Individual plant and ecosystem responses to global change may be regulated by biogeochemical processes and natural weather variability, and changes in plant and ecosystem processes may occur rapidly, may occur only after a time lag, or may not occur at all. During the first PER grant period, we observed changes in plant and ecosystem processes that would fall under each of these time-response intervals: plant and ecosystem processes responded rapidly to added summer rain, whereas most processes responded slowly or in a lag fashion to N-deposition and with no significant response to crust disturbance. Therefore, the primary objectives of this renewal grant were to: (1) continue ongoing measurements of soil and plant parameters that assess primary treatment responses; (2) address the potential heterogeneity of soil properties and (3) initiate a new suite of measurements that will provide data necessary for scaling/modeling of whole-plot to ecosystem-level responses. Our experimental approach included soil plant-water interactions using TDR, neutron probe, and miniaturized soil matric potential and moisture sensors, plant ecophysiological and productivity responses to water and nitrogen treatments and remote sensing methodologies deployed on a radio control platform.

We report here the most significant findings of our 4 year study.

ABOVEGROUND PERENNIAL PLANT PRODUCTION [S. Smith, PI]

Plant growth measurements [B. Newingham]
We examined the growth responses of three perennial species at the MGCF in the following treatments: control, monsoon, 10N, 40N, monsoon + 10N, monsoon + 40N, and disturbance. The plant species included *Lycium pallidum*, *Pleuraphis rigida*, and *Larrea tridentata*. Several growth parameters were collected for each species to represent plant production; all measurements were taken on growing tips of the plant except for the amount of biomass removed by rabbits (see below). Only a few parameters are presented here and figures are only shown for some growth parameters of *L. tridentata*.

Growth measurements were taken in 2004, 2005 and 2006, which had average, wet and average years of annual precipitation (Fig. 1). Growth measurements on *L. pallidum* and *P. rigida* were taken bi-weekly during the growing season, and measurements were taken monthly on *L. tridentata* throughout the year. The phenology and length of the growing season for both *L. pallidum* and *P. rigida* varied depending on the amount of natural precipitation in a certain year; therefore, the start and end date of data collection varied among years.

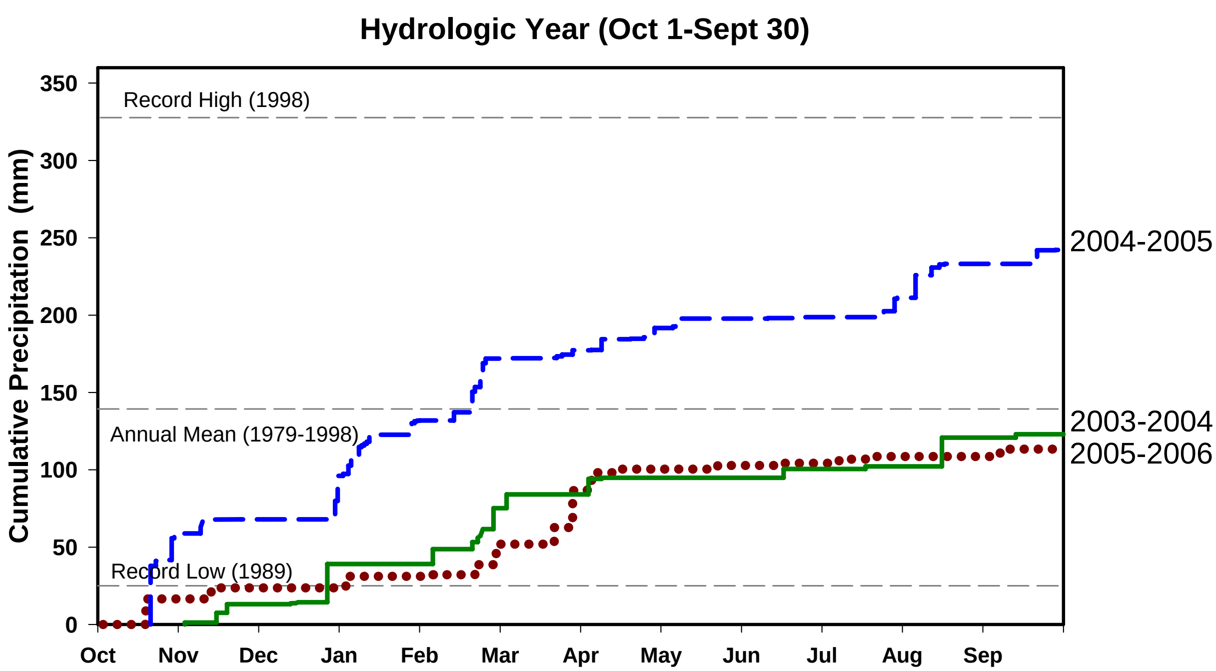


Fig.1 Precipitation over three growing seasons corresponding with data from 2004, 2005, and 2006. Note that the hydrologic year in this area is considered to be October 1 to September 30. Annual precipitation was 113.3 mm during 2003-2004, 242.1 mm during 2004-2005, and 122.9 mm during 2005-2006.

Results

Lycium pallidum is a drought deciduous shrub that usually produces leaves in late April and loses its leaves in June. For *L. pallidum*, the number of whorls (short shoots), number of long shoots, and percent damage by insects were quantified. Regardless of treatments, *L. pallidum* growth was greatest in 2005, while very little growth occurred in 2006. During all three years, *L. pallidum* did not respond to monsoon treatments within that same year and remained leafless after monsoon treatments. Residual effects of the previous year's watering had a negative effect on *L. pallidum* whorl production early in the season in the two average years of precipitation, but there was no effect of monsoons on long shoot production. Nitrogen deposition had no effect on whorl production; however, the number of long shoots increased in response to N addition in all three years. Surprisingly, we found a positive effect of disturbance on whorl production in the wet year of 2005; however, disturbance slightly decreased long shoot production in 2004 and 2005. Plots with monsoon + N treatments mimicked those of the monsoon treatment, and there was no added benefit of adding N in those plots. Overall, growth was not affected by any treatments in 2006. No striking patterns emerged from the herbivory data except that there are large errors associated with assessing herbivore damage, particularly in the control plots.

Pleuraphis rigida is a C_4 perennial grass, which is generally green mid-May to September. We determined the number of leaves, stem length, and number of flowers produced by *P. rigida*. Over all treatments, *P. rigida* growth varied among years, where substantial growth occurred in the spring of 2004 but then drastically tapered off mid-summer. Less initial growth occurred in 2005 and 2006, and the growing season of 2005 was extended until late fall.

In contrast to *L. pallidum*, *P. rigida* has more potential to respond immediately to monsoon events since it is a C_4 plant and is still active in late summer. In 2004, *P. rigida* leaves and stem length drastically increased immediately following monsoon treatments; however, this late-season response was not seen in 2005 and 2006. Surprisingly, monsoons had a negative effect on stem length through the whole 2005 growing season. Nitrogen deposition had a positive effect on both leaves and stem length in 2004 but negative effects in 2005. Disturbance negatively affected leaves and stem length early in the season in 2004 and 2005, but these effects neutralized later in the season. Plots with monsoon + N treatments were similar to the monsoon plots; however, monsoon + N-treated plants grew 50% less in 2005. No parameters responded to treatments applied in 2006. Additionally, no treatments had strong effects on flower production.

Larrea tridentata is a C_3 shrub, which is evergreen and actively grows April to September. We measured the number of leaves, branches, meristems, buds, flowers, fruits, stem length, and herbivore damage by insects and rabbits. Measurements were taken monthly from January to December in each year. We only present data on relative growth rate (RGR; based on stem length) during the active growing season (April to September) and herbivore damage by rabbits. The RGR of *L. tridentata* varied among years with moderate growth in 2004, greatest growth in 2005, and negative growth in 2006 (Fig. 2).

Over the entire 2004 growing season, monsoon treatments had a positive effect on the RGR of *L. tridentata*; however, N treatments had no effect on RGR (Fig. 2). RGR during April-May was comparable between monsoon and no monsoon treatments; however, plants receiving summer monsoonal rain had higher growth rates than non-irrigated plants during June through September. The lack of a nitrogen effect on RGR was consistent throughout the season.
In 2005 there was no effect of monsoons on *L. tridentata* RGR for the entire growing season (Fig. 2). Most growth occurred April to July, with negative RGR during August and September for monsoon-

treated plants. Although data suggested there was less RGR without N addition, this was not statistically significant. RGR during the 2006 growing season was mostly negative, with only moderate growth in April to May in monsoon and monsoon + 10N plots.

The effects of disturbance on the RGR of *L. tridentata* depended on the growing season. Disturbance had a negative effect on RGR over the entire 2004 season, with most negative effects being seen in mid- to late summer (Fig. 3). Data from 2005 showed similar patterns as 2004 although treatment differences were not significant for any of the dates examined. Growth was almost consistently negative in control and disturbed plots in 2006, with a surprising positive effect of disturbance on RGR in June-July.

It was observed in the late summer/early fall of 2005 that rabbits were clipping off *L. tridentata* branches. Although we did not measure rabbit population growth, it appears that the wet season of 2004-05 resulted in an increase in rabbit numbers. Of course, this damage affects our ability to estimate growth in *L. tridentata.* In October 2005, we began assessing how much biomass was removed by the rabbits by collecting all clipped biomass from 4 plants per plot. In order to access the clipped branches, we had to step into the experimental plots. Therefore, biomass removal by rabbits was only measured in disturbed plots. Most biomass removal occurred in the late summer and fall of 2005 and 2006 (Fig. 4). In October and November 2005 and June and October 2006, considerable amounts of biomass were removed. During these four months, biomass removal was higher in monsoon plots than no monsoon plots. There was no effect of N addition on biomass removal of *L. tridentata*. The biomass removed during 2005 and 2006 partially explains the negative growth seen on *L. tridentata* growing tips, as several branches were lost due to rabbit herbivory.

Discussion

Our results indicate that summer monsoons, nitrogen addition and disturbance can have variable effects on different plant functional groups. Underlying all of these responses is the natural precipitation received within a hydrologic year. It is important to consider not only the annual amount of precipitation but also the timing of precipitation. Examining natural precipitation (Fig. 1) helps us interpret the growth data seen in these three perennial species.

Plant growth responses to disturbance were intriguing. The disturbance treatment was intended to reduce N inputs into the ecosystem by disturbing soil microorganisms that increase plant nutrient availability. Disturbance had negative effects on the growth of *P. rigida* and *L. tridentata* in some years but not all. The negative effects of disturbance on *P. rigida* may be due to disrupting free-living N fixers associated with *P. rigida* roots. Further investigation is needed to assess what causes negative growth in *P. rigida* when the soil is disturbed. At this point, we are unsure of the mechanism behind the negative effects of disturbance on *L. tridentata*.

Since the three perennial species responded differently to these treatments, it is probable this will eventually have an effect on plant community composition; however, the effects on plant communities may not be immediately realized since these are such slow growing species. While the C_4 grass, *P. rigida*, and the C_3 evergreen, *L. tridentata*, positively responded to monsoon treatments, the treatment likely comes too late in the season for the drought-deciduous *L. pallidum* to respond. However, over several years *L. pallidum* may adapt to this change and responses may be seen later on. Nitrogen addition had inconsistent effects on plant growth with most responses by *L. pallidum* and *P. rigida*. Contrary to predictions, monsoon + nitrogen treatments did not have synergistic positive effects on plant growth.

Changes in plant growth will not only affect plant community composition but will likely have cascading effects in the ecosystem. Increases in plant growth may cause responses by invertebrate and vertebrate herbivores, as seen in the rabbit biomass removal data. Insect sampling was also conducted in experimental plots during 2004 and 2005. Preliminary results from 2004 found that insect abundance increased immediately following monsoon treatments, but N addition had no effect on insect abundance. Further investigation in insect responses and linking these with changes in plant growth are needed.

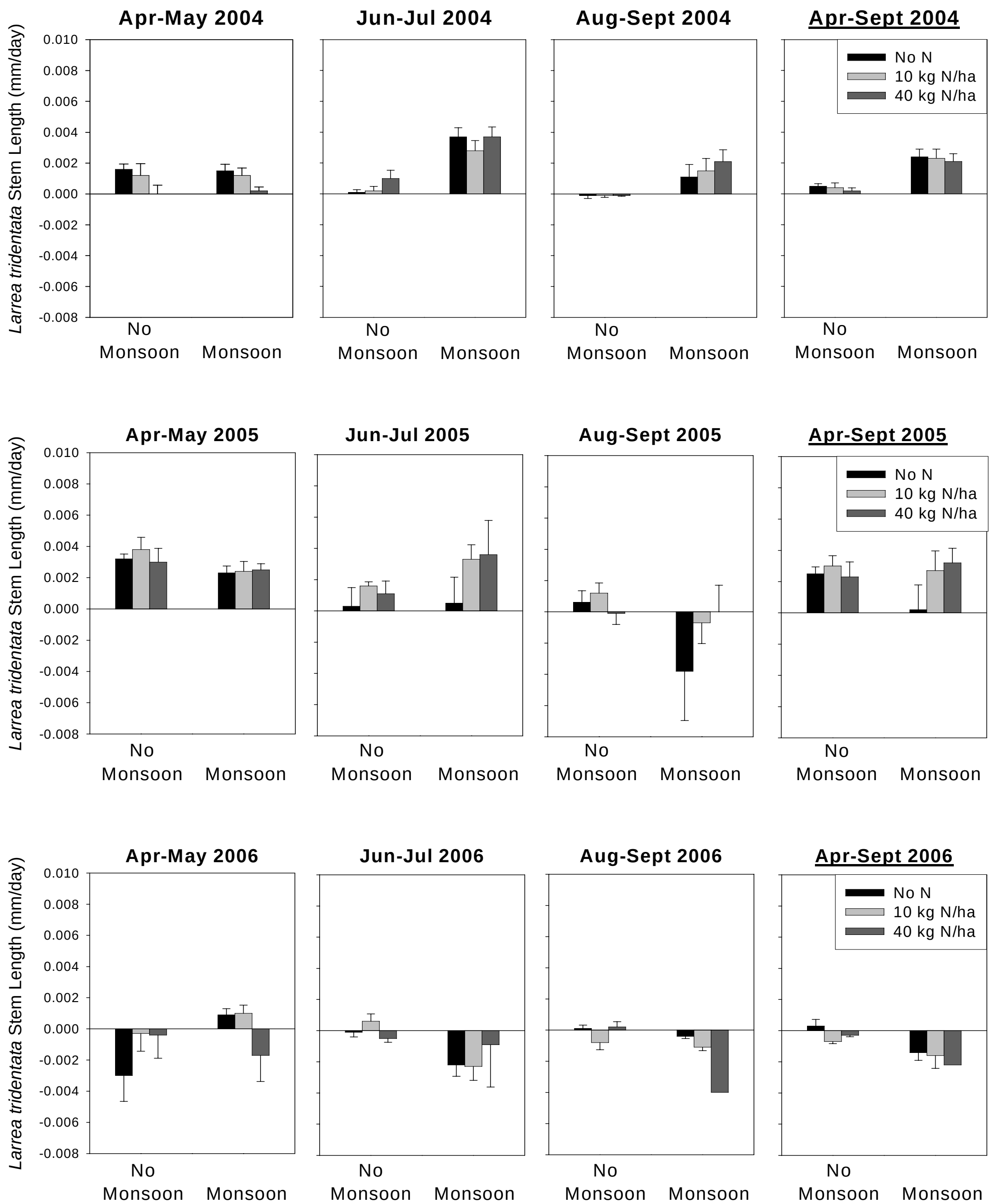


Fig. 2 Relative growth rate of *Larrea tridentata* in response to simulated summer monsoons and nitrogen addition ($CaNO_3$). Measurements were taken on 50mm growing tips, which were marked each spring. Error bars represent ± 1 standard error.

