Southwest Arroyo Restoration: Expansion of a Hydro-Ecological Resource
Cañada Bonita, NM

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Department of Natural Resource Management

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Master of Science in Natural Resources Management

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Abstract

Developing and restoring moisture retaining areas or patches in arid Southwest landscapes has gained importance in recent decades. Arroyos, specifically those on high desert plateaus, may through cost-effective restoration provide a resilient hydro-ecological niche during uncertain precipitation and prolonged droughts. This research addresses two questions related to this role: 1. what are the microclimatic differences between an arroyo and the adjacent upland and the relationships between soil moisture and reduced sun and wind exposure; and 2. how effective are restoration structures (e.g., one rock dams) in arroyos in enhancing those differences. To address these questions, a local arroyo and associated upland were monitored for one year. Field results were incorporated into the evapotranspiration equation with solar and wind adjustments used to compare the arroyo and its upland counterpart. The initial data indicate that arroyos may conserve significant quantities of soil moisture throughout the growing season and into early spring. Combined with precipitation and runoff data, measurements provide a predictive system of soil water loss through evapotranspiration (ET) on a per acre basis which is essential in hydrologic analyses and ecological water management.

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Introduction

Often seen along roads, hillsides, pastures and fences, arroyos are common landscape features in the Southwest that effectively channel runoff during precipitation events. Arroyos, which act as ephemeral or intermittent streams, are characterized by steep, often vertical walls, a stepped longitudinal profile, and abrupt headcuts (Fig. 1 and 2) at knickpoints (e.g[WL1]., Bull, 1997; Elliot et al., 1999; Heede 1966; Karlstrom 1988; Kirkby et al., 2003; Patton & [WL2]Schumm, 1975; Perroy et al[WL3].[WL4], 2012[WL5]). Headcutting, an abrupt vertical drop that exposes the subsoil, represents a positive feedback process and is linked to arroyo widening, increased flow velocity, reduced bank vegetation, and reduced water quality. Due to their impacts on surrounding hydrology, arroyos are often associated with landscape desertification. They are both the product of and a contributor to the desertification process (Forward et al., 2008) . Types of arroyos vary and are categorized according to a variety of parameters such as depth to width ratio, stream bed type (silt, sand, cobble), sinuosity, and slope (Zeedyk & Clothier, [WL6]2009).

Figure 1. Arroyo headcut advancement in an agricultural setting, Gonzales Ranch, NM, 2016[WL7]. Photograph by the author.

Figure 2. Arroyo headcut advancing into sandstone bedrock, Cañada Bonita, NM, 2016. Photograph by the author.

Arroyos are most common during interglacial transitional periods; however, they occur in almost any setting at various scales, and are often a result of anthropogenic and/or natural land disturbance (road drainage, severe grazing, fire) followed by intense, isolated rainfall events (Murphy et al., 2007). Due to these storm events, culverts are often used to direct excess runoff away from structures or beneath roadways. However, at their outlet, the channeling of water may create or exacerbate arroyo formation toward undesirable locations such as pastures, homes, and businesses. Excavating and installing such drainage systems may also introduce invasive plant species which benefit from disturbance and have the potential to reduce native plant communities and agricultural yields (Elliot et al., 1999). Additionally, the sediment carried via arroyos may cause property damage and may enter stream and river systems decreasing dissolved oxygen and increasing nutrient loads, which may harm aquatic organisms (Bennet et al., 2000; Casali et al., 2003; Elliot et al., 1999; Poesen et al., 2003; Thorne[WL8] et al[WL9]., 1986).

Historically, arroyos have been viewed as a permanent scar on the landscape with minimal and even negative ecological value as they may restrict farm equipment and livestock as well as reduce water infiltration and lower water tables by channeling water and more efficiently moving it through the landscape giving it little or no time to sink into the soil. The impact of arroyos on the landscape may be even greater if climate change results in less frequent but more intense precipitation events (Delworth & Manabe, 1988; Gee & Bauder 1986; Karl et al., 1998; Meehl et al., 2007). Urbanization and the reduction in permeable surfaces is a major contributor to storm runoff which often carries contaminants from parking lots and roadways. Left untreated, arroyos may increase in-channel width and depth, and may expose bedrock which is the complete removal of the soil layer. In arid regions, one inch of soil may take millennia to develop and only a few minutes to be translocated (Montgomery 2007). Hasty and temporary solutions including backfilling arroyos can be expensive as well as material intensive and may not treat the underlying cause of arroyo formation.

More recently, through research discussed here, arroyos are being viewed in an exciting new way; that is, in facilitating and fostering highly diverse ecological niches in a hotter more arid environment. Arroyos can be managed to retain precipitation while encouraging sedimentation particularly during drought. Managing such valuable hydro-ecological resources may be an important consideration as the climate changes. Currently, little data exists, however, to support this new ecological role in landscape management.

The annual variation in precipitation in the Southwest often creates a dilemma for gardeners, farmers, ranchers, land managers and land owners particularly when irrigation is regulated and may be reduced or eliminated during times of drought. However, if the runoff entering arroyos can also be stored within the soil, arroyos, unlike their adjacent upland counterparts, may serve as biological oases or refuges under prolonged drought conditions, thereby preserving local diversity.

