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The Importance of Long-term Observations for Understanding Dryland Soil-Water-Vegetation-Climate Dynamics

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Abstract

The Southwest Watershed Research Center (SWRC) of the United States Department of Agriculture-Agricultural Research Service has been conducting arid and semiarid (dryland) watershed research since 1953. This included establishment and continuous operation of the Walnut Gulch Experimental Watershed (WGEW) in southeast Arizona. The 149 km^2 ephemeral watershed is one of the most densely instrumented dryland research catchments in the world with a drainage area greater than 10 km^2. This instrumentation captures many aspects of the hydrological cycle including how precipitation is partitioned into soil moisture, runoff and evapotranspiration and its subsequent effects on sediment transport, vegetation productivity, carbon sequestration, and groundwater recharge. The long-term, high-resolution record of observations on the WGEW enables understanding of the mean and variability of the hydrological processes, not well characterized with shorter term records, that fail to capture the large variability common to dryland regions. This presentation will highlight trends in temperature, precipitation, and runoff over the WGEW observation period. Additional research findings made by the SWRC and collaborators on erosion; plant productivity and carbon sequestration; the facilitation of soil water redistribution by plant roots; and groundwater recharge will also be presented.

The Importance of Long-term Observations for Understanding Dryland Soil-Water-Vegetation-Climate Dynamics

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BACKGROUND, LONG-TERM RECORDS, REMOTE SENSING

Background

The Walnut Gulch Experimental Watershed (WGEW) is operated by the Southwest Watershed Research Center (SWRC), USDA-ARS in Tucson and Tombstone, Arizona, USA (https://www.ars.usda.gov/pacific-west-area/tucson-az/southwestwatershed-research-center/) as part of the ARS Experimental Watershed Network and Long Term Agro-ecosystem Research (LTAR) network (https://ltar.ars.usda.gov/ - Goodrich et al., 2021). The WGEW is a tributary of the San Pedro River, it is located in southeastern Arizona, and surrounds the town of Tombstone. It is representative of roughly 60 million hectares of grass-and shrub-covered rangeland found throughout the semiarid southwestern US and northern Mexico. Average annual precipitation for the period of 1956–2020, as measured by six gauges, is 310 mm, with approximately 60% falling during the summer monsoon.

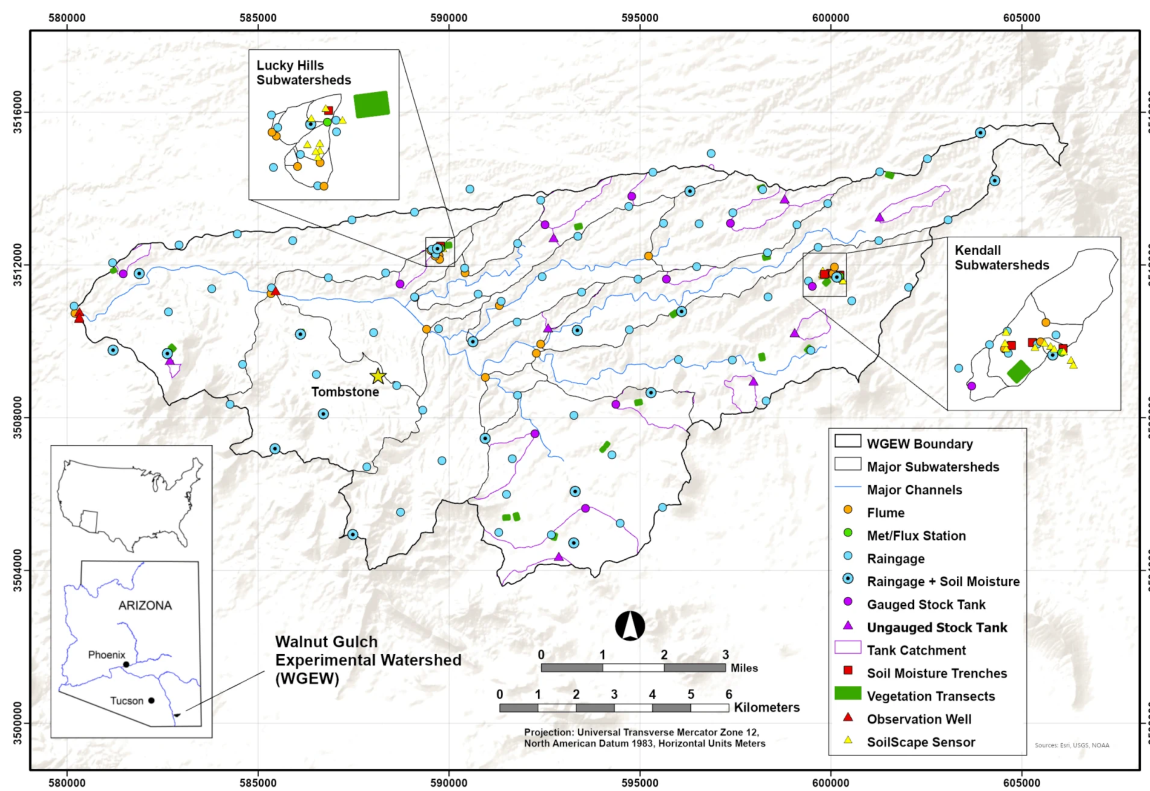

Figure 1. Hydro-meteorological, runoff, and additional instrumentation and measurement sites within the USDA-ARS WGEW.

Long-term Records of Precipitation, Temperature, Runoff, and Remote Sensing

The current rain gauge network consists of 101 gauges. Runoff is measured for 29 sub-watersheds and the entire WGEW (Stone et al., 2008). Figures 2 thru 5 illustrate the time series of mean precipitation, temperature, SPEI and runoff over the entire WGEW. Interannual variability is large for precipitation, SPEI, and runoff. Trends in runoff are dependent on the period of record examined (Goodrich et al, 2008 - WRR rainfall persistence). The southwest United States, including the WGEW, is experiencing a megadrought that began in 2000 (Szejner et al., 2021).

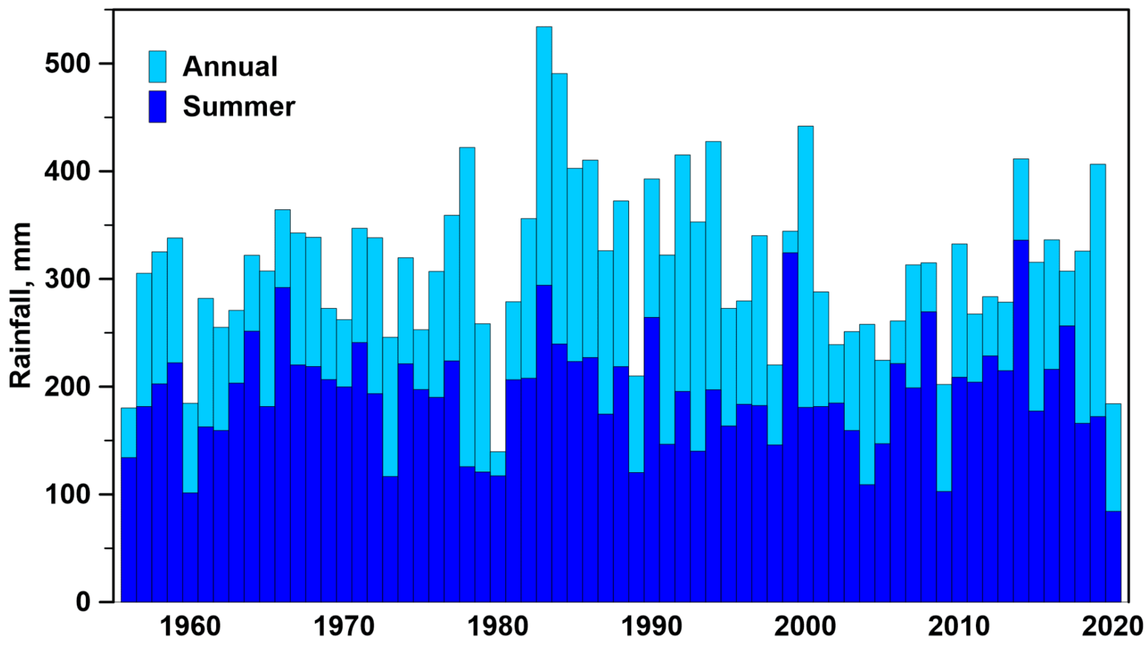

Figure 2. Annual and summer WGEW yearly rainfall totals for 1956–2020.

