Historical and Current Hydrological Research at the USDA/ARS Jornada Experimental Range in Southern New Mexico

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Abstract

The USDA/ARS Jornada Experimental Range (JER) (738 km^2), north of Las Cruces, NM, was established in 1912 to assess the impact of grazing in an arid land environment. The majority of rainfall occurs during June-September with an annual mean of 241 mm. Ecophysiological studies employing stable isotopes are underway to identify the sources of water uptake for shrubs and grasses and how the temporal and spatial variability affects the amount and sources of water used by various species. Infiltrometer and rainfall simulation studies are being used to quantify the role of soil biota in controlling soil surface hydrology in arid and semi-arid environments, and to define the resistance and resilience of different soils and plant communities to different disturbance regimes. Previous work at Jornada quantified the interception of rainfall for different shrubs and infiltration rates in rootplowed areas. Runoff was measured with a 2.8 m^3/s critical depth flume on a shrub dominated 7.4 ha watershed from 1977-1986. These flow measurements were re-activated in 2003. Runoff and sediment measurements were also made on plots, microwatersheds, and stock ponds. Because of the aridity of Jornada, there have been numerous rangeland rehabilitation treatments with the goal of slowing or reversing the shrub encroachment into grasslands. The most effective treatments have revolved around redistribution of surface runoff and its effects on infiltration and soil moisture. Simple, low profile, water ponding dikes seem to have had the best success in achieving a positive vegetation response.

Keywords: Jornada Experimental Range, grazing, rangeland rehabilitation, watershed studies, ecophysiology

Introduction

The U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Jornada Experimental Range (JER or Jornada) in Southern New Mexico has a long history of research, experimentation, and monitoring on rangeland vegetation change. The JER was established in 1912 with some research plots and data records having been maintained since then. In 1977, the site was selected as a Biosphere Reserve as part of the United Nation's International Man and the Biosphere program. In 1981, the National Science Foundation selected Jornada as a Long-Term Ecological Research (LTER) site. These different programs and research efforts at Jornada have produced a 90+ year history of ecological research on processes related to vegetation change, desertification, hydrology, and range management.

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The Jornada Experimental Range (783 km^2) lies 37 km north of Las Cruces, NM on the Jornada del Muerto Plain in the northern part of the Chihuahuan Desert. It is located between the Rio Grande floodplain (elevation 1,186 m) on the west and the crest of the San Andres Mountains (2,833 m) on the east. Jornada is typical of the Basin and Range physiographic province of the American Southwest and the Chihuahuan Desert. The Jornada basin is an internal drainage system with no surface runoff exiting the basin to the Rio Grande.

The climate of Jornada is characteristic of the northern region of the Chihuahuan desert with abundant sunshine, low relative humidity, wide ranges of daily temperature, and variable precipitation both temporally and spatially. Precipitation, which averages 241 mm yr^{-1}, mainly occurs as localized thunderstorms during July, August, and September. The average monthly maximum temperature ranges from 13°C in January to 36°C in June. Potential evaporation is approximately 10 times the average precipitation.

Jornada is the most arid North American grassland. Grasses on the plains are entirely C4 plants. Shrubs and suffrutescents are commonly C3 plants. More than 490 plant species have been identified on Jornada.

Grass communities of black grama [*Bouteloua eriopoda*], which once dominated the landscape, have been susceptible to encroachment by shrubs during the last century. Vegetation surveys made in 1855, 1915, 1928, and 1963 show that total area dominated by grass had decreased from 90% in 1858 to 23% in 1963 (Buffington and Herbel 1965). Droughts, grazing by livestock and native fauna, and shrub seed dispersal by livestock have all contributed to the spread of shrubs. Conversion from grass-dominated to shrub-dominated vegetation on these deep coarse texture soils characteristically has resulted in the formation of coppice dunes (Buffington and Herbel 1965), resulting in increased spatial heterogeneity of critically limited nutrients (especially N) required for plant growth (Schlesinger and Pilmanis 1998) and increased wind erosion.