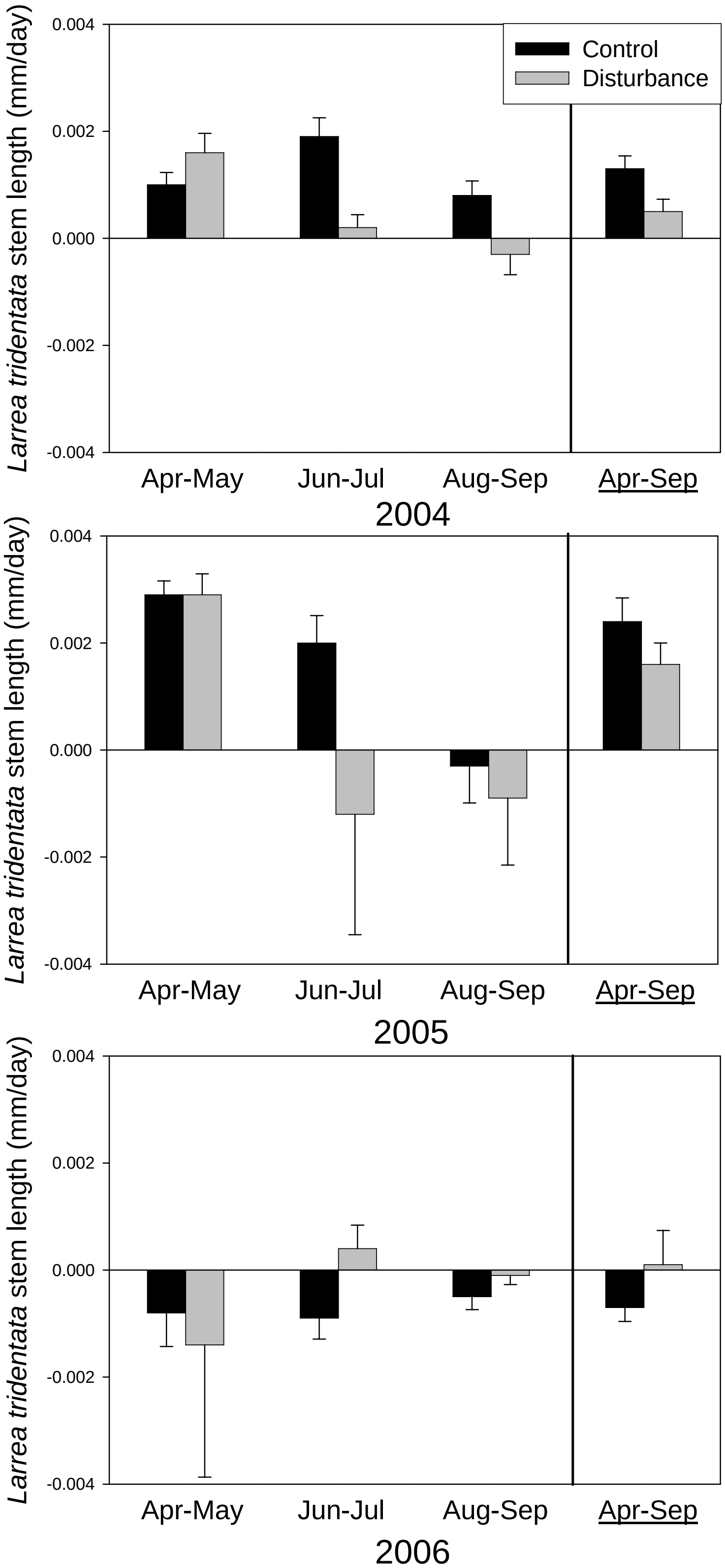


Fig. 3 Relative growth rate of *Larrea tridentata* in response to soil disturbance. Measurements were taken on 50mm growing tips, which were marked each spring. Error bars represent ± 1 standard error.

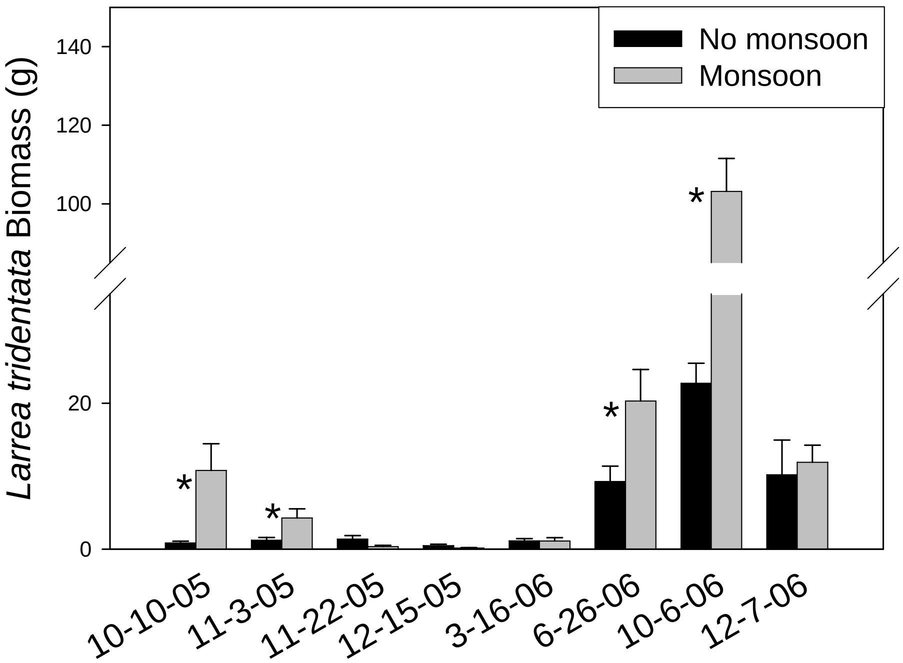


Fig. 4 *Larrea tridentata* biomass removed by rabbit herbivory in response to simulated summer monsoons. Nitrogen addition had no effect on the amount of biomass removed; therefore, means include no nitrogen, 10N, and 40N treatments. Error bars represent ± 1 standard error. Asterisks represent $P < 0.05$.

WATER BALANCE [R.Nowak, PI]

Soil water measurements [C.D.Holmes, K. Allcock]
Soil water content among different plots was monitored by measuring volumetric soil water content with a neutron probe (Model 503 Hydroprobe, Campbell Pacific Nuclear Corporation, Martinez, CA, USA). To characterize deep soil moisture, a 2-meter deep neutron probe access tube was installed in a plant interspace near the center of each of the 96 MGCF plots. Neutron probe measurements began in March 2001 and have continued until present time; data from March 2001 to June 2006 are included in this report. Neutron probe measurements typically are taken at 4-week intervals, except during summer irrigation treatments and following specific rainfall events, when measurements occur at shorter intervals to better characterize the rate of water gain and loss. Measurements were made at 0.20 m soil depth and then at 0.2 m depth increments to a soil depth of 1.80 m. To facilitate the comparison of soil water data for different increments of soil depth, we converted the neutron probe measurements of soil water from volumetric percent soil water to an equivalent depth of water (mm). We followed the procedures in Anderson *et al.* (1987) to determine the total amount of water in the soil profile from the surface to a depth of 1.90 m (i.e., half the 0.2m depth increment past the 1.80 m depth reading) (Nowak *et al.* 2004).

Statistical analyses

We used two approaches to compare and analyze the experimental data. The first approach was to use a longitudinal (time series) data analysis on the entire data set using a radial smoothing technique (SAS Proc Glimmix, type = rsmooth) to model the covariance for each plot through time (SAS 9.1, © SAS Institute 2002). In order to maximize the predictive power of the radial smoothing model, we included the amount of precipitation, time (days) since irrigation, and all treatment interactions. The second approach we used was to divide the data set into time periods focusing on the sampling dates during the summer irrigation treatments as one time period (July – August) and the sampling dates between the irrigations as another time period (September – June). By splitting the data set in this manner, we were able use an equally spaced autoregressive repeated measures ANOVA (SAS Proc Glimmix, type = ar1) to analyze the data.

For the detailed analyses of soil moisture responses during the irrigation months (July – August), we omitted the non-irrigated plots. In the absence of precipitation, soil moisture was extremely low in non-irrigated plots, and the variance was proportionally low, resulting in very unequal variances between irrigated and non-irrigated plots (thus preventing convergence of the statistical model). Nitrogen addition treatment, irrigation number (first, second or third), crust disturbance, and precipitation were the fixed effects. Random effects were block and plot. The detailed analysis of the months between the irrigations (September – June) were done in a similar fashion except that the non-irrigated plots were included. Mean comparisons for significant factors in the ANOVAs were made with the "lsmeans/diff" command in SAS. Because the large sample size and many sampling dates lead to high denominator degrees of freedom for F tests, $P< 0.01$ was considered significant. In all cases, we modeled the data using a lognormal error distribution in Proc Glimmix (this is equivalent to performing a log transformation on raw data and running a Gaussian or normal model). For all analyses our random effects were blocks and plots, and we used the Random _residual_ option of Proc Glimmix to model the covariance structure (either a spline fit for the radial smoother or an autoregressive model for the repeated measures analyses).

Results

Radial smoothing model

There were no significant interactions between any of the nitrogen or crust treatments for total soil water content (TSWC) or at any of the individual depths. For TSWC and for water content at each depth, the continuous variables of days since irrigation (DSI), days, precipitation, and the interaction of these three terms were nearly always significant. For TSWC, the only additional interaction that was significant was precipitation x DSI x irrigation. The 20 and 40 cm depths showed identical results and are the only depths where an irrigation effect was significant (Fig. 5). All of the depths from 60 to 180 cm responded similarly with the only significant factors being the continuous variables mentioned above and the interaction of those variables. The only exception to this was a significant interaction of DSI x days x N at the 180 cm depth.

Irrigation months (July – August)

It is important to remember that for this analysis only the irrigated plots were used. There were no significant interactions between any of the nitrogen treatments for total soil water content (TSWC) or at any of the individual depths. For TSWC and the 20, 40, and 60 cm depths, irrigation number (1, 2, or 3) (Fig.6) and crust (Fig.7) were significant. The only other significant factor in this analysis was the interaction of precipitation x irrigation for TSWC and for the 20 cm depth.

Between irrigation months (September – June)
For TSWC and all other depths, the factor of month and the interaction of month x precipitation were all significant. For TSWC, there was a significant irrigation effect, irrigation x month effect, and a nitrogen effect. The 20 and 40 cm depths showed similar results with irrigation x month and precipitation x irrigation being significant. However, there was a significant irrigation effect at 40 cm and not at 20 cm. The 60 to 120 cm depths all showed similar results in that there was significant nitrogen x crust and irrigation x nitrogen x crust interactions. At 60 and 80 cm, there was a significant irrigation x month effect, and at 60 and 120 cm, there was a significant irrigation effect. The 140 to 180 cm depths were very similar in that the irrigation effect continued to be significant. There was also a nitrogen effect at 160 and 180 cm.

Some other highlights of our findings that do not particularly relate to any one of our analyses are that an additive effect occurs with subsequent irrigations, which drives the water deeper into the soil profile with each 25 mm irrigation event (wetting front increased from about 40 to 60 to 80 cm from the first to third irrigation) (Fig.8). Also, by the end of the 3rd irrigation (mid-August) irrigated plots had about 3.5 times more soil water content (%) than non-irrigated plots in the top 1 meter of soil (Fig.8). Another interesting finding has been the response of all plots to a large pulse rain event that occurred in December 2004. In December 2004 we received approximately 29 mm of rain in one event. The wetting front from this large pulse event took approximately five months to reach 180 cm (the deepest measurement we take) (Fig. 5).

Our initial hypothesis was that plots that were irrigated, had intact biological soil crusts, and no nitrogen additions would have higher overall soil moisture content. We must reject our overall hypothesis and conclude that the combination of irrigation, intact soil crusts, and no nitrogen additions does not lead to higher soil moisture. Obviously, there were times throughout the year when irrigated plots had higher soil moisture than non-irrigated plots as well as plots with crust were wetter than plots with disturbed crust. There were also occasions when there was a significant nitrogen effect, but the effect was never consistent in that plots with nitrogen addition were at times wetter and at times dryer. There was never a time when all plots representing all three of the treatment factors had higher soil moisture than the other plots at the same time of year.

Discussion

Radial smoothing model
The radial smoothing model showed that there is a correlation between the irrigation treatment and the amount of precipitation that is received in a given year. This is an important finding because it helps explain why in some years the irrigation effect lasts longer into the following year than in other years. The radial smoothing model also showed a significant interaction of DSI x irrigation for TSWC and at the 20, 40, and 60 cm depths. This result suggests that there is significantly more soil moisture to a depth of 60 cm as a result of the irrigations (Fig.8), but that the effect is dependant on the amount of time since the last irrigation, which is what we would expect to see. The radial smoothing model, being a predictive model and not a mean comparison model, was helpful to us by allowing us to use the entire data set and identifying overall trends in the data as well as the DSI interactions.