The opportunities provided by the ecologically unique arroyos are potentially many and may warrant positive action especially in the face of a hotter drier climate. The years 2012 and 2015 held the records for the warmest global temperatures (NOAA 2016). Access to runoff and nutrient rich sediment gives arroyos the potential to store water for longer periods than the surrounding landscape while supporting vegetation against harsh arid climates and strong, drying winds. Additionally, arroyos provide shelter and a food source for a wide range of animals thereby increasing pockets of biodiversity throughout the landscape and thereby increasing opportunities for habitat and range management. A treated arroyo may increase ecological values and ecosystem services. Additionally, the vertical aspect of arroyos facilitates a multi-tiered ecosystem which may support and increase biological diversity. These characteristics make arroyo systems a potential opportunity rather than a landscape misfortune. Restoring arroyos as opposed to ignoring them may serve a renewed purpose. Little data have been collected, that characterize the temporal hydrologic properties of arroyos, especially with respect to the increased soil moisture associated with supplemental vegetative patches and simple management (e.g., one rock dams).

A variety of structures and restoration techniques are used throughout the world to reduce the damage caused by erosion. The ultimate goal of arroyo restoration and management is to recruit vegetation, enhance biological diversity, and create or restore moist patches within the landscape. The restoration techniques incorporated in this study include stabilization of headcuts, the addition of zuni bowls in plunge pool sections, filter dams (Fig. 3), and the placement of one-rock dams (Fig. 4) along the drainage. By stabilizing the arroyo channel, flow velocities are reduced during storm events and head-cutting may be eliminated.

Restoration structures within the channel further reduce the negative impact of water from lateral channels while encouraging infiltration. In the Southwest, a structure currently known as a one-rock dam (ORD), has been used for centuries by Native Americans to reduce erosion and reduce the effects of flood events. A one-rock dam is a structure built with a single layer of rock across the cross section of a drainage. These permeable, inexpensive, low-cost structures can stabilize the bed of a channel by slowing the flow of water, increasing roughness, recruiting vegetation, capturing sediments and gradually raising the bed level over time, (Sponholtz, C. 2007[WL10]). One-rock dams slow down and retain flowing water, allowing it more time to soak into the soil while capturing sediment. This increased water retention supports microorganisms in the soil that in turn increase organic matter, biogeochemical cycling and plant life. Increasing moisture retention may allow dormant seeds to germinate (Zeedyk & Clothier, [WL11]2009). Although there is ample anecdotal evidence that these arroyo restoration treatments work, there is very little scientific data documenting the effectiveness or success at retaining moisture and creating unique ecological opportunities at a particular site.

Figure 3. Before and after photos of a zuni bowl and filter dam within an arroyo system at Cañada Bonita, NM (Summer 2015). Photograph by the author.

Figure 4. One rock dam (ORD) built across the drainage at Cañada Bonita, NM (Summer 2015). Photograph by the author.

Studies in Spain (Fitzjohn [WL12]et al., 1997) utilizing Time Domain Reflectometry (TDR) to measure soil moisture in a gully catchment showed the importance of relatively small moisture retaining areas on the landscape and introduced the notion of a soil moisture mosaic. The soil moisture mosaic idea involves increasing sheet-flow infiltration in the area of concern thereby reducing runoff and soil particle dispersion which is crucial on sloped or hilly landscapes to increasing local soil retention. TDR technology uses an electric pulse to determine the relative amount of water in a soil, then expresses it as a volumetric percentage. In the study, a similar automated TDR system was employed to simultaneously monitor sites along the adjacent upland and within the channel. My research takes this preliminary research a step further by using TDR and other microclimatic measurement tools to compare upland and arroyo environments after installing a variety of structures, including ORD's, within an arroyo system and using a rock mulch on the adjacent upland. These treatments create a local soil moisture mosaic.

This research quantified the microclimatic conditions within a moderately deep arroyo (3-4 m) and the effect on the microclimate (humidity, temperature, and wind speed) of installing ORD's within the arroyo channel. Additionally, the microclimatic differences between the upland area and the restored section of the arroyo channel are addressed including a representation of moisture loss on a per acre basis. To assess this, the Penman-Monteith equation for evaporative losses was used, which incorporates solar radiation, orientation, polar coordination, elevation, wind speed, humidity, and temperature (Allen et al., 2005; Honsberg & Bowden 2014; Howell & Evett 2006; Jensen et al., 1990; Monteith 1965; Penman 1948).

If soil moisture and relative humidity are significantly higher within the arroyo restoration sites, due to reduced direct sun exposure and increased retention of runoff moisture, snow fall, frost, and dew effects, these sites might actually serve as prime locations for restoration efforts. Arroyos may provide a unique, alternate growing zone compared to the adjacent land thereby adding significant new features to the landscape. Future land management should take these differences into consideration as similar sites in lower latitudes often accommodate mature, prospering ecosystems. The data reported in this thesis provide insight into the management of arroyos on a much broader scale. This information will also be shared with local community organizations and land managers as it highlights their potential to have a lasting effect on an otherwise degraded landscape that has been influenced by centuries of anthropogenic impacts.