To complement the programs of ground measurements, a campaign called JORNEX (the JORNada EXperiment) began in 1995 to collect remotely sensed data from aircraft and satellite platforms to provide spatial and temporal data on physical and biological states of the Jornada rangeland. A wide range of ground, aircraft, and satellite data have been collected on the physical, vegetative, thermal, and radiometric properties of the major ecosystems (grass, grass/shrub transition, and shrub) typical of the Jornada rangeland and of southwestern U.S. deserts. Data from different platforms have allowed the evaluation of the landscape at different scales. These measurements are being used to quantify hydrologic budgets and plant responses to change in components in the water and energy balance at Jornada. Data have been acquired twice a year from 1995 through 2003.

Sources of Plant Water Use

The interactions between plants and hydrology are critical in aridland systems. Plants are a pathway for water transport from soil to atmosphere. Plants determine the subsurface location of water lost to transpiration by having roots accessing water stored in various soil layers. Plant available water is water stored within the soil profile at soil water potentials that plants can extract. Differences in soil characteristics and topography create heterogeneous patterns of plant available water across the landscape. Highly variable rainfall events may also make water temporarily available to plants in shallow soil layers. The ability of different plant species or plant functional types (e.g. shrubs versus grass) to use these various water sources is a function of plant characteristics such as plant age, rooting characteristics, and carbon assimilation capacity. Plant water source use also is also a function of environmental factors such as the relative availability of water sources and the recent patterns of absolute soil moisture. The ability of various plant species or plant functional types to exploit various water sources will in part determine species success and competitive interactions.

We sampled dominant shrub species at the JER on various geomorphic surface and soil types throughout the growing season to determine which water sources the three dominant shrub species tarbush [*Flourensia cernua*], honey mesquite [*Prosopis glandulosa*], and creosotebush [*Larrea tridentata*] were using. Water source use was determined with stable isotopic methodology. Rainfall in this region is bimodal, and because of this seasonal variation, the natural abundance ratios of hydrogen and oxygen stable isotopes vary considerably among different source waters. Winter rainfall is isotopically distinct from summer monsoon rainfall. Winter rainfall percolates deeper and is the primary source of recharge for deep soil water. Summer rainfall is usually in isolated storms that recharge only shallow soil water. Since there is no isotopic fractionation during plant uptake of water from the soil (White et al. 1985, Ehleringer and Dawson 1992, Brunel et al. 1995), stable isotope methodology is a tool for determining plant water source (Ehleringer and Dawson 1992).

Stable isotopic methodology determines the ratio of heavy hydrogen (deuterium) to light hydrogen (H^2:H) in extracted water samples. Stable isotope ratios of hydrogen in water are expressed using delta notation (δ) in parts per thousand (‰) as:

$$\delta D = (R_{sample}/R_{standard} - 1) \times 1000 \quad \text{(Eq. 1)}$$

where R_{sample} and $R_{standard}$ are the molar ratios of D/H or $^{18}O/^{16}O$ of the sample and standard water. We extracted plant and soil water with cryogenic vacuum distillation (Ehleringer and Osmond 1989, Smith et al. 1991). Plant water and soil water samples were analyzed for hydrogen isotope ratios (δD) using a dual inlet isotope ratio mass spectrometer (Delta-S, Finnigan –MA, Bremen, Germany). A chromium reduction furnace attached on-line to the mass spectrometer was used to convert liquid water to hydrogen gas (HD-Device, Finnigan-MAT, Bremen, Germany). Plant water was compared with soil water values to determine from which soil layers plants obtained their water.

Preliminary results indicate species-specific differences in water source use. Creosote, which grows on gravelly sandy loam soils on the JER, appears to be highly responsive to summer rainfall and resultant pulses of shallow soil moisture. Mesquite, growing on deep loamy fine sands and loamy sands, did not appear to use substantial amount of shallow soil water and relied primarily on water stored deeper within the soil profile. In addition to these preliminary results, analyses of a thirteen-year data set on soil moisture patterns collected from the Jornada LTER showed as much variability within three replications of these different community types as between the different communities in patterns of volumetric soil moisture measured with a neutron probe.