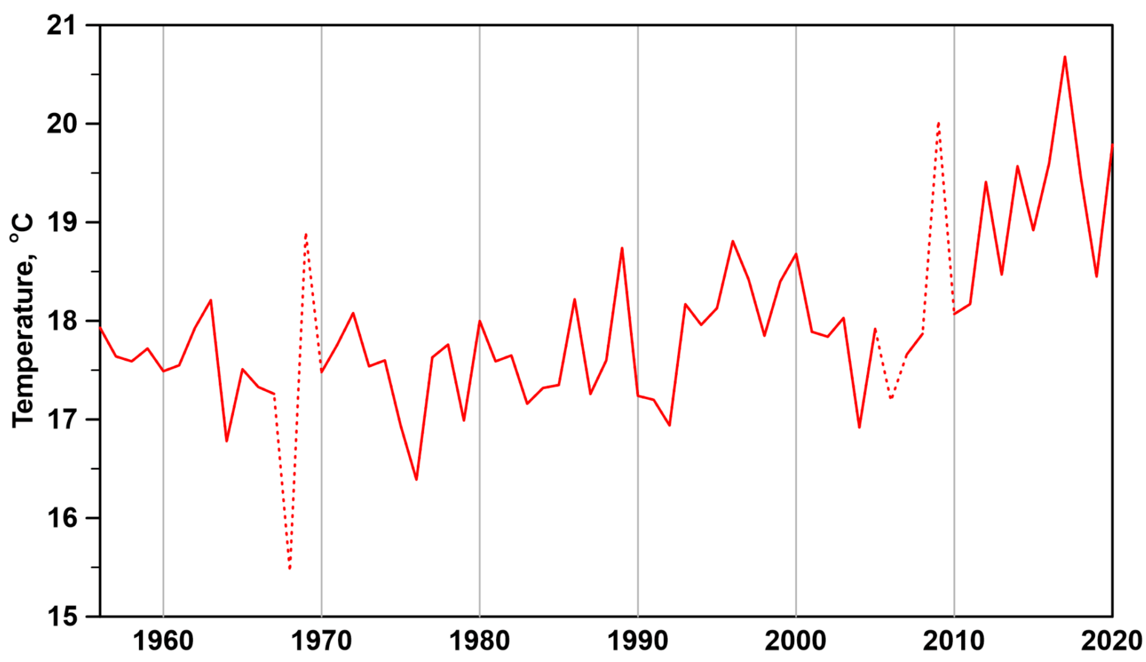

Figure 3. Annual mean temperature at Tombstone, Arizona for 1956–2020. The dashed lines indicate periods with missing data.

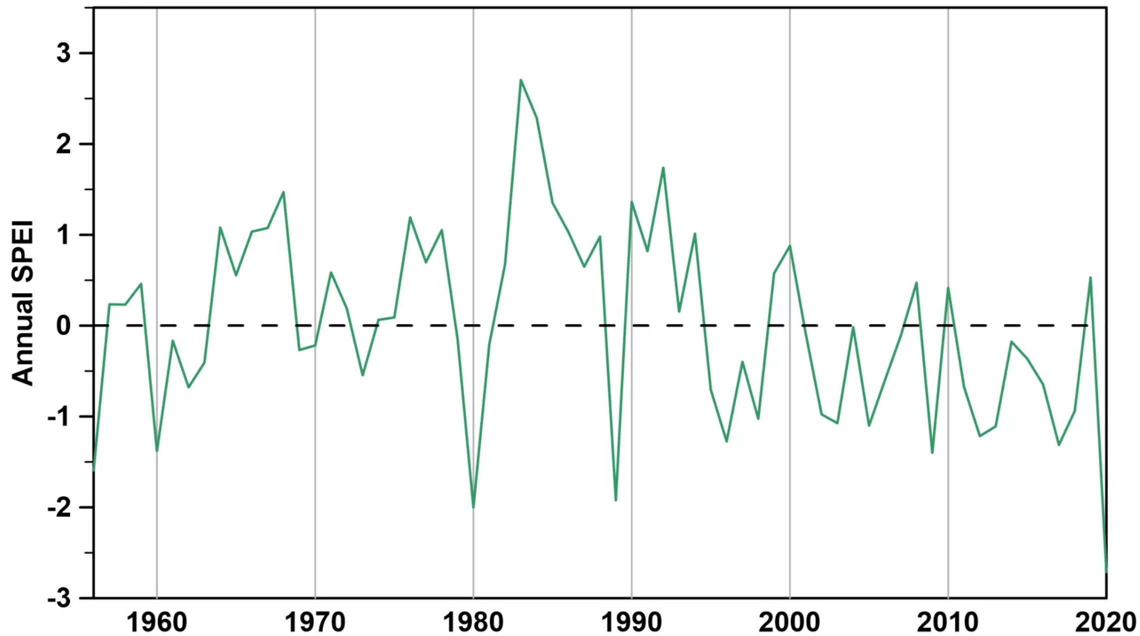

Figure 4. Annual Standardized Precipitation-Evapotranspiration Index (SPEI) at WGEW for 1956–2020.

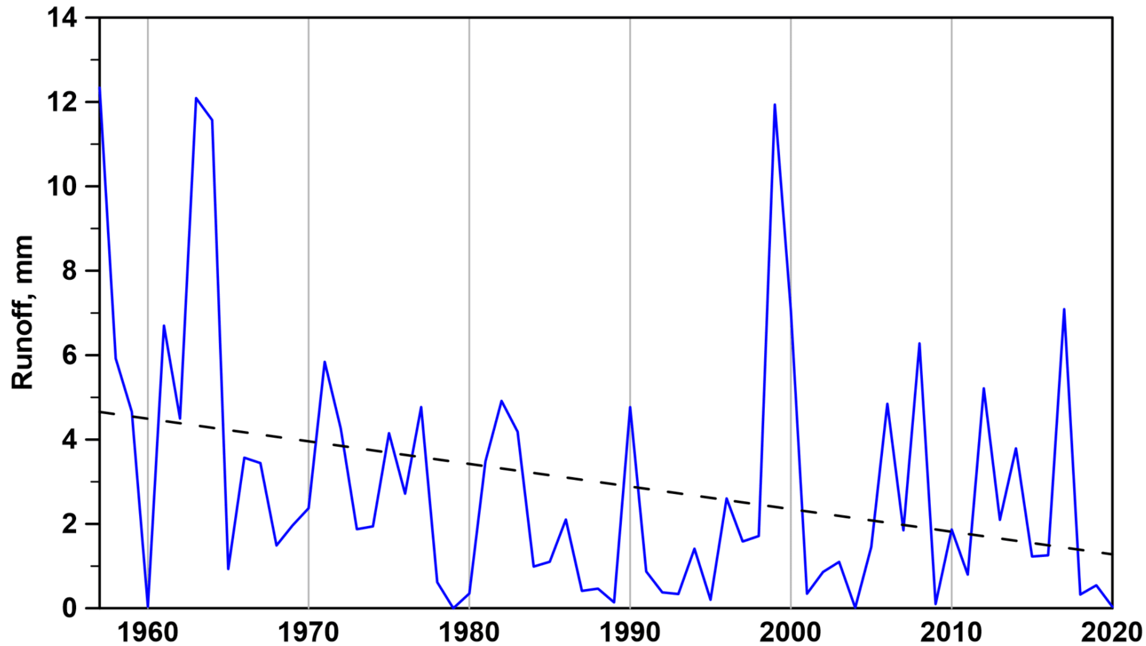

Figure 5. Annual WGEW runoff volume for 1956–2020. The dashed line indicates a significant linear trend.