Literature Review

Gully Formation and Erosion

Soil erosion is part of a larger global geologic cycle common during interglacial periods. However, within the past 50 years, human related activities have accelerated an otherwise slow process by degrading or desertifying 5 billion ha of land worldwide. Erosion accounts for 85% of that degradation (Brady & Ray, 2010). As the proportion of land area to people decreases, resources such as timber and rangeland are increasingly exploited for farmland. The destruction of native plant communities, combined with a reduction in biomass and natural vegetation leads semi-arid landscapes and rangelands in a downward spiral, resulting in degradation and low productivity (Brady & Ray, 2010) Recent estimates place annual erosion costs from agriculture at $44 billion per year. Worldwide, the annual loss of 75 billion tons of soil costs the world approximately $70 per person per year (Eswaran [WL13]et al. 2001). A study by Perroy et al. (2012) on Santa Cruz Island, CA, directly ties in the above average stocking rate of 250+ sheep/km² and the consequent vegetative loss to arroyo development following the monsoon season of 1878. The contemporaneous nature of arroyo systems marks them as a key resource for remediation and research in many fields including agronomy, hydrology, archaeology and pedology. While the direct dollar value of erosion in the desert Southwest may not be great, the ecological effects are enormous.

Arroyo Stabilization and Management

In order to influence erosion and sedimentation in arid environments, understanding the factors that increase soil stability is crucial (Goudie 2006). Much of the work involved in arroyo restoration is based on understanding the erosive factors at work within often unconsolidated soils. Although many studies focus on climatic and anthropogenic causes of arroyo formation, there has been little research into the factors that facilitate resisting erosion naturally such as increased organic matter and improved soil structure (Perroy et al., 2012). Perroy et al. (2012), also recognize that regardless of similar external drivers such as climate and tectonics, the natural variability of individual systems, such as vegetation and stream profile, result in varying degrees of stability. Thus, the theme of arroyo management is customizing channel stability in order to maximize resource utilization.

Soil Moisture

The ability of the soil to retain moisture and structure is largely determined by texture, organic matter content, and surrounding environmental conditions. The analysis of soil moisture content and texture in arid environments is, therefore, important to understand as it varies both temporally and spatially (Baker & Allmaras, [WL14]1990). Aside from oceanic currents, soil moisture is perhaps the most important factor that influences climate (Delworth & Manabe, 1988). Because soil serves as the hydrologic intermediary between atmosphere and evapotranspiration, soil health is often an indicator of the quality of the local environment. According to Nabhan (2013), the ability to store and harvest soil water within the vicinity of its intended use provides a cost-effective alternative to both irrigation pumping and dam maintenance, both of which are increasing in cost. Additionally, storing water within the soil supports soil microbes critical for building soil structure and nutrient cycling. Belnap et al. (2005) discuss inevitable nutrient pulses and their fate associated with microbial activity in semiarid landscapes and the importance of retaining such inputs within the stream-riparian ecosystem. When precipitation amounts exceed the capacity of soil interspace to hold that water, otherwise conserving systems leak vital nutrients.

Arroyo Restoration and Management

Microclimates promote soil health through processes of plant and animal growth which fundamentally alter soil structure. Moist, shaded patches found in arroyos provide both wind and thermal buffers protecting organisms from both hot spells and catastrophic freezes. The value of a localized thermal buffer is further accentuated on high desert plateaus >1500 m where atmospheric pressure is reduced promoting increased evapotranspiration and solar insolation. Stone and rock mulch has also been in use by New Mexico Pueblo Cultures for centuries Sponholtz (2007).

The stone structures known as ORD's, imitate natural riffle sections in ephemeral streams during flow events. The term one-rock describes the height of the structure i.e., one rock high. Rock placed more than one layer in height is discouraged as flood events can easily carry these rocks away. The ability of a stream to move particles of various sizes increases along with depth and velocity, and the largest particle that can be moved at any given time is termed stream competency (Zeedyk & Clothier, [WL15]2009). In addition, flow depth and velocity relates to the size of rocks needed to build a stable structure. For instance, if a 6" flow is expected, 18 lb. or larger stones should be used Sponholtz ([WL16]2007). To increase the effectiveness of rocks and prevent local scouring, soil removed from the channel during structure construction should be redeposited between the ORD along with grass seeds when possible to further stabilize the structure over time.

Figure 5. Image illustrating sediment and branches withheld by ORD Cañada Bonita, NM, 2014. Photograph by the author.

It has been demonstrated that one of the most effective materials in maintaining soil moisture and capturing sediment is rounded river stone (Zeedyk & Jansens, [WL17]2004). The smooth surface of these stones reduces drag and facilitates percolation. In September 2014, an isolated storm transported and deposited large quantities of angular sandstone into the study site while a nearby structure constructed from rounded river stone remained intact while retaining sediment and branches carried with the storm (Fig. 5). This action prompted the use of much larger stones when constructing permeable filter dams and rounded river stone in smaller structures and rock mulches.

In some regions[WL18], such as the Central Plateau in Burkina Faso, Africa, stone structures greater than 50 m in length have been used in agricultural settings. Sorghum harvests for example, from land restored with rock dams, range up to 1.9 t/ha compared with a yield of 1 t/ha from equivalent, untreated land (Critchley et al., 1992).