Irrigation months (July – August)
By partitioning the irrigations from the rest of the data set we were able to examine the additive effect of each irrigation. Both Fig.6 and Fig.8 show the additive effect of each subsequent irrigation with TSWC being the most dramatic change in soil moisture. From the first to the third irrigation, irrigated plots gained approximately 13 additional mm. Thirteen mm may sound low considering that

25 mm is added during each irrigation treatment, however, because the irrigation treatments take place in the middle of the hottest time of year there is a significant loss of soil moisture due to transpiration and evaporation. One of the most interesting findings from our analysis of the irrigation treatment was a significant crust effect (Fig.7) for TSWC and the 20, 40, and 60 cm depths. These results suggest that for a brief amount of time after the irrigation treatment (less than 1 month), plots with intact biological crusts retain a slightly higher soil moisture content. Although plots with intact biological crusts remain wetter for only a brief time, this finding may be important for summer annual plant species that are near the end of their phenological cycle.

Between irrigation months (September – June)
The most important finding from our analysis of the months between irrigation was the amount of time that the irrigation effect persists. The irrigation x month effect for TSWC and the 20, 40, and 60 cm depths persists on average four months after the third irrigation (December of each year). The 80 cm depth also showed a significant irrigation x month interaction, but the effect only lasted on average two months after the third irrigation. The only exception to this was 2001-2002 when the irrigation effect lasted into the first part of 2002. We were particularly interested to find out if the irrigation effect lasted into the next growing season for perennial species which is approximately March to May of each year. If the irrigation effect were to last into the following growing season, then those plants in the irrigated plots would most likely have an advantage over plants in un-irrigated plots. Another important finding from this analysis was that there was a significant interaction between precipitation and irrigation at the 20 and 40 cm depths. This result indicates that in years when there is relatively low precipitation, the irrigation effect persists longer at the shallower depths. When significant rainfall occurs, the irrigation effect tends to be “washed” out. At this time, we are unable to adequately explain some of the unusual significant interactions that occur at the deeper depths. Interactions such as nitrogen x crust and irrigation x nitrogen x crust only occurring at the depths of 60 to 140 cm may simply be due to transient fluctuations in soil moisture and do not seem at this time to be biologically relevant.

The large precipitation event that occurred in December 2004 has had some interesting effects on the soil moisture over the entire profile that we measured. This large precipitation event may be driving some of the odd significant interactions at the deeper depths of the soil profile. It is also interesting to note the time that was required for the moisture from this event to penetrate our deepest measuring depth. Fig. 5 shows clearly that water took five months to reach the 180 cm depth.

In conclusion, the irrigation effect does not generally persist into the following growing season, instead lasting only until about December of each year after which values converge with non-irrigated plots. There was not a significant, year-long effect of intact biological crusts and nitrogen additions as we initially hypothesized. Any significant nitrogen effect that occurs tends to be transient throughout the year and inconsistent among the three nitrogen treatments. Crust treatment effects are only apparent among irrigated plots with intact crusts being wetter for a brief period immediately following the irrigations. Similar to other studies of soil moisture in the Mojave Desert (Yoder and Nowak 1999, Nowak *et al.* 2004), evidence suggests that whatever amount of soil moisture that is present in the soil profile will be utilized by the vegetation due to water being such a limiting factor. Overall, the only consistent effect is the irrigation effect, which could potentially by itself be important for summer annual species and the phenology of perennial species such as *Larrea tridentata* and others that drop seeds during the summer monsoon season.

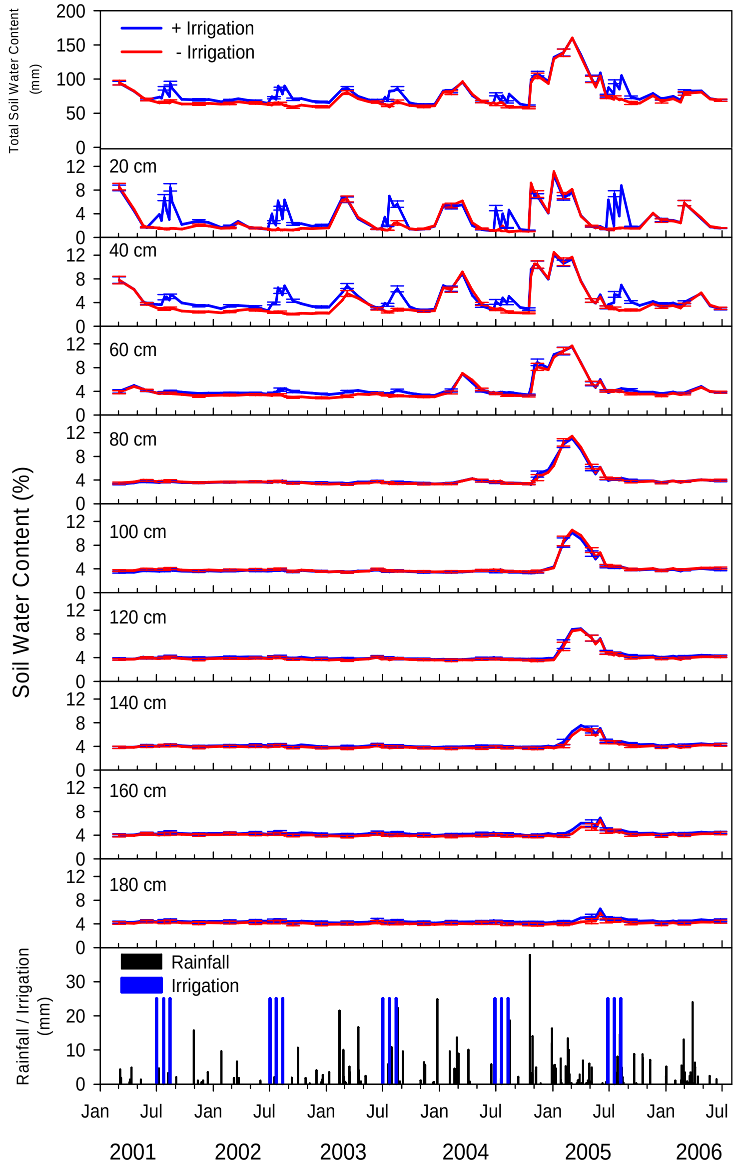


Fig. 5 Total soil water content (mm) (top panel) and soil water content (%) for all data from March 2001 to June 2006. Bottom panel shows precipitation (black bars) And irrigation (blue bars) events for same time period. Error bars are 1 SE.

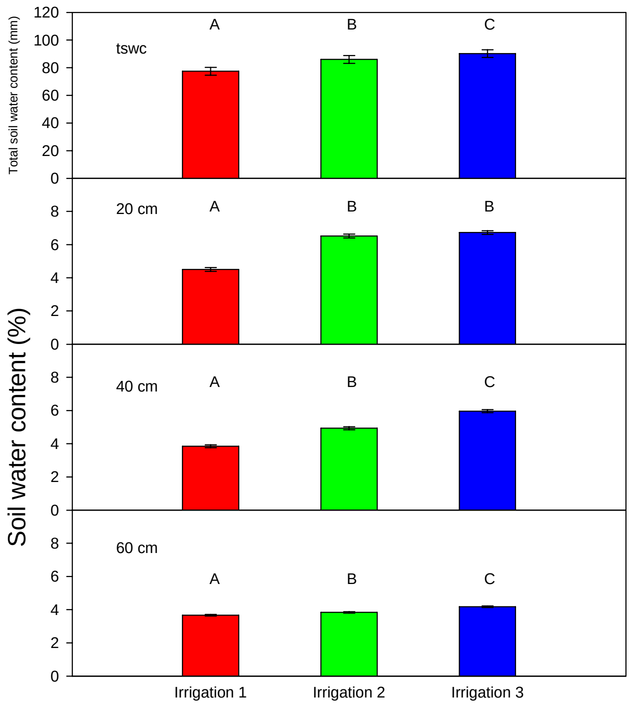


Fig.6 Comparison of the total amount (mm) of soil water gained from the first to the third irrigation and the amount of soil water (%) gained at the 20, 40, and 60 cm depths. This data is an average of all irrigated plots immediately after each irrigation. Bars with same letter are not significantly different. Error bars are 1 SE.

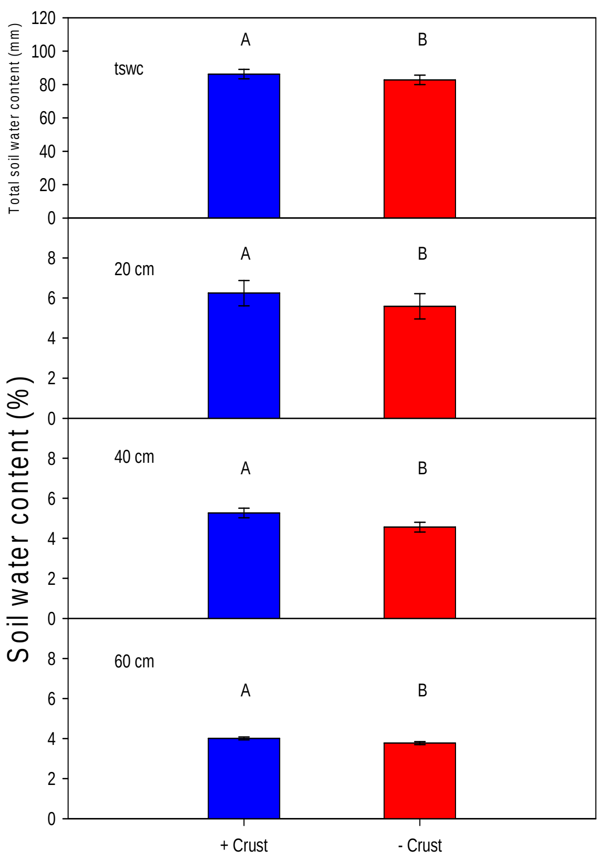


Fig.7 Comparison of crust treatments of TSWC and depths that were statistically significant among irrigated plots immediately after the third irrigation. Bars with same letter are not significantly different. Error bars are 1 SE.

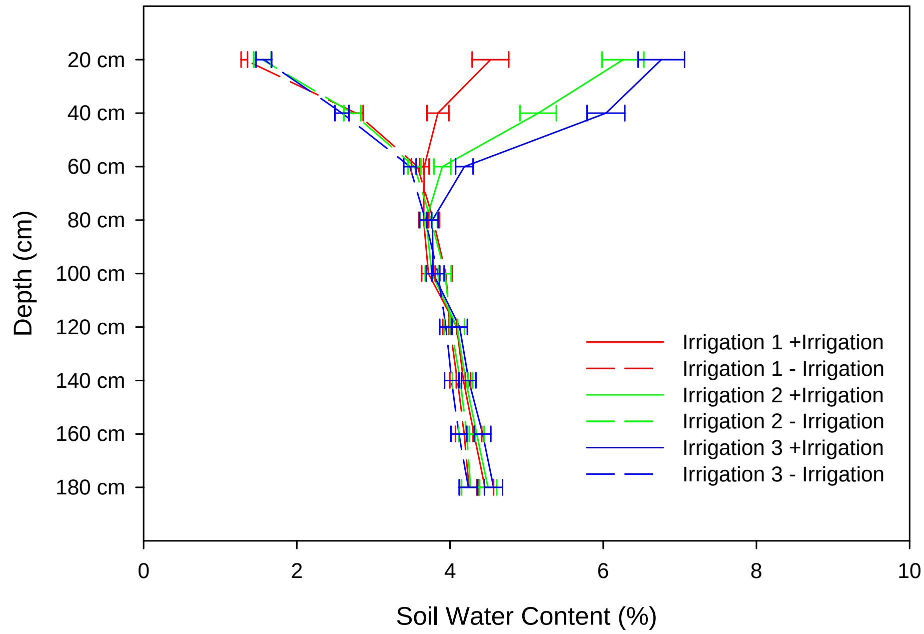


Fig.8 Soil profile comparison of irrigated vs. non-irrigated plots showing the additive effect of each irrigation as well as amount of soil water (%) gained fro the first to the third irrigation. Error bars are 1 SE.

NEAR-SUFACE WATER BALANCE [M.Young, PI]

Soil water balance was measured throughout the MGCF using a variety of instruments. The text below focuses on measurements from two miniaturized sensors that can be used with automated data loggers, thereby allowing for unattended data collection at time intervals no longer than 4 hours. The first sensor, known as a heat dissipation unit (HDU), embeds a heating wire and thermocouple into a ceramic plug, which is buried in the soil. The heating wire is energized and the temperature response is recorded. Water moves into and out of the ceramic plug based on matric potential gradients, but the temperature response is affected by the thermal properties of the ceramic, which depends on the soil water content. Each unit is calibrated using temperature response as a function of soil water potential. The second sensor is the dual probe heat pulse (DPHP). The DPHP is similar in general concept to the HDU. A heating wire is energized and the temperature response is recorded at the thermistor; however, the DPHP differs from the HDU in that the wires are embedded in separate hypodermic needles (not a ceramic plug), which are buried directly into the soil. The temperature response is a function of the thermal conductivity and volumetric heat capacity—both a function of water content—all of which are obtained from the measurement.

1. HDUs - During the performance period that began in late 2004, soil water potential was measured in four research plots using 64 HDUs. A total of 16 sensors were installed in each of four plots receiving no treatment (control, CW1), summer irrigation (CW2), crust disturbance (CW12), and irrigation plus crust disturbance (CW4). Data collection continued every four hours during the year. Overall, the monitoring system performed well, though we experienced some damage from rodents during the year, including the permanent loss of two sensors in plot CW12. Though some

instrument downtime occurred during the ~3 years since system installation, very little transient data were lost because of the lower than average precipitation during the last 18 months. The data showed upward gradients during summer periods, illustrating the very dry soil water conditions near ground surface. Sensors responded quickly to precipitation events (Fig. 9), where a 16.5-mm precipitation event caused a rapid reduction in soil water potential (less negative) for all sensors installed in the intercanopy microsite and all sensors—except for the 30-cm depth—installed underneath the canopy. Although depth of wetting front can be affected by local microtopography, the results for this event show that canopy interception can reduce water entering the soil beneath canopies. Data from eight precipitation (or irrigation) events that occurred in 2005 were analyzed for wetting front depths and propagation velocities using a three-way analysis of variance (ANOVA). The results of the ANOVA tests (site x treatment x depth) for the precipitation events provided some interesting results when comparing wetting front velocities as a surrogate for total infiltration. First, differences in mean values of wetting front velocities differed by treatment (crust versus no crust; $p=0.024$, $\alpha=0.05$). These results indicate that either a larger percentage of total precipitation entered the disturbed soil, or water entry into disturbed soil occurred more rapidly than in undisturbed soil, or both. Second, mean wetting front velocities between undercanopy and interspace sites were almost identical, differing by less than 3%, which was somewhat surprising given that canopy interception should reduce the amount of precipitation reaching ground surface and hence available for infiltration. It is likely that the sparse and open architecture of Mojave Desert plant species plays an insignificant role in canopy interception of precipitation.