Effects of Soil Biota

Tension and single ring infiltrometers are being used together with rainfall simulation to quantify the role of soil biota in controlling soil surface hydrology in arid and semi-arid environments, and to define the resistance and resilience of different soils and plant communities to different disturbance regimes. We used tension infiltrometers to quantify the effects of macropores generated by ants and termites on water infiltration capacity. The effects of soil biota on hydrology are also being evaluated as part of a long-term study on the effects of disturbance. This study was initiated in 1997 and is replicated on five different soils in southern New Mexico. We are using 12.5 cm single-ring constant-head infiltrometers to quantify relative changes in infiltration capacity in canopy and intercanopy zones in response to single and repeated trampling by humans and livestock, and to off-road vehicle traffic. Small-plot (0.5 m^2) rainfall simulation is used to calibrate the infiltrometers within a soil series, where possible, and to calibrate a field soil aggregate stability kit and to explore the relationship between soil aggregated stability, soil microbiotic crusts and erodibility. We are also using small plot rainfall simulation to define the effects of antecedent soil moisture on infiltration capacity reduction by off-road vehicles.

The tension infiltrometer studies showed that both termite and harvester ant activity significantly increases soil water infiltration capacity, and that much of the increase is due to macropore formation. Preliminary results from the long-term surface disturbance studies show that the effects on soil surface hydrology depend on disturbance type, timing, frequency, and intensity, and that these effects vary with soil type and vegetative cover. Soil aggregate stability values from the field kit (Herrick et al. 2001) are negatively correlated with sediment production from small-plot rainfall simulation. Disturbance of wet soils reduces infiltration capacity more than disturbance of dry soil, as predicted by theory and data from cultivated systems.

Preliminary results of the long-term, comprehensive study on the effects of different disturbance regimes on soil surface hydrology demonstrates the importance of integrated, multi-factor, long-term experiments applied across multiple soils: in most cases, the variable effects among sites can be explained by interactions between site characteristics and one or more characteristics of the disturbance regime. The results of the study will be analyzed and published following collection of an additional data set at all 5 sites in fall 2003 and spring 2004. The soil stability kit (Herrick et al. 2001) appears to be relatively sensitive to short-term changes in soil erodibility associated with dynamic soil carbon fractions, supporting its use in rangeland monitoring.

Vegetation Influence on Hydrologic Cycle Components

Tromble (1988) reported on a comparison of rainfall interception by creosotebush and tarbush at Jornada using rainfall simulators. Native stands of creosotebush had 30% crown cover and rainfall loss by interception was approximately 12%. Tarbush had 15% crown cover and intercepted about 6% of the rainfall. Infiltration rates were measured over undisturbed creosotebush stands and areas where creosotebush was rootplowed and seeded. Infiltration rates were greater on untreated plots than treated plots (Table 1). This demonstrated the potential for increased surface runoff and erosion from areas not adequately protected with vegetation cover, especially right after treatments have been performed (Tromble 1980).

Table 1. Difference between treatment means for infiltration rates after 60 minutes (Tromble 1980).

	Treatment **			
	CB wet	RP2 wet	RP6 dry	RP6 wet
Means (cm/hr)	1.39*^{a}	1.80^{a}	2.25^{a}	3.39^{ab}
	CB dry	RP2 dry	CC wet	CC dry
	4.68^{bc}	5.51^{bc}	6.72^{c}	9.41^{d}

Values followed by the same letter indicate no significant difference at the .95 level treatment means according to Duncan's multiple range test. ** CB = control, bare soil; RP2-rootplow, 1972; RP6-rootplow, 1976; CC = control, cresotebush.

Runoff Measurements

A 7.4 ha rangeland watershed dominated by creosotebush and mesquite on the eastern side of Jornada was first gauged in 1977 with a 2.8 m^3/s critical depth flume installed with assistance of ARS personnel at the Southwest Watershed Research Center in Tucson, AZ. The gauge was deactivated after 1986. During the 10 year period, sediment samples were collected with Coshocton wheels during each runoff event for four years. For the 10 year period of record, on average 6 storm flows a year were produced by precipitation over the watershed with almost all occurring during the summer months. The flow measurements were discontinued until May 2003 when the flume was reactivated with remotely telemetered data.
In the seven-year period, 1988-1994, plot runoff was measured from shrubland (dominated by creosotebush) and grassland (in black grama areas) as part of a study on nutrient losses in the Chihuahuan Desert of southern New Mexico. Runoff began at a lower rainfall threshold in shrubland than in grassland. In the shrubland, the runoff coefficient was 18.6% over the seven-year period. In contrast, in two different types of grassland plots, the runoff coefficient ranged from 5.0–6.3% (Schlesinger et al. 2000). The runoff plot dimensions were 2x2 m, and the plots were surrounded by a metal frame on three sides to prevent overland flow from crossing the plot. The total annual runoff averaged 57 mm from the shrubland runoff plots and only 15 mm from the grassland plots. In these studies, only natural rainfall events were studies. Additionally, rainfall simulation experiments were performed on other plots located within grassland, creosotebush shrubland, and mesquite dunefields. Rainfall intensities for these studies were typically 144 mm/hr.