Over Walnut Gulch's almost 70 year-long history as a hydrologic research site, the Southwest Watershed Research Center has developed a rich geospatial dataset. GIS layers for geology, geomorphology, soils, ecological sites, vegetation, hydrography, boundary, and subwatersheds, as well as instrumentation, are available for download from the website (tucson.ars.ag.gov/dap). Remotely sensed data have been collected from ground, aircraft, and satellite sensors. Larger datasets are also available by request, such as aerial photography from 1974, 1988, 2005, 2008, 2009, aerial lidar from 2004 and 2015, and a NEON Airborne Observatory dataset from 2018.

The highly localized precipitation from summer convective storms provide an extreme test of sensors focused on water cycle components. Consequently, the experimental watershed has served as a field validation site representing semiarid rangeland ecosystems for many remotely sensed instruments. Examples include:

- Precipitation - NEXRAD, GPM, TRMM
- Vegetation - Landsat, MODIS (EVI)
- Soil Moisture - AMSR-E, SMOS, SMAP, COSMOS
- Surface Temperature - SALSTICE

The WGEW is an ephemeral watershed where surface runoff is present for short periods of time after high intensity rainfall (30 min. intensity > 25 mm/hr) that occurs almost exclusively during the North American Monsoon (June -Sept.). The water table is roughly 30 to 40 m below most of the watershed ground surface. Many of the larger channels in the WGEW consist of relatively porous sands and gravel that have high infiltration rates. This results in substantial abstractions of runoff by channel transmission losses as illustrated in Figure 6. For this single event, the Flume 6 to Flume 1 transmission losses over this 11 km reach are equal to roughly one-half percent of total annual groundwater recharge to the 3200 km San Pedro basin as estimated from a regional groundwater model.

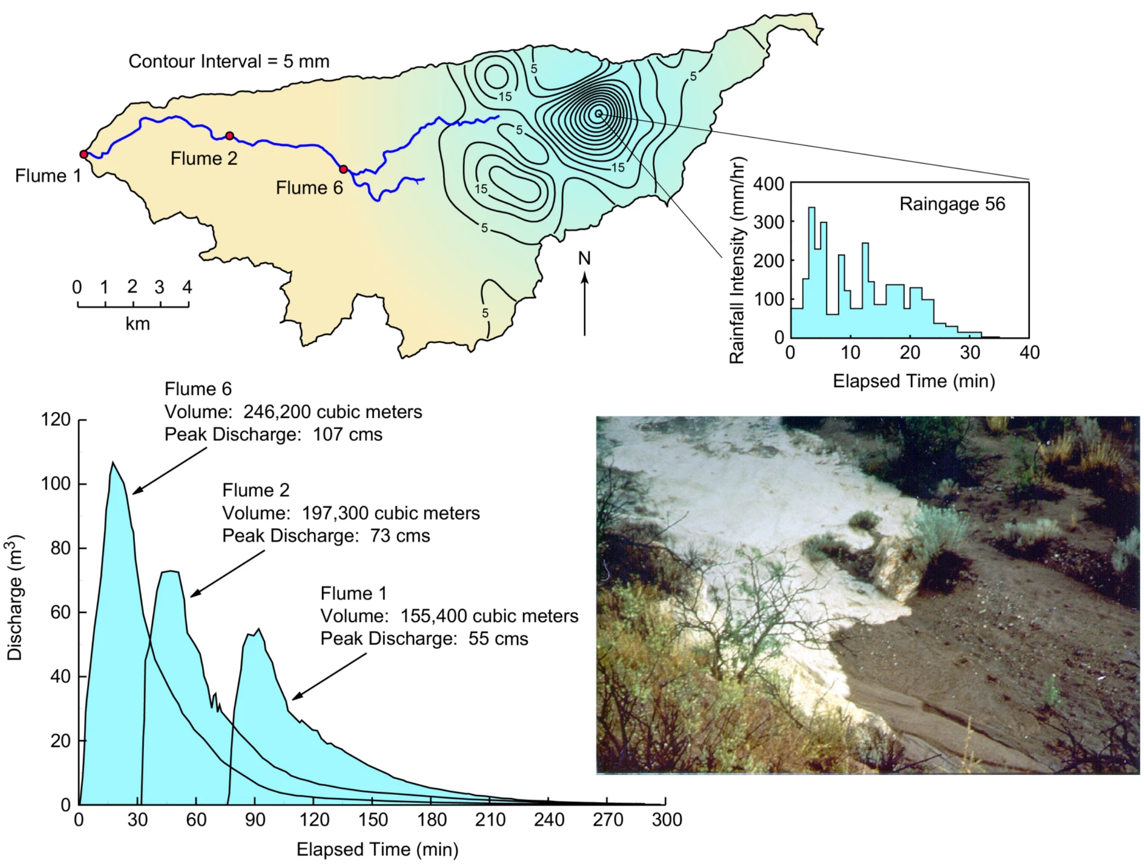

Figure 6. Isohyets of storm event on Aug. 27, 1982 and resulting runoff hydrographs recorded at flumes 6, 2, and 1.

PRECIPITATION INTENSIFICATION, GROUNDWATER RECHARGE, PRECIPITATION MANIPULATION

Precipitation Intensification

Most analysis predicting precipitation intensification has been done at daily or longer time scales. The weighing rain gauges used in the WGEW have been, and continue to be, maintained by professional staff. This includes rigorous QA/QC, resulting in a high quality, long-term record of precipitation suitable for testing sub-daily and sub-hourly intensification (Goodrich et al., 2008). Observations from 59 gauges from 1961-2017 were analyzed for trends in intensity ranging from 5 minutes to 24 hours using both an annual maximum series (AMS) and partial duration series (PDS) approach. Temporal trends in intensities were evaluated with the non-parametric Mann-Kendall test and Sen's method (Demaria et al, 2019). The watershed mean (59 gauges) of rainfall intensities exceeding the 95th percentile have been increasing for all durations longer than 1 hr at a rate of 0.50 to 0.03 mm/hr per decade for the 0.5-to 24-hr durations, respectively. The spatial variability of intensity trends across the WGEW was large as shown in Figure 7. A 30-year moving-window trend analysis indicated that predominantly positive trends started in the 1970s (bar plot insets in Figure 7) when the number of rain gauges reporting positive trends, albeit not always statistically significant, surpasses 50% (see also Figures 7c–7h). Separate analysis on two periods of record (1961-1988) and (1990-2017) indicated that larger events (20-year return period) have become more common and significantly more intense than smaller storms (T = 2yr and 5yr).