2. DPHP – In March 2006, a total of 48 dual-probe heat-pulse sensors were installed for measuring soil water content. A total of 16 sensors each were installed in plots CW1, CW2, and CW4 (control, irrigation, and irrigation plus crust disturbance, respectively). Data collection began approximately April 1 and has continued at four-hour intervals thereafter. Sensors were installed below canopies of *Larrea tridentata* and *Ambrosia dumosa* shrubs and in adjacent interspace microsites. The sensors were installed to address several hypotheses, two of which included: (1) short-duration (or small) precipitation events (i.e., > 2 mm and <10 mm) can be detected using DPHPs; and, (2) moisture dynamics in near surface soils differ depending on the proximity to the canopy microsite and the precipitation distribution.

As the ambient temperature rose during the late spring and early summer, we noted a rise in the diurnal pattern of water content fluctuations that did not appear to be physically realistic (Fig. 10); i.e., higher water contents were recorded during the daytime and lower water contents were recorded during the evening. These fluctuations reduced our ability to discriminate small precipitation events, especially during the summer months when the warmer air temperatures led to variations in surface soil temperatures that exceeded +/- 20°C.

To address the hypotheses listed above, and to make sense of the data being collected, efforts were made to physically explain and correct the fluctuations. These efforts led us to conclude that the original method of analyzing the data would not be sufficient to handle the significant changes in ambient temperature occurring near ground surface. Through collaborations with Gaylon Campbell (Decagon Devices, Inc.), we developed a new algorithm that accounted for the temperature dependencies of thermal conductivity (Young et al., 2007). The algorithm incorporated a Levenburg-Marquardt (LM) parameter optimization scheme that focused on the soil water content, DPHP needle spacing, and drift in background temperature as independent variables, effectively bypassing the thermal properties altogether. The new analytical scheme was tested using data from April 2006 and August 2006, and was compared to two other methods of analyzing DPHP temperature responses (Single Point method and LM uncorrected). The results (Fig. 11) showed that the new algorithm (labeled as "LM corrected"), significantly reduced the fluctuations from +/- 0.05 $cm^3\ cm^{-3}$ to 0.005 $cm^3\ cm^{-3}$. Moreover, the overall behavior of the surface water content was more physically realistic. Following the correction, we re-analyzed all data collected to date. Fig. 12 shows an eight-month dataset for 2006, for the same sensor discussed earlier in Fig. 11, and the sensor response to precipitation events. Using the new algorithm, each of these events was clearly detected. Note also the smooth reduction in water content from April through May as spring temperatures increase, and the rapid drydown of soil water content after precipitation events. The histogram in Fig. 12 shows the number of days (24-hour period) that the surface soil water content exceeded an arbitrarily set value of 0.10 $cm^3\ cm^{-3}$. The graph is presented because previous results (i.e., Brostoff et al., 2005) have shown that photosynthetic activity of biological soil crusts was correlated to water content, especially when values exceed 0.10 $cm^3\ cm^{-3}$. The new method of analysis does allow for an assessment of when the water content of biological soil crusts exceed particular values, and hence the potential to quantify the photosynthetic behavior of the crusts. We know of no other method that provides this type of data in very near surface soils.

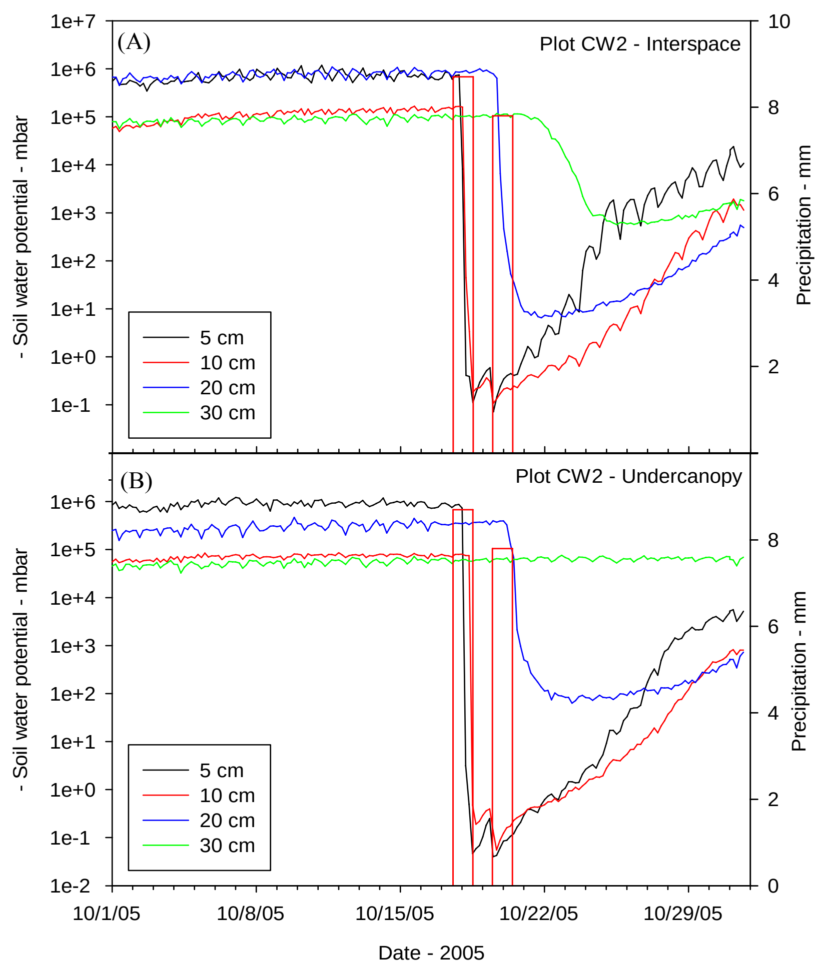


Fig. 9 Plot CW2 HDU response at Plot CW2 for a precipitation event occurring in October 2005 for (A) Interspace and (B) Undercanopy microsites.

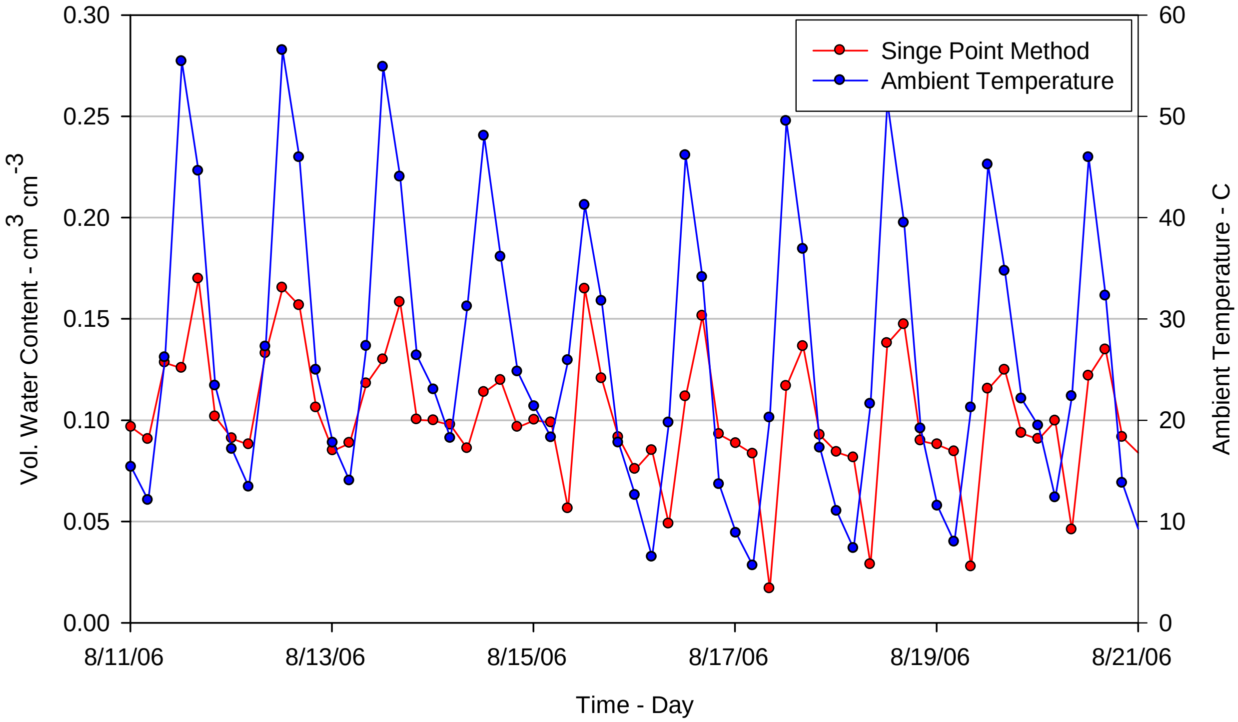


Fig. 10 Example dataset of water content changes as a function of time and ambient temperature for a surface-installed DPHP sensor in Plot CW1. This 10-day dataset is representative of the water content variations seen in other probes across the MGCF.

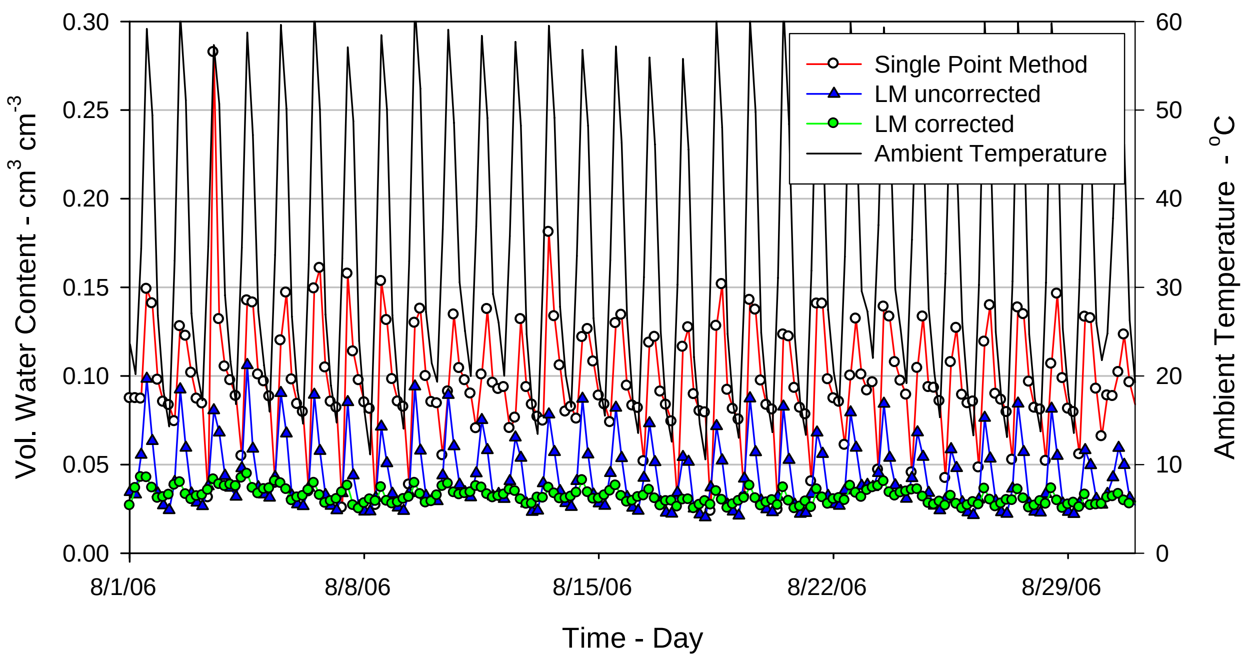


Fig. 11 Water content responses for the month of August 2006, using a surface-installed DPHP sensor, for three different methods of temperature responses.

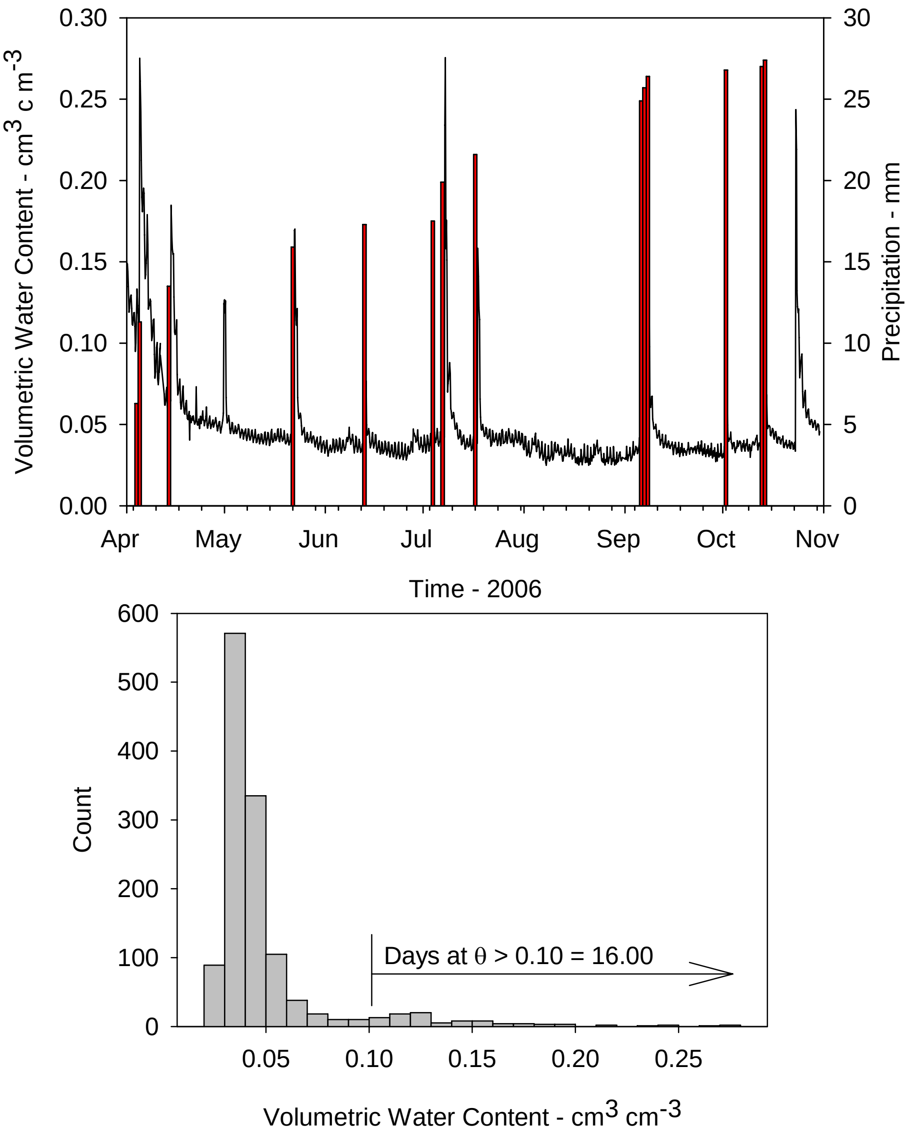


Fig. 12 Water content responses for eight-month time period in 2006, using a surface-installed DPHP sensor. Histogram shows number of days at which surface soil water content equaled or exceeded 0.10.