Two small watersheds on the alluvial piedmont, both within creosotebush shrubland, have been instrumented to monitor natural runoff events. These instrumented watersheds have been collecting data since 1995. One watershed may be characterized as a typical 'dendritic' network in which two tributaries join to form the master stream of the catchment. Flow in both the tributaries and the master stream has been monitored. The second watershed characterizes the discontinuous drainage pattern, which typically occurs on alluvial piedmonts. In this case, two instrumented tributaries discharge into an area of diffuse flow. The outflow from this area of diffuse flow is also monitored. These areas of diffuse flow are significant sinks of runoff, particularly for small events, and appear also to be 'islands of fertility' favorable for plant growth (Wainwright et al. 2002).

In addition to the plot-based field experiments, we have undertaken field experiments to determine (i) the effects of creosotebush on rainfall energy and disposition of rainfall, and (ii) transmission losses in rills on the alluvial piedmont of Summerford Mountain. In 2001, ninety-six miniature flumes and bedload samplers were installed throughout the Jornada Experimental Range. This instrumentation is designed to sample the fluxes of interrill water, nutrients and sediment across ecotones. In 2002, instruments to record maximum flow stage and to sample water for nutrient analysis were installed in 11 rill locations. In 2002, five stock ponds located to represent the range of vegetation communities – creosotebush, tarbush, mesquite, grass, and creosotebush/mesquite mixed – were instrumented to record rainfall and rate of water inflow. The stock ponds allow the investigation of the integration of fluxes at larger scales.

Vegetation plays a very significant role in the hydrology of the Jornada Basin. Beneath creosotebush, mean rainfall intensity was reduced by up to 90% of that falling outside the canopy in rainfall simulation experiments, and mean kinetic energy was reduced by 30% (Wainwright et al. 1999). The reduction in kinetic energy is particularly important, because it weakens sealing beneath the shrubs, thereby enhancing infiltration, compared to intershrub areas. In contrast, these shrubs also direct much of the rain falling onto their canopies through stemflow to a small area of the ground surface surrounding their root crown. In this locality, the rate of stemflow is so high that the local infiltration rate is readily overwhelmed. During high-intensity storms, therefore, a high proportion of stemflow will run off as overland flow (Abrahams et al. 2003). Data for mesquite dunefields are available only for high intensity rainfall-simulation experiments, which indicate an average runoff coefficient at 41.8% at 144 mm/hr (Parsons et al. 2003). However, given the very low infiltration rates for sealed interdune surfaces, this figure suggests that mesquite dunefields may have the highest runoff coefficient of the three vegetation communities.

Rangeland Remediation Treatments

In the 1930s and early 1940s, extensive rangeland treatments were carried out in the Jornada basin in an attempt to reverse the advance of shrubs and re-establish grass dominance. The extensive treatments were conducted by hand, thanks to the presence of a highly organized and an inexpensive labor force in the form of the Civilian Conservation Corps (CCC) in the Jornada basin. After it became evident to Jornada scientists, that reduction of grazing alone would not cause a return to grass, a number of attempts were made to modify surface runoff patterns to slow the runoff and increase infiltration and surface soil moisture, with the hopes of encouraging grass growth. The common treatments using this approach were contour terraces, brush water spreaders, check dams for water redistribution, rootplow seeding, water ponding dikes, and water spreader systems.

Contour terraces and Brush water spreaders were installed throughout Jornada in the 1930s with little or no maintenance of these treatments, they both had lost effectiveness within about 35 years (Rango et al. 2002).