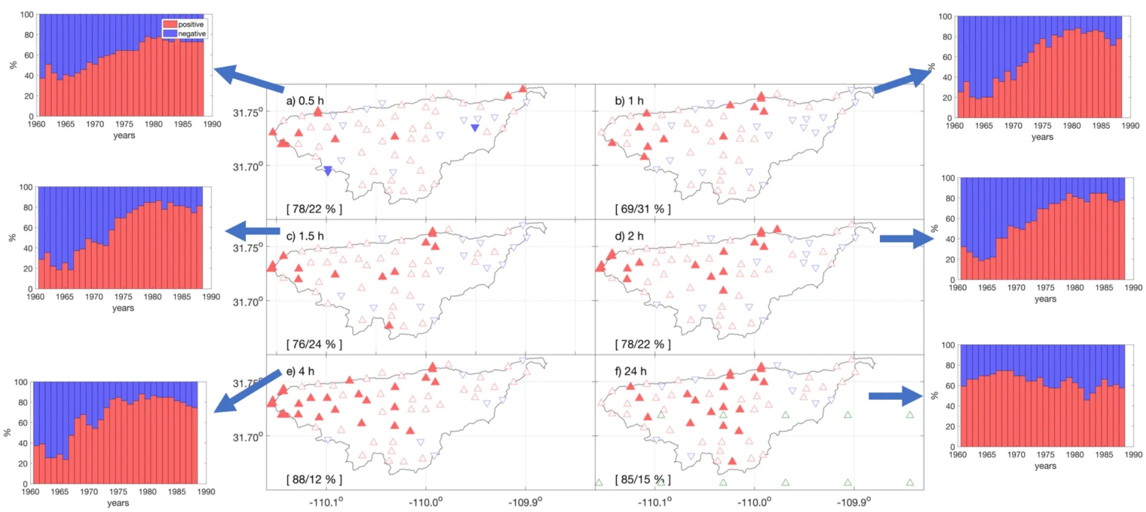

Figure 7. Spatial distribution of PDS trends for the study period (map). The percentage of rain gauges with positive/negative trends is shown between brackets. The insets show percentage of rain gauges with positive/negative 30-year running trends (filled symbol are significant at the 10% level).

Groundwater Recharge

In arid and semiarid regions deep groundwater recharge occurs in only small portions of the basin where flow is concentrated, such as depressions and ephemeral stream channels. Elsewhere, little recharge occurs due to a thick unsaturated vadose zone and upward temperature gradients (Walvoord, 2002; Walvoord et al., 2002). From 1999 to 2002 WGEW wells were instrumented, and microgravity data at these wells was collected along with isotopic runoff samples and detailed vadose zone measurements to investigate deep recharge in the watershed (Goodrich et al., 2004). Figure 8 illustrates runoff depth, water table levels, and gravity change over the study period.

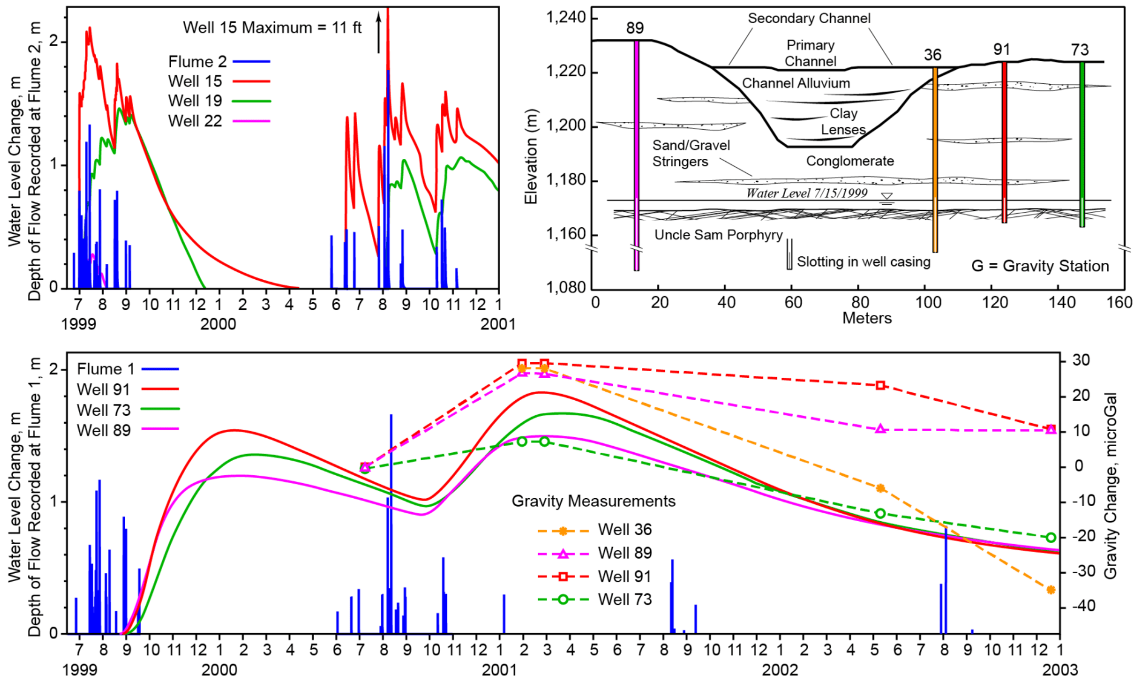

Figure 8. Runoff depth and water level response for a set of shallow wells near Flume 2 (upper left). Vertical cross section near the WGEW outlet at Flume 1 (upper right). Runoff depth, water level, and gravity response for a set of deep wells above Flume 1 (lower).

During the relatively wet 1999 and average 2000 monsoon seasons there was sufficient runoff to overcome thick vadose zone suction forces. In contrast, during the weak monsoon seasons of 2001 and 2002 there was no discernable deep aquifer recharge detected.

Precipitation Manipulation Effects on Soil CO_2 Effluxes

Numerous climate models predict fewer, larger precipitation events over the Southwestern US. This was investigated experimentally using rainout shelters and a series of precipitation treatments. The treatments were carried out during July to September 2020. This experiment only altered the dry interval duration and frequency of precipitation events, while maintaining constant monsoon season total precipitation of 205 mm (~45-year mean from 1975-2019). Within the context of a 45-year climate record for this location, the durations of dry intervals were fixed for each precipitation treatment as follows: 3.5 days (S1), 7 days (S2, climatic normal average dry interval between events), 14 days (S3), and 21 days (S4). Precipitation events were simulated by a digital flow meter using collected rainwater. Events larger than 7 mm were applied in multiple small doses over 30-60 mins to prevent ponding. All plots received 38 mm on July 14, 2020, providing all treatments with sufficient moisture to initiate the summer monsoon growing season. Thereafter the mean (range) precipitation event sizes during the experimental period were 9 (4-14) mm for S1, 17 (8-24) mm for S2, 34 (24-43) mm for S3, and 51 (48-61) mm for S4. The key result is that temporal repackaging of the same summer rainfall amount into fewer, larger storms reduced cumulative seasonal CO_2 efflux from soils.