WATER USE [R.Nowak, PI]

Transpiration of *Larrea* tridentata [C.D. Holmes, K. Allcock]

Although there have been many studies on the morphological and physiological adaptations of *L. tridentata* to low soil moisture availability, there have been relatively few studies on the response of *L. tridentata* to global climate and/or land use changes. The aim of this study was to determine how transpiration of *L. tridentata* would respond to global climate and land use changes. Specifically we hypothesized that *L. tridentata* would have the highest rates of daily mean transpiration when exposed to irrigation, N additions, and disturbed soil crusts. Global climate and land use changes have the potential to affect nitrogen deposition, precipitation patterns, biogeochemical cycling (Schlesinger *et al.*, 1990), and the length of the growing season (Cleland *et al.* 2006). It is unknown how these changes might combine to effect the distribution and abundance of *L. tridentata*.

Sap flow measurements

In May 2004, three 8-12 mm sap flow sensors (EMS Inc., Turisticka, Brno, Czech Republic) were installed on three *Larrea tridentata* individuals in each plot of two complete blocks (72 total sensors). The sensors were allowed to run continuously until November 2005. Sap flow sensors operated on the stem heat balance principle at a constant temperature differential (4° C) (Cienciala and Lindroth 1995, Lindroth *et al.* 1995). Sensors were placed on the smoothest section of a stem that was at least 20 cm long and as far as possible from the ground so as to reduce the effect of any temperature gradient at the ground surface. Once sensors were installed, they were covered with a reflective Mylar shield (supplied by sensor manufacturer) to protect the sensor from the elements as well as act as an insulator from external temperature gradients. Sap flow data were collected every 10 minutes using data loggers (EMS Inc., Turisticka, Brno, Czech Republic), and the daily mean for each sensor were calculated.

Leaf area measurements

To avoid disturbance to the experiment, we were not able to destructively harvest any branches or leaves from the *L. tridentata* plants at the MGCF. Thus, we estimated leaf area using the integrating sphere method (Serrano *et al.* 1997). We estimated leaf area of each branch that a sap flow sensor had been installed on three times during the experiment to monitor any changes in leaf / transpirational area. We also measured the cross-sectional area of each branch that a sap flow sensor had been installed on. We assumed the entire cross-sectional area of each branch was conductive sapwood (Pataki *et al.* 2000). Sap flow measurements were expressed on a transpirational surface-area basis (J_s, $g*m^{-2}*sec^{-1}$) using our calculations of daily mean sap flow in combination with our leaf area measurements.

Statistical analyses

In order to test the effects of irrigation, crust disturbance, and nitrogen enrichment on sap flow rates, we focused on the time immediately following the irrigation events in 2004 and 2005. Two mixed model repeated measures analyses were performed on daily average sap flow values: one analysis encompassed data from June 28, 2004 through August 29, 2004 and the other encompassed data from June 28, 2005 through August 27, 2005. Each time span encompassed three irrigation events (June 28, July 19, and August 9 for 2004; June 28, July 18, and August 8 for 2005) and included 19 days following each irrigation event. We treated 'days since irrigation' as the repeated measure (with values ranging from 0 for the day of irrigation to 19 for the day before the next irrigation) and nested days since irrigation within the irrigation number (first, second or third).

For the detailed analyses of post-irrigation sap flow responses, we omitted the non-irrigated plots. In the absence of precipitation, sap flow was extremely low in non-irrigated plots, and the variance was proportionally low, resulting in very unequal variances between irrigated and non-irrigated plots (thus preventing model convergence). Nitrogen addition treatment, irrigation number (first, second or third), crust disturbance, and days since irrigation (treated as a categorical variable) were the fixed effects. Random effects were block and plot. Initially, the Julian date for each sample point was used to fit a radial smoothing model to the data in order to account for potential temporal autocorrelation between consecutive sample days, but temporal autocorrelation did not account for any significant variation and thus was omitted from the final analyses.

We used SAS Proc Transreg (SAS 9.1, © SAS Institute 2002) to determine the most appropriate lambda parameter of the Box-Cox transformation for each data set. For 2004 data, we used lambda = -1.5, and for the 2005 data, the natural log transformation was most appropriate. SAS Proc Glimmix (SAS 9.1, © SAS Institute 2002) with a Gaussian link function was used to conduct the mixed-model ANOVAs.

Results and Discussion

In both 2004 and 2005, sap flow significantly increased among the 3 different irrigations (Table 1). In 2004, sap flow averaged over the 19 days following the first irrigation was significantly lower than that following the second and third irrigations, but sap flow averaged over the 19 days following the second irrigation was not significantly different than that following the third irrigation (Fig. 13). In 2005, mean sap flow following the each irrigation sequentially increased, with sap flow averaged over the 19 days following the first irrigation significantly lower than that following the second irrigation and that following the second significantly lower than that following the third (Fig. 14). None of the other plot treatments (the two levels of N addition or crust disturbance) were significant, nor were any of the interactions between irrigation, N, and crust disturbance.

The number of days since irrigation was a significant factor in the ANOVA of 2004 data, but not for 2005 data (Table 1). In 2004, sap flow rates were significantly greater during the middle of the time period between irrigations (between 6 and 10 days following the irrigation) than at either beginning or end of the time period between irrigations (0 and 19 days); this rise and fall of sap flux after each irrigation is readily apparent in the data (Fig. 13). Because the "days since irrigation" factor was not significant in 2005, day-to-day changes in sap flow were not significant in 2005 (Fig. 14). A major difference between 2004 and 2005 was the greater number of rain events during the summer 2005. Transitory increases in sap flow on the non-irrigated plots were apparent in both years, and we suspect that the periodic small rain events in 2005 helped sustain sap flux at a relatively constant rate in that year.

Increased sap flux for *Larrea* typically occurred within a day after irrigation or after precipitation (Figs. 13, 14). This rapid response to additional water during the typically hot, droughty summer was unexpected, as *Larrea* is well known for its drought tolerance abilities (Smith *et al*. 1997). However, concurrent measurements of leaf conductance and net assimilation showed that both increased after the irrigation treatments (Barker *et al*. 2006).

Table 1. ANOVA tables for average daily sap flux on irrigated plots only for the day of and 19-day period following each of the three summer irrigations. Data were analyzed with a mixed model repeated measures analyses, where 'days since irrigation' was the repeated measure, and irrigation number, nitrogen addition treatment, and crust disturbance were fixed effects. Random effects were block and plot.

	2004			2005		
Effect	Num df	Den df	P value	Num df	Den df	P value
Irrigation number (IrrNo)	3	837	**<0.001**	2	1288	**<0.001**
Days since irrigation (DSI)	19	837	**<0.001**	19	1288	0.772
IrrNo x DSI	38	837	0.054	38	1288	0.993
Nitrogen (N)	2	3	0.585	2	2	0.347
IrrNo x N	4	837	0.521	4	1288	0.583
DSI x N	38	837	1.000	38	1288	1.000
IrrNo x DSI x N	76	837	1.000	76	1288	1.000
Crust (Cr)	1	3	0.890	1	2	0.584
IrrNo x Cr	2	837	0.422	2	1288	0.960
DSI x Cr	19	837	1.000	19	1288	1.000
IrrNo x DSI x Cr	38	837	1.000	38	1288	1.000
N x Cr	2	3	0.308	2	2	0.989
IrrNo x N x Cr	4	837	0.651	4	1288	0.964
DSI x N x Cr	38	837	1.000	38	1288	1.000
IrrNo x DSI x N x Cr	76	837	1.000	76	1288	1.000

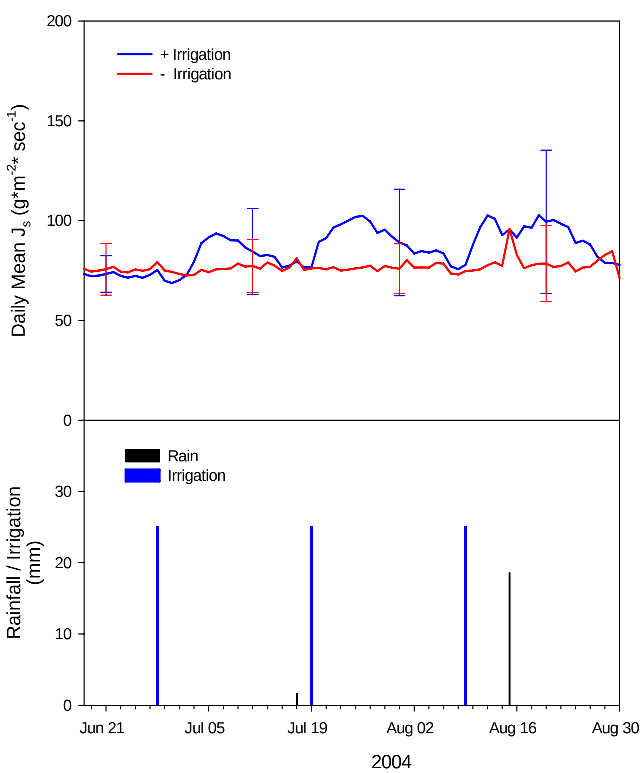


Fig. 13 (Top graph) Daily sap flux of *Larrea tridentata* branches averaged over all irrigated (blue line) and unirrigated (red line) treatments for the time period starting immediately before the first irrigation through 21 days after the third irrigation during summer 2004. Standard deviations for each treatment are periodically shown. (Bottom graph). Occurrence and amount of irrigation and precipitation events during summer 2004.

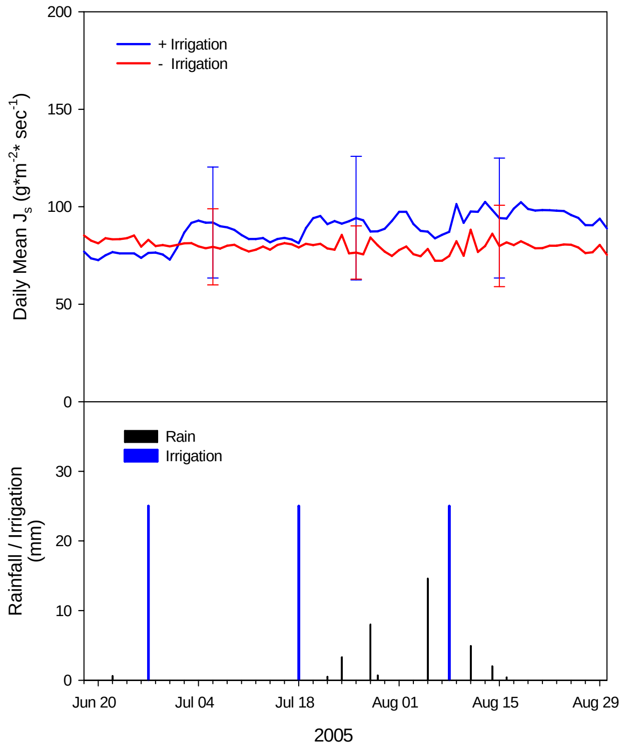


Fig. 14. (Top graph) Daily sap flux of *Larrea tridentata* branches averaged over all irrigated (blue line) and unirrigated (red line) treatments for the time period starting immediately before the first irrigation through 21 days after the third irrigation during summer 2005. Standard deviations for each treatment are periodically shown. (Bottom graph). Occurrence and amount of irrigation and precipitation events during summer 2005.

CHARACTERIZATION OF SOIL PROPERTIES [M.Young, PI]

Soil hydraulic properties are an important consideration in the assessment of water budget, soil evaporation and root water uptake by plants. During an on-site peer review of the MGCF, a reviewer comment suggested that additional attention should be paid to the potential heterogeneity of soil properties among the 96 plots, especially given that the plots extend for several hundred meters across an alluvial fan. To better understand how soils at MGCF might vary spatially, and to augment the data set already available by Titus et al. (2002), soil samples were collected at each of 96 test plots (Meadows et al., 2006). Soil was collected using a split-spoon sampler, with samples contained inside brass rings, each with a 4.8-cm inside diameter. The soil was slightly moist during the sampling, which provided a degree of cohesiveness to the soil; thus, very little material was lost during core extraction which allowed for accurate bulk density determination. The core was then split in the field into two equal-sized samples (0- to 5-cm depth and 5- to 10-cm depth), bagged and labeled. Soil samples were analyzed for particle size using the Laser Light Scattering technique (Digisizer, Micromeretics, Norcross, GA) by the Soil Characterization and Quaternary Pedology Laboratory at the Desert Research Institute in Reno, NV. Bulk density was determined by weighing the dry sample mass and dividing it by the volume of the soil core. A total of 192 samples were collected and analyzed.