The effectiveness of these and similar structures in arid regions around the world has prompted their use in many areas where moisture is uncertain and erosion potential is high. As confined and perched aquifers continue to be depleted and dependence on soils in the Southwest increases, developing strategies to increase available water and decrease erosion are imperative (Gellis et al., 1995; Woolhiser & Lenz 1965).

Soil Properties and Moisture

Installation of ORD's in loam (a mix of sand, silt and clay) soils are preferred as they more readily create the conditions necessary to support and maintain plant growth. Soils with a high clay content have a higher available water capacity due to their increased field capacity and increased nutrient holding capacity. The available water capacity of a soil is also determined by factors such as organic matter, compaction, and salt concentrations. The addition of organic matter and/or sand is one way to improve texture and aeration and increase the water permeability in a soil with a high clay content. In arid regions, salt load is an issue that increases due to well irrigation, which limits a soils water holding capacity (NRCS 2005). As soils often move quickly across a sloped landscape during monsoonal events, the deposited soils at the base of arroyo channels may form a layered structure aiding in seed recruitment and development by retaining varying degrees of moisture within each respective texture layer. The intermittent flow of water through arroyos aids in replenishing nutrients that may not occur as readily in upland sites.

Infiltration

During rainfall events in semi-arid regions, small clay soil particles are dispersed laterally in a manner that clogs soil pores creating what is known as surface sealing or desert pavement. This sealing of the soil leads to soil crusting, increased runoff and soil displacement in unwanted areas (Poesen [WL19]et al., 2003). Contrastingly, however, vegetation and mulches are the most important factors on a landscape in preventing surface sealing while encouraging infiltration, and reducing rainfall impact. Restoration treatments work to reduce surface sealing; however, this project did not examine differences in the surface sealing effect between arroyo bottoms and uplands.

Soil Sponginess

Although arid land restoration pioneers such as Bill Zeedyk have had tremendous success with the use of simple restoration techniques such as ORD's in altering dry landscapes, the quantification of such efforts have remained to a large extent unexplored.

The “sponginess” of a soil refers to its ability to adsorb, release, and transmit vital water and nutrient reserves (Zeedyk & Clothier, [WL20]2009). Because the development of such characteristics in semi-arid environments is crucial to their resilience, quantifying these attributes in relation to soils associated with ORD’s is important. Recent climate forecasts suggest the Southwest should be prepared for a 20% reduction in precipitation with an increase in evapotranspiration of 15-20% within the next four decades (Nabhan 2013). This also includes the prediction that the time between rain events will increase and they will occur at stronger intensities. These changes in climate and moisture suggest that creating even small, stable, moisture retaining areas will be beneficial in the Southwest and globally.

Hydrological Mosaic

Following a soil moisture study of a gully catchment in central Spain, Fitzjohn [WL21]et al. (1997) realized the importance of creating areas across the landscape with varying abilities to absorb and re-absorb moisture as a way to reduce erosion and runoff entering stream systems. It follows that sinks for soil moisture are necessary for capturing runoff produced in saturated or bare areas (sources) on the landscape. Fitzjohn also discusses the notion of a wetness threshold, the idea that when an area is extensively saturated, the extent and magnitude of buffer zones and moisture sinks is crucial in managing overland flow.

Plant assimilation and Bioindicators

Many desert plants are adapted to harsh arid climates enabling them to thrive in a wide range of temperature and light conditions. Plants that utilize the C4 carbon fixation pathway for instance such as cacti have the ability to close their stomata during the day thereby conserving moisture and should be used in restoration efforts. The web soil survey for my study site reveals 1% of the Tuloso-Sombordoro soil area may include riparian vegetation, rare but of high ecological value in desert ecosystems. Ground truthing confirmed the growth of Carex *sp.* on four distinct locations throughout the 120-acre study area in Cañada Bonita, NM, highlighted during years with above average rainfall. Carex *sp.* were found near site C and below site D in the arroyo channel as well as Populus *L*. within 150 m indicating that riparian vegetation previously in a dormant state, may have been released through restoration efforts. Also, below the canopies of the piñon-juniper woodland, Oxalis *sp.* was found which is indicative of the climax state of the biome.

Background/Context

Setting

The arroyo analyzed for this project is located in Southwest San Miguel County on the Cañada Bonita Ranch, NM (35.2459° N, 105.4606° W). It is set along a Southeast backslope with a contributing drainage of approximately 21.5 acres (Fig. 6). Formation of the arroyo was likely due to locally increased runoff resulting from juniper encroachment, reduced grass cover, road construction, and 20th century grazing (overgrazing) practices. Results from the Web Soil Survey (Table 1) reveal that the study site is prone to erosion due to deposited soil being eolian containing a comparatively low fraction of rock fragments within the soil profile, which also features a high suitability for hand planting (O'Geen T. 2012). The soil type labeled RF (Ribera and Sombordoro-Vibo) is set on the posterior and side slopes of the mesa with a moderate slope (<9%).