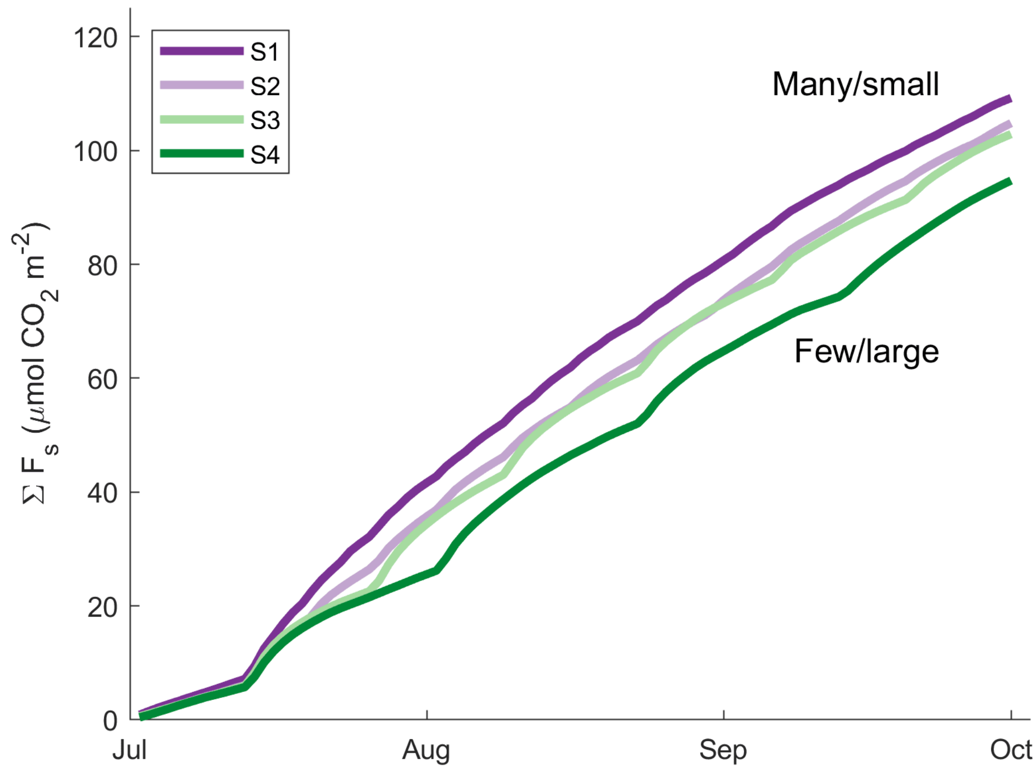

Figure 9. Cumulative daily soil CO_2 efflux (Fs) under four levels of rainfall repackaging during the summer 2020 growing season. S1 to S4 are a gradient from many/small to few/large rainfall events.

EVAPOTRANSPIRATION AND CARBON UPTAKE, VEGETATION CHANGE IMPACTS ON EROSION

Evapotranspiration and Total Carbon Uptake (GPP) - Drought vs Wet

From measurements of rainfall and runoff within WGEW, we know that nearly all of the precipitation that falls within the watershed returns to the atmosphere via evapotranspiration. Likewise, the strong link between rainfall and plant productivity has always been evident by the strong greening response in semiarid regions, but the dynamics of this greening response and how it was related to the total carbon uptake from the atmosphere (gross primary production) was largely unknown. Only in the last few decades have the eddy covariance instrumentation been available to quantify these invisible flows of water vapor and carbon dioxide between the land and atmosphere. In the WGEW and throughout southern Arizona, we have been making eddy covariance measurements at different representative land cover types (e.g., riparian woodlands, grasslands, shrublands, savannas, mountain forests) over the last two decades. The figures below show the response of evapotranspiration and gross primary production at a mesquite savanna site for two highly contrasting water years (1 Nov - 30 Oct) where the summer monsoon rainfall totals went from record lows (2020) to record highs (2021), a true climate whiplash. The 18 year-long record at this site allows us to contextualize the 2020-2021 responses by comparing them to the long-term daily means and their standard deviation.

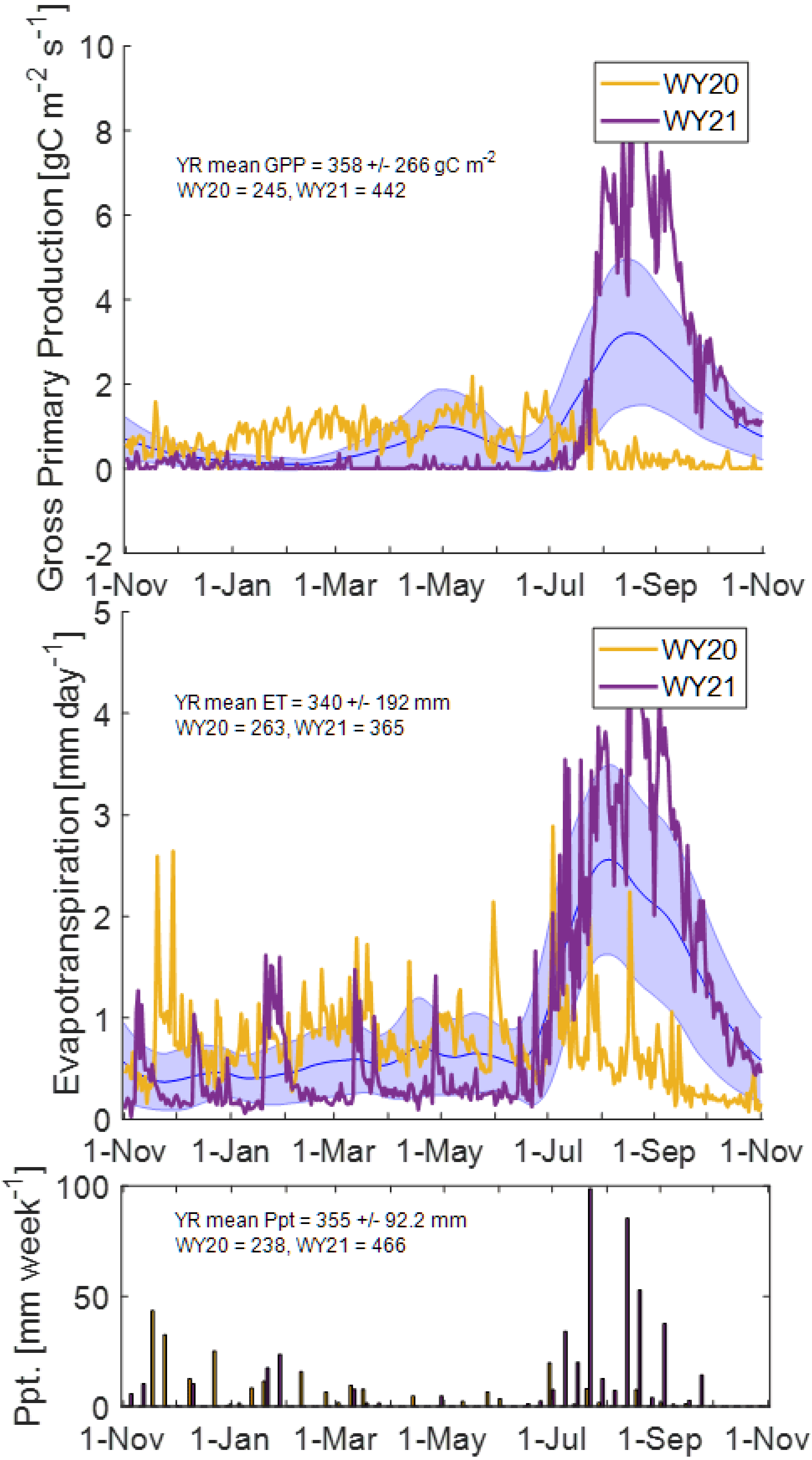

Figure 10. Gross primary productivity (top), Evapotranspiration (middle), weekly precipitation (bottom) at a mesquite savanna site for record dry (2020) and wet (2021) water years. WY 2020 in yellow, WY 2021 in purple. Blue trace and bands are 18 year mean +/- 1 S.D.