Soil hydraulic properties were estimated using the pedotransfer function (PTF) method and the particle size distribution of the samples. The PTF method is essentially a multiple linear regression technique that uses a neural network analysis in combination with a large soils database to estimate the unsaturated hydraulic properties from soil texture. The benefit of this model is that many samples can be analyzed fairly quickly and compared to the results of thousands of other samples based on similar texture and bulk density. The PTF thus relies on a large database of soil textural results and nonlinear regression to estimate the soil hydraulic properties. The relatively minimal soil structure in the area also makes the use of the PTF approach an attractive option. The Rosetta software (Schaap *et al.*, 2001) was used to implement the PTF technique.

Results were examined for spatial structure across the facility using variogram analyses. The results of the analyses show a distinct fining of texture at both depths in the northeast quadrant of the facility (Fig. 15; an area lower in elevation on the alluvial fan), encompassing most of the middle portions of the DE and CE blocks. A pairwise comparison (Tukey) test was done on textural components (gravel, sand and clay) using texture data within each of the eight plot blocks as replicates, and between blocks as treatments. Results showed that textural components were significantly different in the northeast quadrant ($p<0.05$), where the central portion of the DE block showed significantly lower sand content and higher clay content. The PTFs also indicated a pattern of increasing air entry value from the southwest to the northeast of the facility which would manifest in a higher water holding capacity in near-surface soils toward the northeast quadrant. Weak spatial structure was observed for many of the hydraulic properties, with ranges on the order of 75 m.

Textural differences across the site could lead to differences in near-surface soil hydrologic behavior. For example, numerical modeling using HYDRUS-2D (Simunek et al., 1999) included data for a 155-m wide transect that spanned textures ranging from loam to sandy loam, and a 160-day meteorological record from the eddy covariance tower located just west of the site. The results show shallower wetting fronts for the loam-textured soils near plot DE7 and deeper wetting fronts near plot DE11. Evapotranspiration losses were nominally higher in finer-textured versus sandier-textured soils, because the shallower wetting fronts kept water closer to ground surface where roots were present and where soil evaporation could occur. Deeper wetting fronts in the sandier-textured soils led to slightly lower soil evaporation and a reduction in root water uptake. During the simulation period, model results showed that water loss from soils near DE11 was about 8% less than from soils near DE7. Further predictive modeling is being done to examine whether the differences are significant, and whether soil properties by themselves could explain differences in ecosystem productivity. Results will be incorporated into a manuscript to be submitted in late 2007 (i.e., Young et al., 2007).

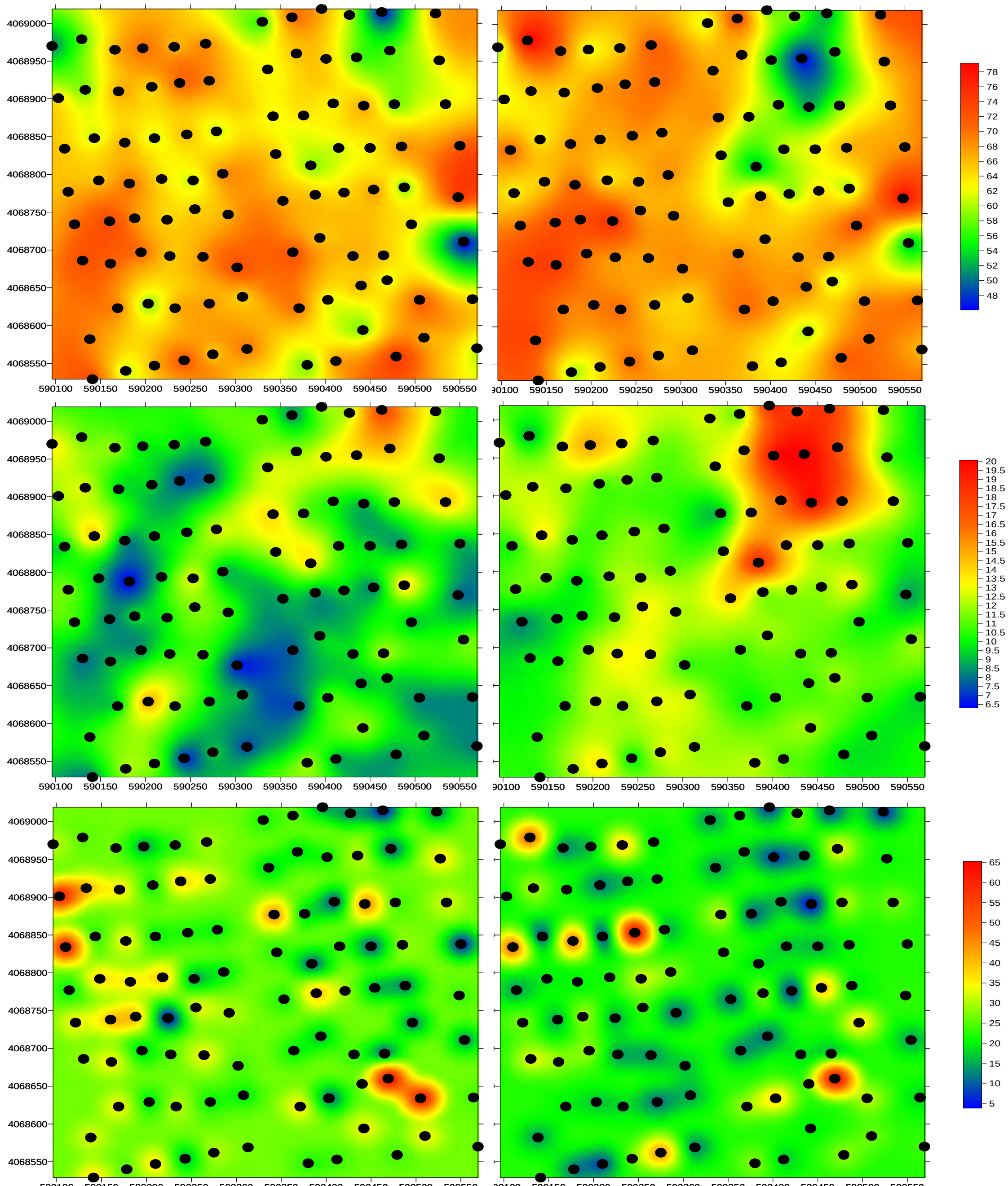


Fig. 15 Contour plots of (A) Sand, (B) Clay, and (C) Gravel contents. Symbols on plots indicate sampling locations. Each location is found toward the north or south of each particular MGCF research plot based on proximity to designated paths.

Remote Sensing Research [L. Fenstermaker, PI]

Background and Hypotheses

The use of remotely sensed data to synoptically assess land surface conditions has been successfully employed for decades. With the development of hyperspectral aircraft platforms and lightweight field spectrometers, remote sensing has become more effective in assessing particular vegetative parameters such as water and pigment content (Serrano *et al.* 2000 and 2002, Gamon 1999) as well as annual net primary productivity when time series analyses are performed (Gamon *et al.* 1995, Prince *et al.* 1995). Current remote sensing sensors and methods have demonstrated applicability to sparsely vegetated arid ecosystems as well as dense canopies (McGwire *et al.* 2000, Serrano *et al.* 2002). For this project two remote sensing platforms were employed at the leaf, canopy and whole plot level to assist in the assessment of a subset of the project's over-arching hypotheses, namely:

- *Increased nitrogen deposition will result in substantial increases in plant photosynthesis and production, particularly in concert with increased rainfall.*
- *Disturbance of biological soil crusts will result in reduced plant production over time due to gradual N-depletion in both soils and vegetation.*
- *Increased summer rainfall will result in increased production as a function of decreased water stress in the summer months; growth forms such as summer ephemerals and perennial grasses will increase more in production than do drought-tolerant xerophytic shrubs.*

Methodology

At the leaf and canopy level, a Unispec field spectrometer (PP Systems, Amesbury, MA) was used to acquire reflectance data. The Unispec has a <10 nm Raleigh resolution within the 310 to 1100 nm range of the electromagnetic spectrum. To examine plot level treatment effects several airborne platforms were considered. The most cost effective type of remote sensing that provides the best spatial resolution is very low altitude digital photography. We researched several platforms (a lift, blimp, radio control airplane and radio control helicopter) to acquire plot images and determined that the radio control helicopter (RCH) was the most effective because it is more stable than a blimp, ensured synoptic coverage of the entire plot within a single image frame unlike the radio control airplane and does not create a disturbance footprint like a lift. Additionally, the RCH can operate under a wide range of environmental conditions and is inexpensive in comparison to heavy equipment or manned airborne platforms. The recent development of a small and light weight digital multispectral camera by Tetracam Inc (Chatsworth, CA) that easily fits within the RCH payload specifications confirmed the choice of an RCH platform.

<u>Multispectral camera and radio control helicopter specifications:</u>

The Agricultural Digital Camera (ADC2) is a three band multispectral camera with a 3.2 megapixel CMOS sensor (2048 by 1536 pixels) that acquires green, red and near infrared image bands that simulate Landsat Thematic Mapper bands 2, 3 and 4. The camera weighs 520 g (18 oz.) with alkaline AA batteries and has the dimensions of 122 by 78 by 41 mm without the lens. The ACD2 has an USB interface, a compact flash memory card and application software that produces a number of image products including a color infrared image, several vegetation indices (NDVI, SAVI) and a canopy segmentation image in addition to standard image color enhancements.

The radio control helicopter (RCH) that was selected for this research was a Predator Gasser manufactured by Century Helicopter Products, San Jose, CA; see Fig. 16. This RCH was recently developed to operate on regular gasoline and 2-cycle oil which provides a longer flight time (45 min), does not produce a noticeable exhaust plume and is inexpensive to operate. The technical specifications of the RCH are: main rotor span of 160.5 cm; tail rotor span of 26.7 cm; overall length of 141.5 cm; height of 46.2 cm; engine: Zenoah Z231, gasoline powered, 2-cycle, 1.4 cubic inch displacement; in hover, main rotor operates at 1600 RPM with a blade tip speed of 112 m sec^{-1} (250 mph); and the carrying capacity is 6800 g (15 lbs) max (note: the components mounted on this RCH, which include camera, altimeter, mount and associated components, weigh approximately 1135 g, e.g., 2.5 lbs). The RCH is operated by a radio transmitter and we selected an 8-channel XP8103 radio, which operates at a frequency of 72.310 MHz. The radio has sufficient output power to provide a maximum flying range of approximately 2290 m (7500 feet), however, the actual flight range is limited by the ability of the human eye to discern the RCH orientation and flight direction. A bracket system with 16 points of individual vibration isolation was developed in-house to ensure stable image acquisition and allow easy mounting of standard digital color cameras as well as the multispectral camera. An on-board altimeter was installed to provide real-time RCH altitude for consistent image spatial resolution. The RCH operates well under a wide range of temperatures; this particular RCH was flown at temperatures ranging from 4° to 43° C. The only environmental factors that impact RCH operation are very gusty winds > 5 m sec^{-1} or sustained wind speeds > 10 m sec^{-1}.

Fig. 16 The Predator Gasser radio control helicopter with the ADC2 camera mounted on the front of the RCH. The bright pink panels make it easier to see the RCH orientation in flight and the spongy orange skids also aid in visual orientation as well as softer landings. The altimeter is mounted mid-way between the engine and tail on the fuselage.

Data acquisition:
Leaf and canopy level remotely sensed data were acquired periodically throughout the 2002 to 2007 growing seasons. Leaf level data were acquired with a bifurcated cable and internal light source within the Unispec system, which provided a consistent and comparable signal regardless of sun angle. The canopy level spectra were acquired using a single cable with no internal light source. Whenever possible, spectra were acquired within the same time frame as gas exchange, water potential and productivity measurements. Typical data acquisition included three measurements per shrub within each plot for the following plant species as well as the soil: *Larrea tridentata, Ambrosia dumosa, Lycium andersonii, Lycium pallidum and Pleuraphis rigida.*

Plot level images were acquired with an ADC2 multispectral camera mounted on the RCH. The RCH was flown to a height of approximately 25 m (80 ft) above ground level and positioned over the center individual MGCF plots. This altitude provided synoptic coverage of the entire plot, which was demarcated with four large white tiles at the plot corners. The camera trigger was depressed via a radio controlled servo. During Spring 2006, field validation data from 10 plots were collected within a 2-week period following image acquisition. The field data included the species name, width of every shrub along the major and perpendicular minor axes, height of the shrub and a visual estimate of percent green cover. From this data, the total percent green cover within each plot was calculated.

Data analysis:
The Unispec reflectance data were converted to 1 nm bandwidths with the "Multispec™" software developed by Faiz Rahman and John Gamon (Ball State University and California State University, Los Angeles). The resulting reflectance spectra were placed into an Excel spreadsheet (Microsoft Corp.) to calculate a suite of vegetation indices, which are listed in Table 2. SigmaStat 3.5 (Systat Software Inc.) was used to perform analysis of variance, t-tests and descriptive statistics for treatment effects by species and time of year.

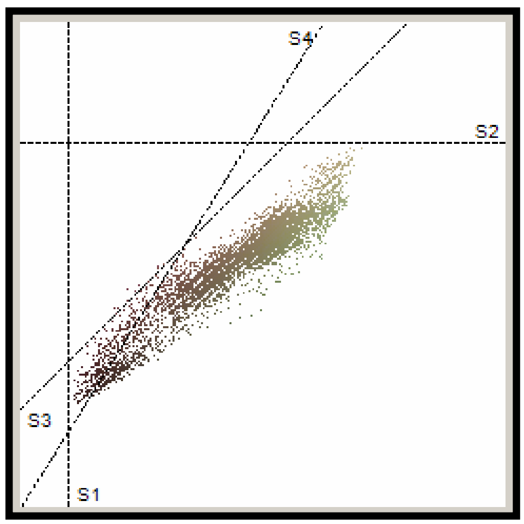
Table 2. Summary of vegetation indices used to assess MGCF treatment effects (R = reflectance at a specified wavelength-nm).