The first several inches are loam transitioning into a clay and sandy loam respectively and finally to bedrock 1m below the surface. The soil labeled TS is comprised of Tuloso, Sombordoro and rock outcrop, set on a scarp slope along a crest which is relatively steep. The land has a high runoff potential and is not suitable for agriculture. A minor component, Ustifluvents, was discovered and accounts for 1% of the TS map unit and is associated with flood plains. This soil type suggests at one time the location served as a riverine riparian ecological site. Local erosion and arroyo incision is often increased by occasional intense storms especially frequent during El Niño cycles. Mean annual precipitation is 38.1 cm with a mean annual temperature of 7.8-12.2°C. The arroyo, with an average slope of 6.25%, begins at an elevation of approximately 1,972 m and extends 310 m along a 260 m long valley decreasing in elevation by 15 m to 1957 m at its termination point where it transitions on to flatter, neighboring lands at a 3.5% slope (Fig. 7). The upper reach of the arroyo is stepped into the bedrock. Along its length, lateral channels also contribute to the system. There are several meanders and plunge pools along the course of the channel. These morphological features were utilized in the planning and implementation of channel restoration treatments. Additionally, bank undercutting and failure has occurred as the arroyo has widened. Field observations indicate erosion is primarily influenced by a reduction in ground cover during dry periods as well as increased runoff wetter periods. Most overland sheet flow, which may become concentrated overland flow, occurs mostly during the monsoon season. Isolated thunderstorms following dry periods often pose problems in the area and late summer storms during September and October have caused the largest flow events and resulting channel incision.

Catchment Area Characteristics

Table 1. Soil and site characteristics for arroyo system and contributing drainage.

	RF	TS
Map name	Ribera-Sombordoro-Vibo	Tuloso-Somb.-Rock outcrop
Ustifluvents	N/A	1%
Classification	Fine-loamy, mixed mesic Typic Haplustalfs	Loamy-skeletal, mixed, mesic Lithic Ustochrepts
Sand	37.7	50.9
Silt	38.6	34.7
Clay	23.7	14.4
Acres in AOI	2.1	19.5
% of AOI	9.6	90.4
HSG	C	D
CN	61	71
Slope	moderate	moderate
Rutting hazard	severe	slight
Hand planting	well suited	Unsuited (rock, clay)
Seedling mortality	low	low
Range prod. lb/A	706	N/A
Ecological site	Pinon, juniper, oak	Pinon, juniper, oak
Wind Erosion T/yr	56	86
K factor whole	.37	.17
pH	7.8	7.5