After the CCC period, numerous implements were designed to exploit the power of agricultural and civil engineering machinery to remove shrubs, prepare seedbeds, create small pits where water could accumulate, and plant seeds. A machine which accomplished all these operations in a single pass, was developed at Jornada in 1967 and tested during the 1960s and 1970s (Herbel et al. 1973, Abernathy and Herbel 1973). Commonly know as the "arid land seeder," it consisted of a 2.4 m wide rootplow pulled by a Caterpillar D-7. A 1.2 m wide conveyor with two side delivery rake wheels to gather severed shrubs from the 2.4 m rootplow swath was pulled behind the rootplow which picked up the severed shrubs and elevated them in the air. A power-operated blade was mounted underneath the conveyor to gouge out shallow basins about 3.6 m long. A press wheel seeder able to handle both small and chaffy seed planted grasses in the basins, and the shrubs dropped off the conveyor to provide temperature-reducing shade for emerging grasses.

In 1972 approximately 9 ha dominated by creosotebush was treated on the JER with the arid land seeder. An excellent stand of seeded grasses was obtained. Production in 1978 was 997 to 1,566 kg/ha compared to practically nothing on untreated areas. Contour strips 7.3, 14.6, and 29.2 m wide with either a 1-1 or 2-1 watershed above the strips were rootplowed and seeded in 1976. In 1978 the water harvesting strips yielded 2,817 kg/ha of forage vs. practically nothing on a control area. However, these treatments resulted in relatively high levels of soil surface disturbance that increased erosion susceptibility (Herrick et al. 1997).

Range water spreaders are systems of dikes and berms constructed to automatically divert flood water flows from gullies or arroyos, and to spread flow over adjacent rangeland to promote a positive vegetation response. In 1974, a serpentine water spreader was constructed below Yarbrough Dam in the southeastern part of JER in the foothills of the San Andres Mountains. Also, a diversion dam was constructed in the adjacent Lion's Den Canyon to divert more water into Yarbrough Dam. Operations were started in 1976, only to cease in 1977 because of a leak in the dam. Despite operating for just a year, vigorously growing vegetation was recorded on aerial photography where soil moisture was increased because of ponding and retention of water for longer time periods than allowed by natural, flashy runoff in these arid regions.

At about the same time as the construction of the Yarbrough Dam water spreader, smaller water ponding structures were being installed at four other sites at Jornada from 1975-1981. These water ponding dikes were of varying sizes and heights, usually about 60m in length and from 7.5-30 cm high. Various associated treatments were combined with the dikes including rootplowing, seeding, and application of municipal biosolids. These experiments were abandoned by 1984 because the principal investigator retired, there was little plant response, and the dikes required periodic maintenance. But, when the dikes were re-examined and re-measured in 1997 (Walton et al. 2001), significant recovery of native species was noted. In arid regions, significant rainfall events and subsequent runoff are not frequent, so it may be necessary to maintain treatments for longer periods than would be necessary in humid regions in order to encounter the precipitation events that would activate the treatments or support plant response.

Future Work

Future work in sources of plant water will investigate the water use behavior of mesquite and black grama across a larger range of soil type with differing depths to petrocalcic. Experimental additions of precipitation to plots of mesquite and black grama will be employed to understand the minimum storm size requirements for species-specific response and the importance of petrocalcic depth and development on plant community structure. We plan to continue to work on the effects of disturbance regime on soil surface hydrology, and to expand it to determine how disturbance at different spatial scales can be used to promote the restoration of degraded systems. A new project designed to define how petrocalcic horizons control soil water availability to different plant species was initiated in 2003. The focus of future runoff measurements is *i*) monitoring of natural events, and *ii*) upscaling of field measurement and monitoring to the landscape scale. Investigations will be made to determine the best ways to conduct spatially explicit sampling of surface properties and soil moisture in order to scale up to landscape units.

The most effective rangeland treatments to provide a positive rangeland vegetation response in the Jornada basin seem to revolve around the manipulation and redistribution of the surface runoff process, which in turn affect infiltration and soil moisture. Some of the best example rehabilitation treatments (water ponding dikes and water spreaders) will be repeated in the future and extended to larger areas, such as a series of arroyos.

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