Watershed Management – Vegetation Change Impacts on Erosion

To assess impacts of chemical brush management treatments at the Walnut Gulch Experimental Watershed, ARS researchers conducted a series of rainfall and overland flow simulation experiments on treated (tebuthiuron herbicide) and untreated (control) study sites. Results showed that 5-yrs post-treatment, the chemically-treated shrubland had shorter basal gap lengths (distances between the bases of vegetation), which were associated with less cumulative runoff and soil loss during overland flow experiments. The study highlighted the utility of widely implemented rangeland monitoring methods (i.e., foliar canopy cover and basal gaps) to assess changes in vulnerability to runoff and erosion (Johnson et al, 2021).

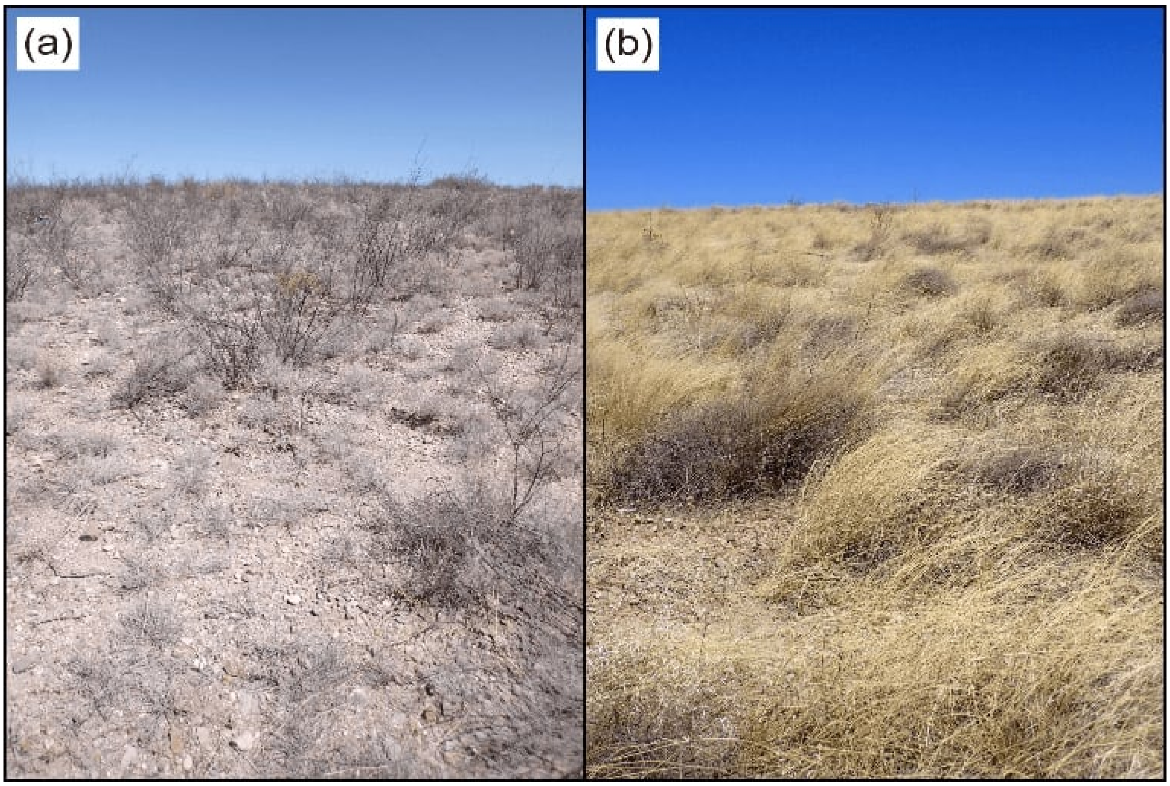

Figure 11: Oblique photographs (June 2018; prior to monsoon onset) of the control (untreated) area (a) and the area treated with tebuthiuron herbicide in 2013 (b). The dominant shrub in (a) is whitethorn acacia (note premonsoon drought deciduousness); the dominant grasses in (b) are Lehmann lovegrass and bush muhly.

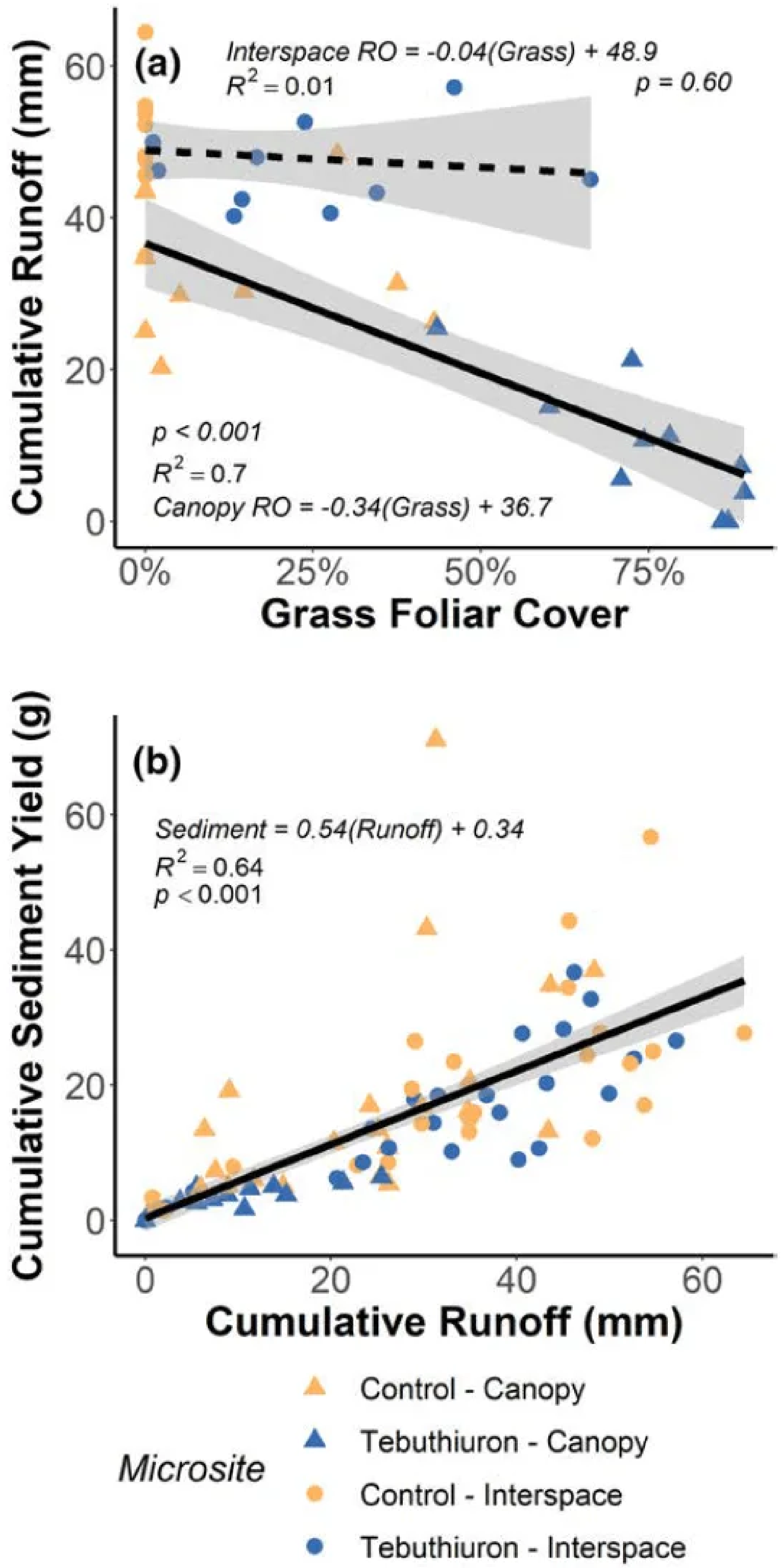

Figure 12. Regression of grass foliar cover and run-off by microsite during fine-scale (0.5 m) 120 mm h−1 intensity rainfall simulations (a). Regression of cumulative run-off and cumulative sediment yield at all rainfall intensities (b). Gray bands denote 95% confidence interval.