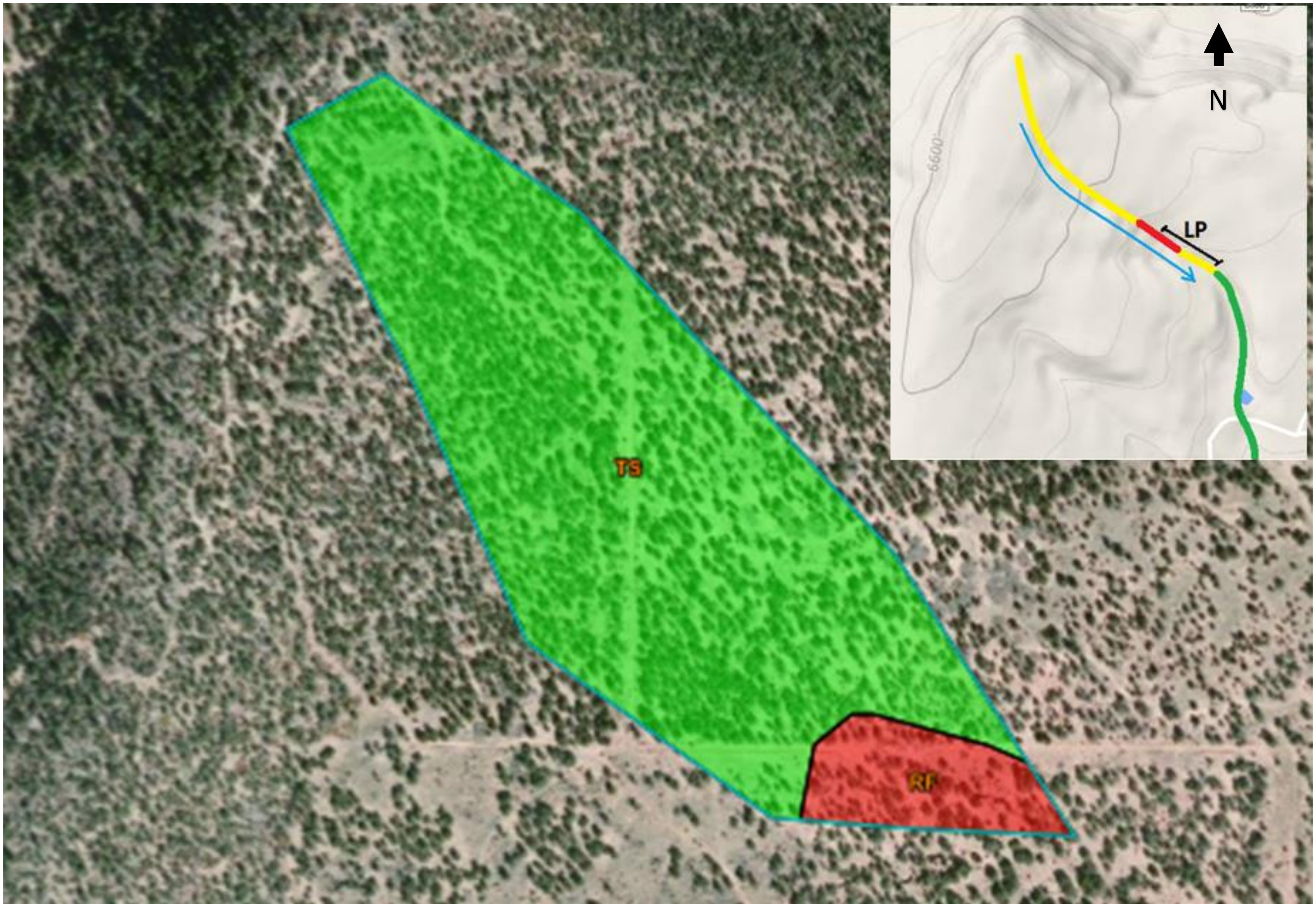

Figure 6. Image detailing contributing drainage, outlined blue (21.5 A), dominant soil types (TS, RF), longitudinal profile section 'LP' and arroyo slope. Source of Image: Natural Resources Conservation Service Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov Coordinate System: Web Mercator (EPSG:3857).

Figure 7. Image detailing arroyo, valley length, direction, and surrounding vegetation. Cañada Bonita Ranch, San Miguel County, NM. 35.2459° N, 105.4606° W Image data © 2016 Google.

Methods/Approach

Site Selection

Four sites were selected on the Cañada Bonita Ranch for detailed monitoring based on their restoration potential. Two sites were selected within the restored arroyo section which is classified as a Type A channel (Zeedyk & Jansens, 2004). Characteristics of these channels are that they are deeply incised, disconnected from the floodplain, and lacking sinuosity. Upland sites were identified adjacent to each arroyo-site on the neighboring upland. These upland sites are representative of the surrounding landscape. The arroyo used in this study is representative of other arroyos occurring within the area having similar depths, slope, orientation, and vegetation.

Stream Morphology

Cross sections (Fig. 8) were measured using a Soki Set 610 Total Station and stadia rod taking measurements in 0.1m increments where possible. Cross sections provided an accurate assessment of depth and side wall slope. The arroyo longitudinal profile was mapped beginning at the bedrock headcut (Fig. 2) and every 3-5m for 134 m downstream. These data were used to create a slope profile (Fig. 8) that was used to determine structure type and appropriate placement.