Index	**Description**	**Wavelengths (nm)**
PRI	Photochemical reflectance index	$(R_{531} - R_{570}) / (R_{531} + R_{570})$
SR	Simple ratio	(R_{800} / R_{660})
Chl	Chlorophyll index	$(R_{750} - R_{705}) / (R_{750} + R_{705})$
NDPI	Normalized difference total pigment to chlorophyll a index	$(R_{680} - R_{430}) / (R_{680} + R_{430})$
WBI	Water band index	(R_{900} / R_{970})
NDVI	Normalized difference vegetation index	$(R_{800} - R_{660}) / (R_{800} + R_{660})$
NPQI	Normalized phaeophytinization index	$(R_{415} - R_{435}) / (R_{415} + R_{435})$
λ_{RE}	Red edge (wavelength of maximum slope)	(between 680 and 740 nm)
R:FR	Red to far red index	R_{660} / R_{730}
WBI:NDVI	Water band index to NDVI	WBI/NDVI

Field et al., 1994; Gamon and Surfus, 1999; Gamon et al, 1997; Peñuelas et al., 1993a and b; Peñuelas and Filella, 1998; Serrano et al., 2000.

The ADC2 multispectral images were processed with the PixelWrench software (Tetracam, Inc., Chatsworth, CA). Preliminary analyses included: 1) conversion of images to color infrared using a color profile matrix; 2) rotation of images to north-up and cropping images to the plot perimeters; and 3) color enhancement. To estimate percent green canopy cover, a canopy segmentation subroutine was used to separate soil and shadow from green canopy cover by defining the range of soil pixel values within the red/near infrared spectral space. The user selects soil and shadow pixel areas within the image (ensuring that the brightest and darkest soil pixels are selected). Five threshold or sieve values are then selected to define the soil spectral space within the red - near infrared region. The first sieve value is the red minimum of the soil pixels, sieve 2 (S2) is the maximum NIR soil value, sieve 3 and sieve 5 are the intercept and slope of a threshold line just above the brightest soil pixels within the red to near infrared spectral space and sieve 4 is the slope of a line with a zero intercept that also thresholds the brightest soil pixels. Trial and error revealed that the automatic detection algorithm followed by user manipulation of sieves 1, 2 and sometimes 5 yielded the most accurate results that are reproducible. The red to near infrared spectral region of soil pixels within one of the MGCF plot images is displayed in Fig. 17 along with the appropriate position of the five sieve values. All scales of remotely sensed data were compared to field data using standard statistical tests such as linear regression, analysis of variance and t-tests using SigmaStat software (Systat Inc).

NIR Band



Red Band

Fig.17 The red to near infrared spectral space of a continuum of dark to bright soil pixels is displayed above. The PixelWrench canopy segmentation sieve values appropriate for this cluster of soil pixels are shown. (Sieve values are represented by the lines labeled S1 to S4; sieve 5 is the slope of the line labeled S3.)

Results

Leaf and Canopy Level Results

Vegetation indices from leaf level *Larrea* spectra were regressed against gas exchange measurements that were acquired within a 1 hour period of time. The results revealed a curvilinear fit between the daily integrated photosynthetic rate and the Photochemical Reflectance Index (PRI). The PRI is a measure of xanthophyll activity and hence photosynthetic radiation-use efficiency (Peñuelas and Filella, 1998). As light intensity becomes greater a dissipation of excess energy in the pigment bed associated with photosystem II occurs to protect the leaf. The PRI becomes more negative as more energy is dissipated via the xanthophyll cycle (Barton and North 2001). The PRI has also been found to become more negative with an increasing ratio of carotenoid to chlorophyll pigments (Sims and Gamon 2002). As expected the PRI measured for *Larrea tridentata* became more negative with decreasing daily integrated photosynthetic rates (Fig. 18) and there was a significant difference between irrigation treatments for this index, which indicates a higher photosynthetic rate with irrigation. The PRI data acquired in the morning had a much higher r^2 in comparison to the data acquired in the afternoon when leaf tissue became more stressed. It is likely that the afternoon PRI measurement occurred after photosynthesis had declined or shut down due to moisture and heat stress.

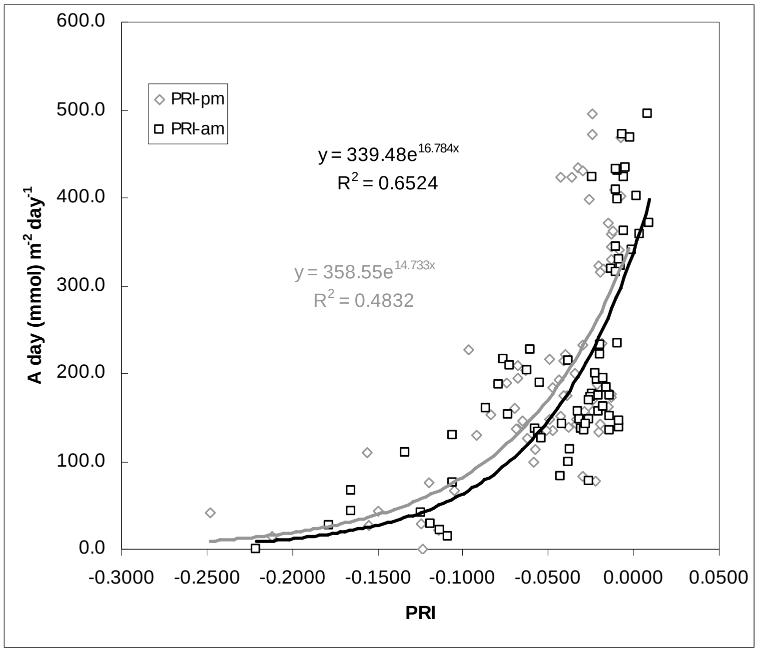


Fig.18 The photochemical reflectance index (PRI) is plotted against the daily integrated photosynthetic rate for *Larrea tridentata*. The morning PRI measurement is more closely correlated to photosynthetic rate than the afternoon PRI measurement. (Data from Naumburg and Fenstermaker)

Statistical analysis of all vegetation indices at the leaf and canopy level generally revealed a significant difference between the irrigated and non-irrigated plots, but no significant effect from the nitrogen additions or crust disturbance. There were some instances, however, where the Normalized Difference Pigment Index (NDPI) was significant between nitrogen and crust disturbance treatments for some species. The NDPI is sensitive to a ratio of total pigment to chlorophyll a and has been found to be well correlated to chlorophyll content (Peñuelas et al. 1995), and chlorophyll content typically increases in response to nitrogen addition. Time of year, prior precipitation events and plant species played a significant role in the performance of vegetation indices (Fig. 19). At the whole plot level a significant difference between irrigated versus non-irrigated treatments is significant after irrigation treatments despite the sparse vegetation cover (<20%) (Fig. 20).

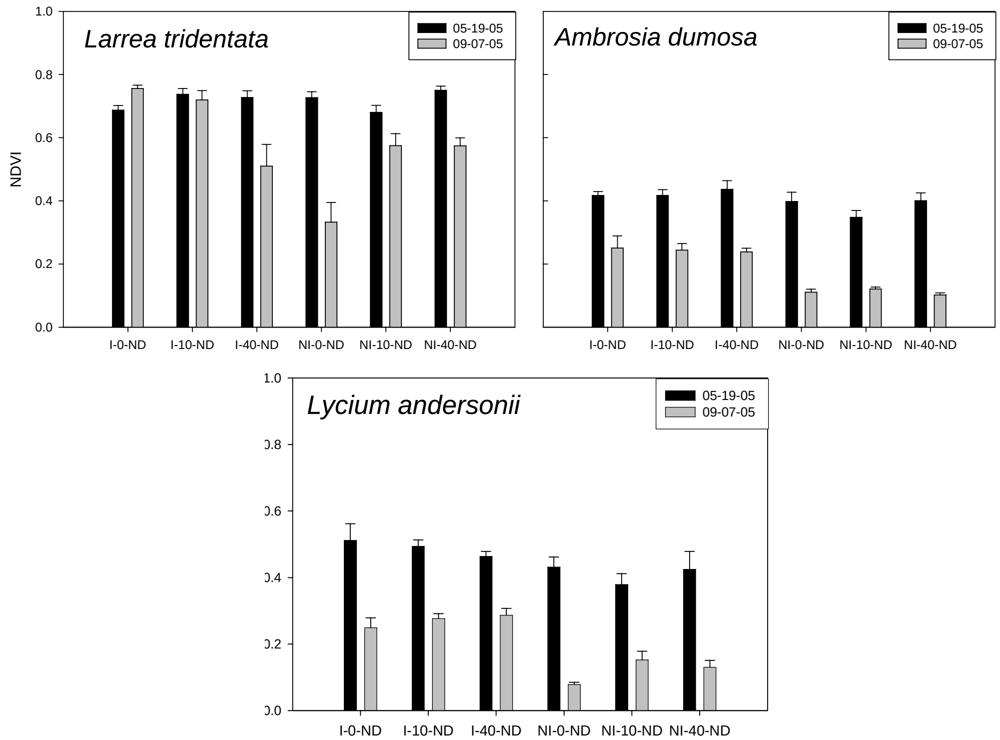


Fig.19 Plots of Normalized Difference Vegetation Index (NDVI) values at two times of year (May 19 and Sept 7, 2005) for three different species.

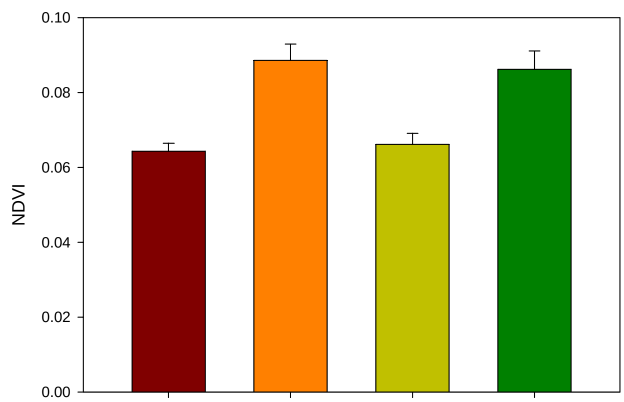


Fig. 20 Irrigated (H2O) vs non-irrigated treatments are significantly different at the whole plot level at the end of the summer irrigation treatment (Gamon and Fenstermaker).

Plot Level Results

The final construction of the radio control helicopter (RCH) and mounting of the ADC2 multispectral camera were completed prior to Spring 2006. Images were acquired for every plot in blocks AW, BW, CW and BE between May 3 and May 24, 2006. Images were also acquired following the third irrigation treatment in mid-August for all plots in blocks AW, BW, CW, DW, BE and DE. Figure 21 displays examples of the multispectral image data products for a single plot using the Tetracam Inc. PixelWrench software. When comparing the images to green vegetation in the field, it was possible to discern green vegetation clumps as small as 10 by 10 cm. As stated previously the field validation data were acquired in ten plots immediately following the spring image acquisition. These data were summed and a percent green canopy cover was calculated for each plot. A linear regression relationship with a repeatable r^2 of 0.82 was determined between the field data and the results of a semi-automated canopy segmentation analysis (Fig. 22). Given that the percent green cover determined in the field was a subjective determination, it is likely that the canopy segmentation analysis provides a better estimate of green canopy cover than the 0.82 r^2 would indicate.

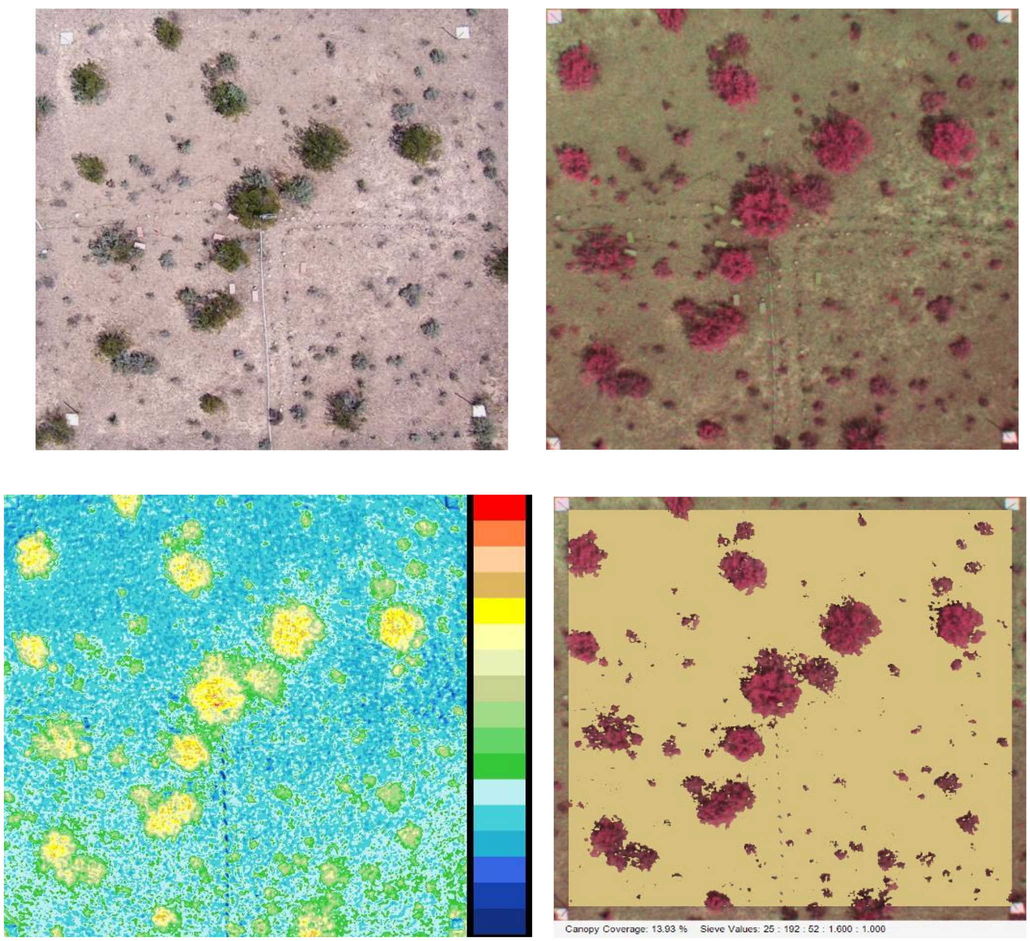


Fig. 21 From top left clockwise, the above images of the same MGCF plot are: a standard color photograph, a color infrared image from the ADC2, a canopy segmentation image with soil color coded tan and a NDVI image where warmer colors indicate a higher density of vegetation.