IMPACTS OF DROUGHT-INDUCED VEGETATION SHIFT, EROSION ESTIMATION USING ISOTOPES, CONCLUSIONS

Drought-induced Vegetation Shift – Impacts on CO_2 Exchange, Runoff & Erosion

Two severe drought years (2004 and 2005) resulted in a net release of carbon dioxide (25 g C m^{-2}) and widespread mortality of native perennial bunchgrasses and shrub species at the Kendall desert grass-dominated subwatershed. NEE was markedly suppressed in drought years and cumulative NEE showed perhaps a small uptake in 2004 and net release in 2005. Above average summer rains in 2006 alleviated drought conditions, resulting in a large flush of broad-leaved forbs and negative total NEE (−55 g C m^{-2} year1). Starting in 2007 and continuing through 2009, the ecosystem became increasingly dominated by the exotic grass, Lehmann lovegrass, and was a net carbon sink (−47 to −98 g C m^{-2} year^{-1}) but with distinct annual patterns in NEE.

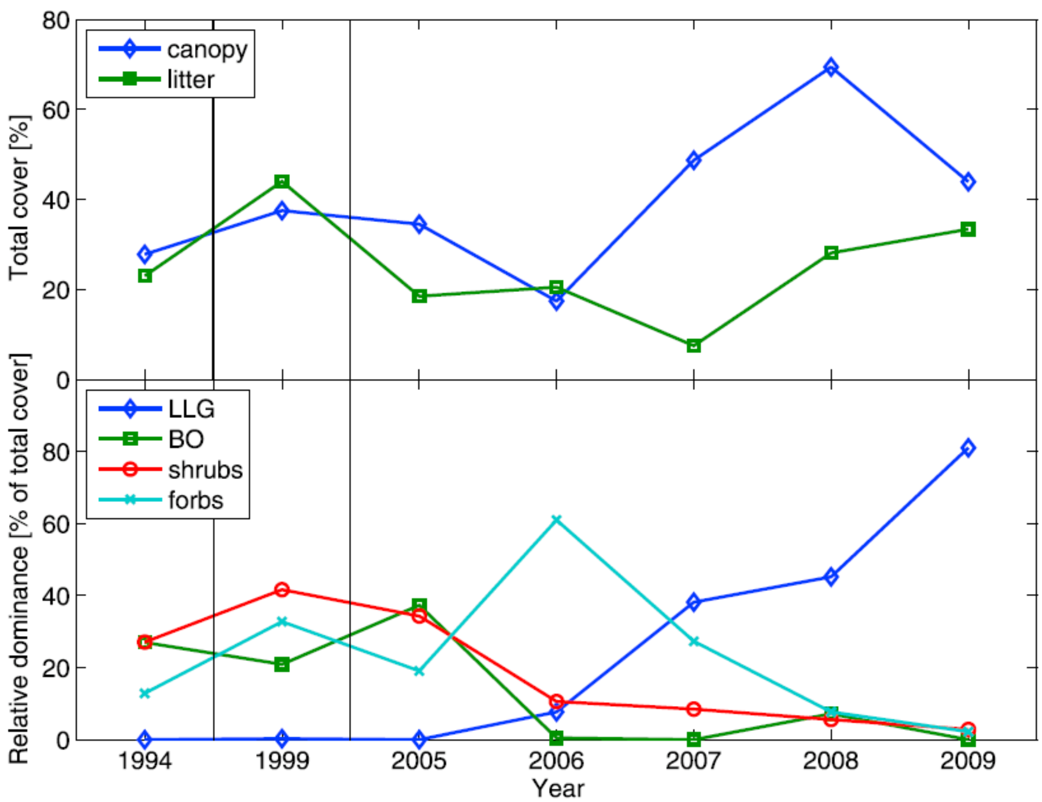

Figure 13. Total plant canopy and ground litter cover and the relative dominance of Lehmann lovegrass (LLG), blue grama grass (BO), shrubs, and forbs. Vertical lines indicate discontinuous yearly sampling.

The combined canopy and litter cover low in 2006 had profound ramifications on plot and small watershed runoff and erosion. Three distinct periods in ecosystem composition and associated runoff and sediment yield were identified according to dominant species: native bunchgrass (BO: 1974–2005), forbs (2006), and the invasive Lehmann lovegrass (LLG: 2007–2009) were examined to assess changing vegetation on runoff and erosion. The loss of plant cover in 2006 resulted in a lowered threshold for runoff generation. This increased the fraction of rainfall events that produced runoff to 23.4%, more than triple the long-term average (7.2%). In addition, the 2006 average sediment concentration (3.7 g L^{-1}) was over six times higher than the 1974-2005 average (0.58 g L^{-1}).

The native vegetation mortality resulting from the 2004 and 2005 drought also had a profound effect on the net ecosystem exchange of carbon dioxide (NEE). Because water is the dominant driver of the system, we normalized the components of NEE by the total ET and found that the ratio Reco/ET was relatively constant in all six years. However, Gross Ecosystem Production (GEP)/ET, a measure of ecosystem water use efficiency, plummeted in 2005 and then increased in 2006 and 2007 and decreased somewhat in 2009, but not to pre-2006 levels (Figure 14). On a net exchange basis, NEE/ET continued to decrease to 2008 after peaking in 2005.