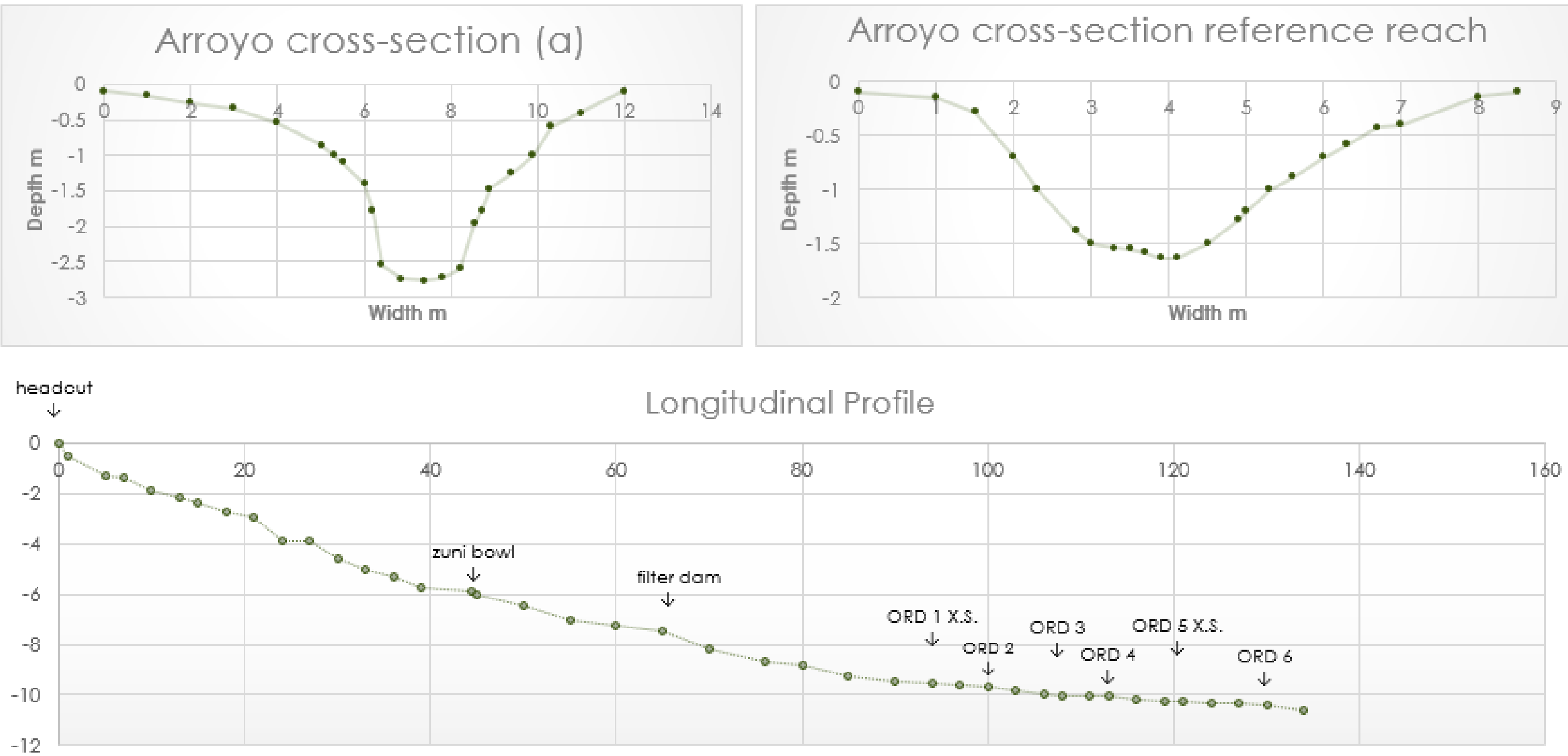

Figure 8. Graphs representing arroyo cross section at Site A, the reference cross section 120m downstream and measured longitudinal profile.

Structure Placement

The one-rock dam structures were built and developed according to the procedure outlined in the "Erosion Control Field Guide" (Natural Resource Conservation Service 2005). Adhering to the 3:1 slope rule described in the document, the rock dams were strategically placed in areas that maximized the efficiency of the structure in capturing water and sediment and encouraging meandering while reducing maintenance. The structures are effective at capturing sediment and are designed to be effective for 3-5 years; however, they require seasonal maintenance to prevent failure by filling spaces with smaller stones or adding additional layers of stones once they no longer act as a permeable barrier in the channel. The structures are built with heavy rounded river stones that reduce drag as opposed to angular stone that can easily be dislodged during flow events. Constructed during the winter or dormant season, these structures settle into the channel bottom and capture and store snow melt, spring runoff, and monsoonal rains.

Restoration Monitoring

Equipment used in the field included four EM50 digital/analog data loggers along with sixteen accompanying sensors ((MPS-2 water potential/temp (4), GS1 soil and media moisture (6), VP-3 Humidity/temp (4), Davis cup anemometer (2) courtesy of Decagon Inc. Fig. 9)), as well as a handheld TDR 100 soil moisture sensor used in creating a soil moisture grid (Fig. 10). Time Domain Reflectometry (TDR) has proven to be a reliable method for assessing soil moisture and pinpointing faults below the surface in the telecommunications industry and is accurate within 2% (Topp et al. 1980). Precipitation was monitored using two-cylinder rain gauges, installed within the arroyo and on the adjacent upland and by direct measurement during snowfall events. The EM50 digital/analog data loggers provided simultaneous readings from the 16 sensors every 4 hours beginning on January 1, 2015 at 08:00 a.m. through December 31, 2015. The sensors employed in the study included four VP-3 sensors installed at each of four site locations which monitored both temperature and humidity 0.3 m above the soil surface for the purpose of microclimate comparisons. Also included were 6 GS-1 water content sensors. A GS-1 sensor was installed 0.15 m directly beneath each of the four treatment sites A-D laterally into undisturbed soil (Fig. 9).

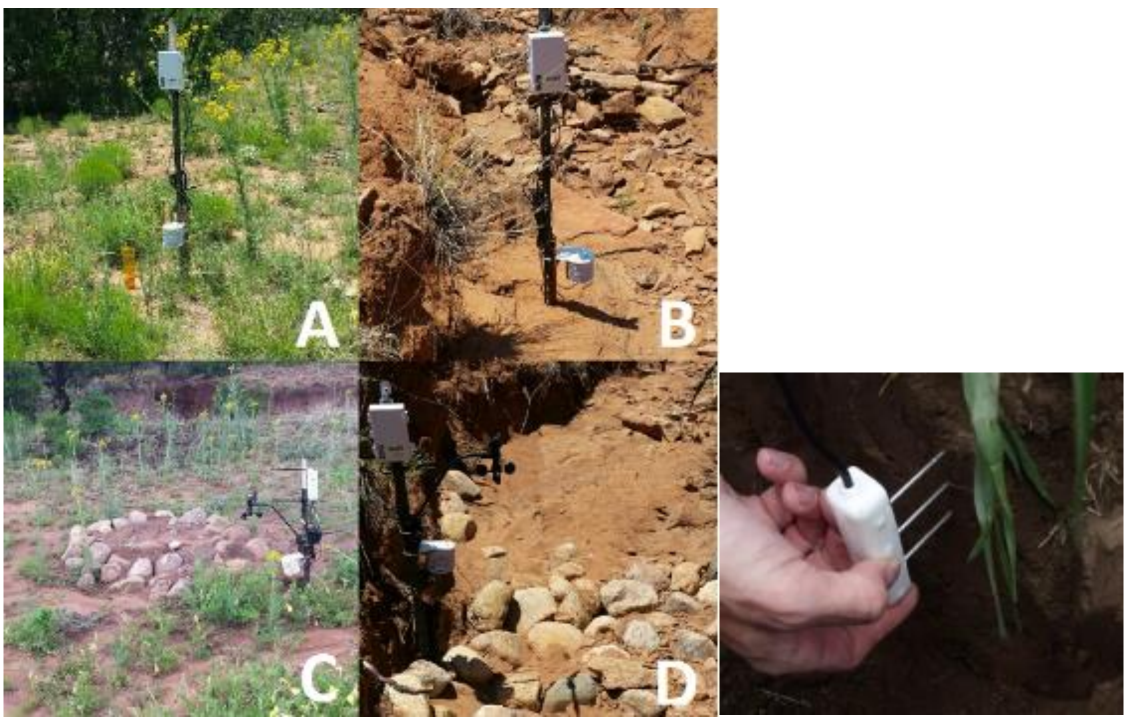

Figure 9. Photos showing equipment placement, structures, rain gauge, and TDR on sites A-D. Photograph by the author.