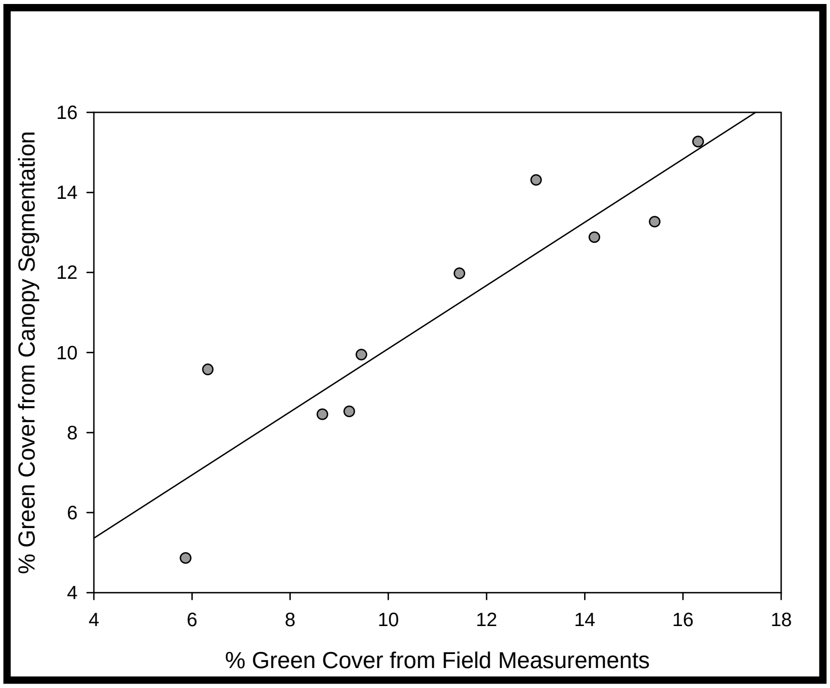


Fig. 22 Linear relationship between field and image based estimates of percent green cover is displayed above (repeatable r^2 of 0.82).

Examination of treatment effects on whole plot canopy cover revealed a statistically significant difference between irrigated and non-irrigated plots and this difference was maintained more than six months past the previous summer's irrigation treatment (Fig. 23). Some whole plot nitrogen and soil crust disturbance effects are apparent but not significant for all treatment pairs. It is likely that over time, that the difference in cover between irrigated and non-irrigated plots will increase.

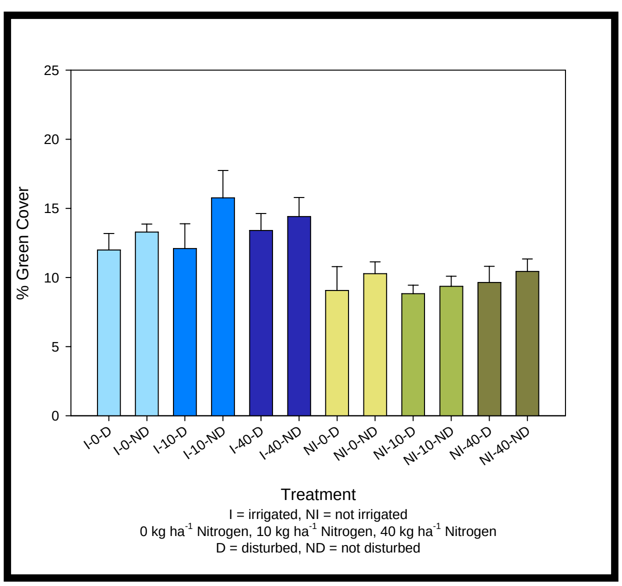


Fig. 23 Average percent green cover (from canopy segmentation analysis) reveals a significant difference between irrigation treatments (n=4, P <0.001).

Discussion

The remote sensing platforms used in this research provided data at several scales that are in agreement with and extend the results of field measurements. The leaf and canopy level vegetation indices data clearly show a significant irrigation treatment effect, which was anticipated because water is a primary limitation to plant physiological activity and growth in arid regions. There were instances where one of the pigment indices (e.g., NDPI) indicated a significant difference between nitrogen and crust disturbance treatments for some plant species. It is likely that these indices are providing an early assessment of treatment effects.

The successful development and deployment of a radio control helicopter (RCH) multispectral platform provided synoptic coverage and enabled an assessment of whole plot treatment effects in a timely manner. Despite inherent differences in canopy cover among individual plots,treatment effects are discernable. At the plot scale there is a significant increase in cover between irrigation and no irrigation, a negative impact of crust disturbance for all treatment combinations and a possible trend of increased canopy cover with increased nitrogen addition. In fact the plot-level canopy segmentation analyses revealed a potential for carry over of summer-precipitation treatment effects into the following growing season, which was not detected at the leaf level by Barker et al. 2006.

The continuation of high spatial resolution multispectral imagery acquisition over time will provide an effective tool to detect changes in canopy cover and composition at the individual shrub level as well as the entire plot. As stated in the Plant Growth section, the slow growth rates of these desert shrubs compounded with the variability in natural precipitation plays an important role on plant response to treatment effects. Given the results to date, plant response to the nitrogen and crust disturbance treatments at all scales are likely to be more significant over time.

REFERENCES

Barker DH, Vanier C, Naumburg E, Charlet TN, Nielsen KM, Newingham BA, Smith SD (2006) Enhanced monsoon precipitation and N deposition affect leaf traits and photosynthesis differently in spring and summer in the desert shrub *Larrea tridentata. New Phytologist* 169:799-808.

Brostoff WNM, Rasoul Sharifib, Rundel PW (2005) Photosynthesis of cryptobiotic soil crusts in a seasonally inundated system of pans and dunes in the western Mojave Desert, CA: Field studies. *Flora* 200: 592-600.

Cienciala E, Lindroth A (1995) Gas-exchange and sap flow measurements of *Salix viminalis* trees in short-rotation forest. I. Transpiration and sap flow. *Trees – Structure and Function* 9:289-294.

Gamon JA, Field CB, Goulden ML, Griffin KL, Hartley AE, Joel G, Peñuelas J, Valentini R (1995) Relationships between NDVI, canopy structure and photosynthesis in three Californian vegetation types. *Ecological Applications* 5:28-41.

Gamon JA, Serrano L, Surfus JS (1997) The photochemical reflectance index: an optical indicator of photosynthetic radiation-use efficiency across species, functional types, and nutrient levels. *Oecologia* 112:492-501.

Gamon JA, Surfus JS (1999) Assessing leaf pigment content and activity with a reflectometer. *New Phytologist* 143:105-117.

Lindroth A, Cermak J, Kucera J, Cienciala E, Eckersten H (1995) Sap flow by the heat-balance method applied to small-size *Salix* trees in a short rotation forest. *Biomass and Bioenergy* 8:1-7.

McGwire K, Minor T, Fenstermaker L (2000) Hyperspectral Mixture Modeling for Quantifying Sparse Vegetation Cover in Arid Environments. *Remote Sensing of Environment* 72:360-374.

Pataki DE, Huxman TE, Jordan DN, Zitzer SF, Coleman JS, Smith SD, Nowak RS, Seemann JR (2000) Water use of Mojave Desert shrubs under elevated CO_2. *Global Change Biology* 6:889-897.

Peñuelas J, Baret F, Filella I (1995) Semiempirical indexes to assess carotenoids chlorophyll-a ratio from leaf spectral reflectance. *Photosynthetica* 31(2):221-230.

Peñuelas J, Filella I (1998) Visible and near-infrared reflectance techniques for diagnosing plant physiological status. *Trends in Plant Science* 3:151-156.

Peñuelas J, Filella I, Biel C, Serrano L and Save R. (1993b) The reflectance at the 950-970 nm region as an indicator of plant water status. *International Journal of Remote Sensing* 14:1887-1905.

Peñuelas J, Gamon JA, Griffin K, Field CB. (1993a) Assessing community type, plant biomass, pigment composition, and photosynthetic efficiency of aquatic vegetation from spectral reflectance. *Remote Sensing of Environment* 46:1-25.

Prince SD, Goetz SJ, Goward SN (1995) Monitoring primary production from earth observing satellites. *Water Air Soil Pollution* 82:509-522.

Schlesinger WH, Reynolds JF ,Cunningham GL, Huenneke LF, Jarrell WM, Virginia RA, Whitford WG (1990) Biological feedbacks in global desertification. *Science* 247:1043-1048.

Serrano L, Gamon JA, Berry J (1997) Estimation of leaf area with an integrating sphere. *Tree Physiology* 17: 571-576.

Serrano L, Peñuelas J, Ustin SL (2002) Remote sensing of nitrogen and lignin in Mediterranean vegetation from AVIRIS data: Decomposing biochemical from structural signals. *Remote Sensing of Environment* 81:355-364.

Serrano L, Ustin SL, Roberts DA, Gamon JA, Penuelas J (2000) Estimating water content of chaparral vegetation from AVIRIS data. *Remote Sensing of Environment* 74:570-581.

Sims D and Gamon J (2002) Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment* 81:337-354.

Smith S.D., R. K. Monson, J.E. Anderson (1997) *Physiological Ecology of North American Desert Plants.* Springer-Verlag, Berlin.

PRODUCTS

Journal Publications

2007

Young MH, Campbell GS, Yin J (2007) Correcting dual-probe heat-pulse readings for ambient temperature fluctuations. *Vadose Zone Journal*. Accepted.

Nadeau JA, Qualls RG, Nowak RS, Smith SD, Blank RR (2007) Responses of enzyme activities involved in C, N, and P mineralization to short intense precipitation events in the Mojave Desert. *Soil Biology and Biochemistry* 52:305-320.

2006

Barker DH, Vanier C, Naumburg E, Charlet TN, Nielsen KM, Newingham BA, Smith SD (2006) Enhanced monsoon precipitation and N deposition affect leaf traits and photosynthesis differently in spring and summer in the desert shrub *Larrea tridentata. New Phytologist* 169:799-808.

Hartle RT, Fernandez GCJ, Nowak RS (2006) Horizontal and vertical zones of influence for root systems of four Mojave Desert shrubs. *Journal of Arid Environments* 64:586-603.

2005

Barker DH, Stark LR, Zimpfer JF, McLetchie ND, Smith SD (2005) Evidence of drought-induced stress on biotic crust moss in the Mojave Desert. *Plant, Cell & Environment* 28:939-947.

Stark, LR, L Nichols II, D N McLetchie, and M L Bonine (2005) Desiccation tolerance in a desert moss: a leaf regeneration assay based on gender. *International Journal of Plant Sciences* 166:21-29.

2004

Stark LR, Nichols L, McLetchie DN, Smith SD, Zundel C (2004) Age and sex specific rates of leaf regeneration in the Mojave Desert moss *Syntrichia caninervis*. *American Journal of Botany* 91:1-9.

Wilcox CS, Ferguson JW, Fernandez GCJ and Nowak RS (2004) Fine root growth dynamics of four Mojave Desert shrubs as related to soil moisture and microsite. *Journal of Arid Environments* 56:129-148.

Conference Papers

2007

Fenstermaker LF, Knight EA (2007) Assessing Climate Change Treatment Effects with a Radio Control Helicopter Multispectral Platform. Abstracts, The Ecological Society of America, 92nd Annual Meeting, August 5-10, 2007, San Jose, CA.

Holmes CD, Nowak RS (2007) Response of soil moisture content to five years of predicted global climate change treatments in the Mojave Desert. Abstracts, The Ecological Society of America, 92nd Annual Meeting, August 5-10, 2007, San Jose, CA.

Newingham BA, Smith SD (2007) Thunderstorms, SUVs and ATVs: what do they mean for Mojave Desert perennials? Abstracts, The Ecological Society of America, 92nd Annual Meeting, August 5-10, 2007, San Jose, CA.

Young MH (2007) Measuring water content in near-surface soils with large changes in ambient temperature. Presented at the Environmental Sensors Symposium. Boise State University, Boise ID, Oct 26-27, 2007 (Invited).

2006

Verburg P, Young, A, Stevenson, B, Glanzmann, I, Arnone, J, Nowak, R (2006) Response of fine roots to experimental nitrogen and water additions in a Mojave Desert ecosystem. Abstracts, The Ecological Society of America, 91st Annual Meeting, August 6-11, 2007, Memphis, TN.

2005

Barker DH, Nielsen K, Charlet TN, Smith SD (2005) Simulated summer monsoon rain and N-deposition in the Mojave Desert affects photosynthesis of *Larrea tridentata* differently during dry and wet years: evidence from a 3-year study. Abstracts, The Ecological Society of America, 90th Annual Meeting, August 7-12, 2005, Montreal, Quebec.

Holmes CD, Nowak RS, Young MH (2005) Intact biological soil crust does not affect soil moisture content in the Mojave Desert. Abstracts, The Ecological Society of America, 90th Annual Meeting, August 7-12, 2005, Montreal, Quebec.

Newingham BA, deSoyza A, Smith SD (2005) Linking changes in insect abundance with plant productivity in response to increased precipitation, nitrogen deposition and CO2 in the Mojave Desert. Abstracts, The Ecological Society of America, 90th Annual Meeting, August 7-12, 2005, Montreal, Quebec.

2004

Barker DH, Sikula N, Charlet TN, Smith SD (2004) Effects of simulated global change scenarios on photosynthesis in the evergreen *Larrea tridentata*. Abstracts, The Ecological Society of America, 89th Annual Meeting, August 1-6, 2004, Portland, OR.

Holmes CD, Nowak RS, Hartle RT (2004) Response of Soil Water Balance to Predicted Global Climate Change Treatments in the Mojave Desert. Abstracts, The Ecological Society of America, 89th Annual Meeting, August 1-6, 2004, Portland, OR.

Irvin SA, Zimpfer JF, Smith SD (2004) Effects of global change on Mojave Desert annual plant communities. Abstracts, The Ecological Society of America, 89th Annual Meeting, August 1-6, 2004, Portland, OR.

Newingham BA, deSoyza A, Smith SD (2004) Effects of elevated CO_2, enhanced summer rainfall, and nitrogen on productivity of the perennial grass, Pleuraphis rigida. Mojave Desert Science Symposium, Redlands, CA.

Smith SD, Sikula N, Charlet TN, Newingham BA, Barker DH (2004) Effects of simulated global change scenarios on growth and productivity in the evergreen Larrea tridentata. Abstracts, The Ecological Society of America, 89th Annual Meeting, August 1-6, 2004, Portland, OR.