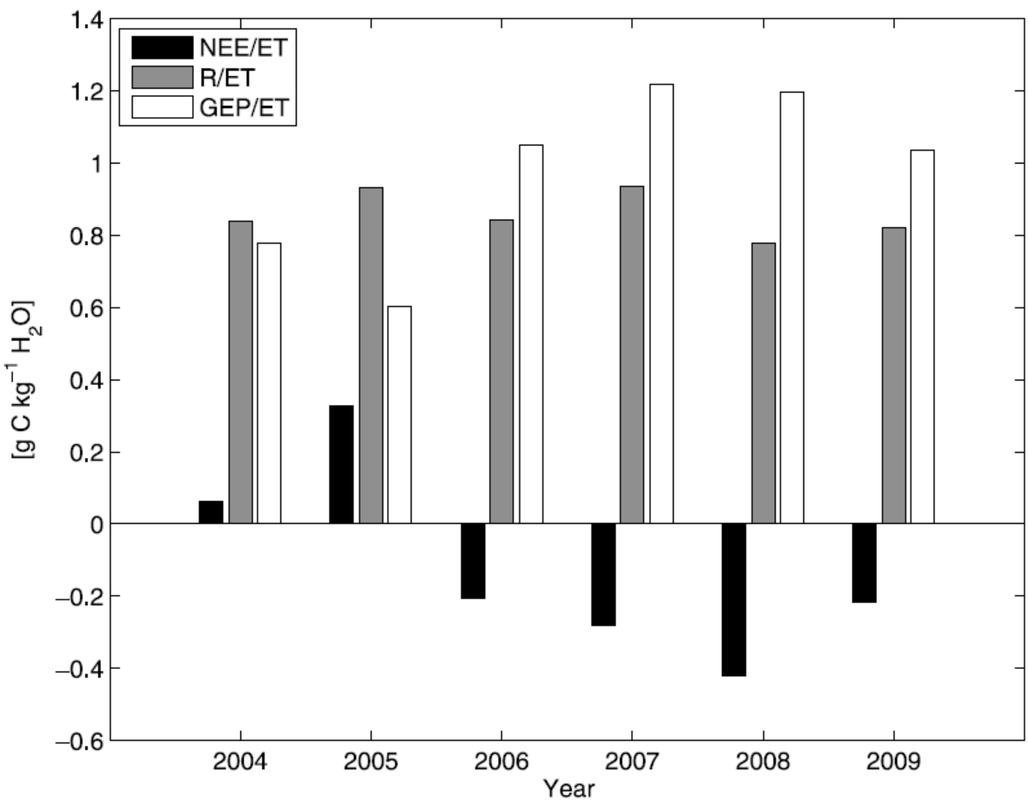

Figure 14. Ratios of total June–November net ecosystem exchange (NEE), respiration (Reco), and gross ecosystem production (GEP) divided by evapotranspiration (ET).

These findings contradict our hypothesis that a shift in community composition from a diverse C4 bunchgrass assemblage to dominance by an exotic C4 bunchgrass would not affect behavior of ecosystem carbon dioxide exchange. In another aspect of feedbacks, the large runoff and erosion events likely transported significant amounts of carbon out of the eddy covariance tower footprint.

Catchment Scale Erosion Estimation and Dating Using Isotopes

Determination of catchment scale erosion rates and sediment yield chronologies is important for predicting management impacts on erosion and the long-term soil sustainability. Three sub-watersheds on the WGEW (44 ha, 92 ha, and 150 ha) with stock ponds at their outlets were selected to investigate the applicability of the ^{210}Pb and ^{137}Cs isotopic method for sedimentation chronology. Runoff is measured out of the stock pond and periodic topographic surveys are used to estimate sediment accumulation. A transect of accumulated core sediment samples in each of the stock ponds was collected (Figure 13). Each core was analyzed in 15 cm increments for ^{210}Pb and ^{137}Cs activity. Isotopically estimated sediment yields (0.5 – 1.5 t ha^{-1} y^{-1}) were in good agreement with those obtained via survey and sediment sampling (Nichols, 2006, Nearing et al., 2007) (Figure 14). Some management operations (mesquite removal, dredging) could also be identified on the chronosequence. This was the first isotopic analysis of pond deposition backed by direct measurements of sedimentation demonstrating the ^{210}Pb and ^{137}Cs technique can be a useful tool for estimation of erosion rates on small arid watersheds.

Figure 15. Stock pond #208 and location of the sampled profiles.

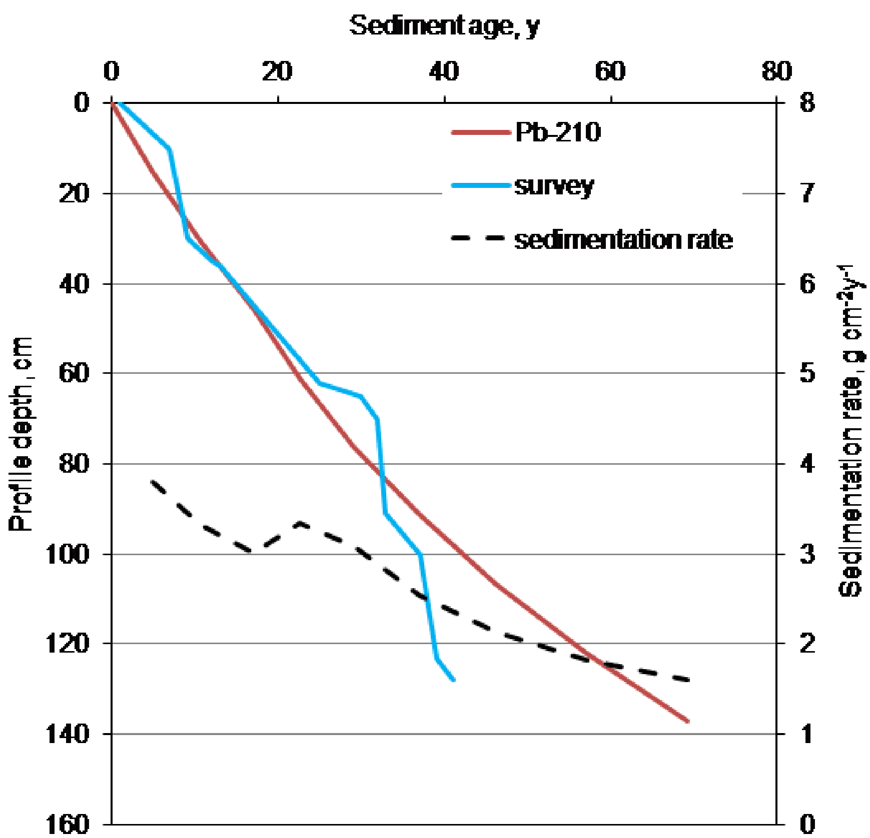

Figure 16. Comparison of sediment age in pond 208 between direct survey measurements and the ^{210}Pb method.

Conclusions

The USDA-ARS Walnut Gulch Experimental Watershed is an unparalleled arid/semiarid outdoor laboratory to investigate ecohydrology interactions and feedbacks to changing climate and management effects. Its long-term operation (60+ years) with high frequency and spatially dense measurements prior to pronounced atmospheric warming offers the opportunity to compare a variety of pre- and post-warming observations. The precipitation intensification example presented herein is one example of such analysis. The context and importance of the vegetation change due to drought in the Kendall subwatershed on erosion and runoff would likely have not been possible as part of a typical 3 to 5 year grant based investigation. The rich research history enabled by the WGEW can be found in the publications available at

https://www.tucson.ars.ag.gov/unit/Publications/Search.html

Observations and supporting remotely sensed and geospatial data emanating from the WGEW and from the Santa Rita Experimental Range are available at

https://www.tucson.ars.ag.gov/dap/

Beyond scientific advances, research and observations at the WGEW and other USDA-ARS Experimental Watersheds have led to a number of important societal benefits (Goodrich et al, 2021). Eight of nine operational long-term ARS Experimental Watersheds are now part of the Long-Term Agro-ecosystems Research (LTAR) Network (Steiner et al, 2016). The LTAR network will enable multidecadal, transdisciplinary, and cross-location science to ensure the long-term sustainability of U.S. agriculture. LTAR's primary goals are to (1) intensify agricultural productivity, (2) improve the ecosystem services related to agricultural production; and (3) improve rural prosperity. LTAR will sustain a land-based infrastructure for research, environmental management testing, and education that enables understanding and forecasting of the nation's capacity to provide agricultural commodities, ecosystem services, and rural well-being under changing environmental, economic, and societal conditions. Additional details on the LTAR network can be found online (https://ltar.ars.usda.gov/).

Acknowledgments

The WGEW and its associated 60+ years of high-quality observations would not have been possible without the many dedicated USDA-ARS SWRC staff in both Tombstone and Tucson, Arizona. The vision and commitment of early ARS and Soil Conservation Service scientists and administrators to construct and operate the WGEW and the entire ARS National Experimental Watershed Network for the long term are to be commended. This research is also a contribution from the Long-Term Agro-ecosystem Research (LTAR) network. We would like to thank Carl Unkrich for preparation of the graphics and layout of this poster.

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