Two GS-1 sensors were installed at the same depth 0.15 m, 3 m upstream/upland at sites C ² and D ² in the same manner. These measured volumetric water content per cubic meter influenced by the rock mulch and the ORD. Four MPS-2 matric potential/temperature sensors were also installed 0.15m below each of the four sites laterally into undisturbed soil. In addition, a Davis Cup anemometer was installed in the arroyo and on the adjacent land affixed to a t-post at ground level which monitored wind speed, gusts, and direction. The TDR-100 was used to collect soil moisture data from 10' x 10' sections of a 150' x 50' grid on the adjacent upland. Soil moisture data was collected three times between March and June 2015 (Fig 10). Combined with atmospheric parameters (Table 2), these data are analyzed and used in determining site specific evapotranspiration rates for specific days. Figure 11 shows the locations of the monitoring sites.

Figure 10. 150' x 50' soil moisture grid along the adjacent upland March (left), April (center) and June (right). Corresponding colors represent volumetric water content as a percentage.

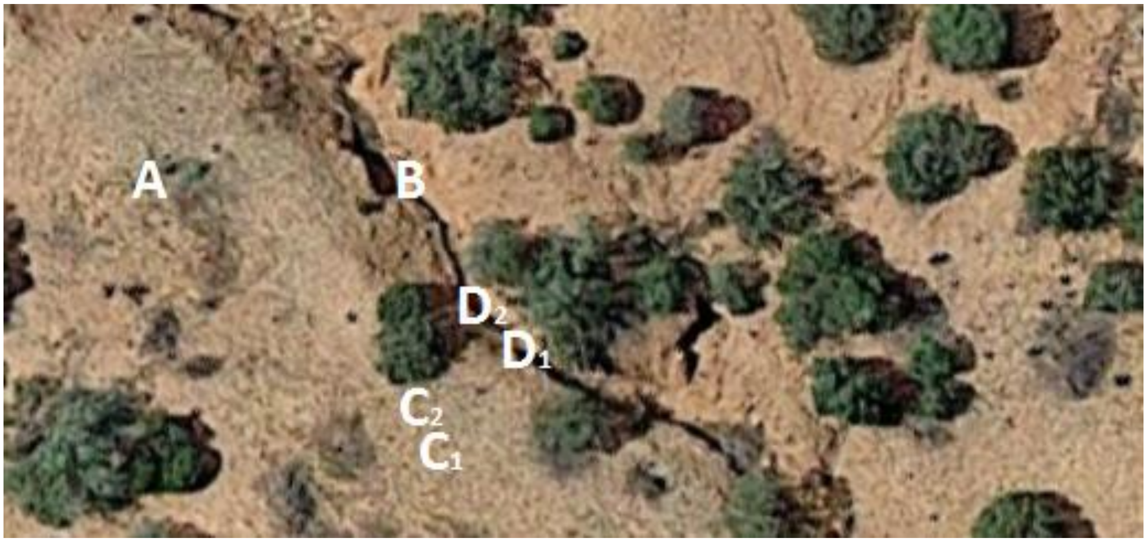

Figure 11. Satellite image detailing specific site and sensor location within the arroyo and on the adjacent upland. Image data © 2016 Google.

Table 2. Variables used in estimating evapotranspiration rates.

Variables	March	June	September
T ° C (A)	8.1	25.7	20
μ2 m/s (D)	1.44	0.9	1.26
Δ kPa ° C	0.07306	0.19439	0.143
Humidity %	51.4	15.7	50.3
Rn MJ/m²/d (ar)	6.99	8.66	8.01
γ kPa ° C	0.053	0.053	0.053
ea kPa	0.83	0.97	0.81
(e°s - ea) kPa	3.31	5.205	4.723
Cn short	900	900	900
cd short	0.34	0.34	0.34
Cn tall	1600	1600	1600
cd tall	0.38	0.38	0.38
ETs(U)mm/day	3.75	7.62	6.34
ETs(A)mm/day	2.66	5.44	4.50

Calculating Evapotranspiration

The FAO Penman-Monteith method to estimate ETo can be derived where, ETo = reference evapotranspiration, mm day-1; Rn = net radiation at the crop surface, MJ m^2 d-1; T = mean daily air temperature at 2 m height, °C; u2 = wind speed at 2 m height, m s-1; es = saturation vapor pressure, kPa; ea = actual vapor pressure, kPa; es-ea = saturation vapor pressure deficit, kPa; Δ = slope of the vapor pressure curve, kPa ºC-1; γ= psychrometric constant, kPa °C-1.

The average monthly temperature was used in calculating Δ and was recorded at a height approximately 0.3 m above the soil surface unlike the 2 m suggestion. However, the mean daily temperature was used as T in the calculations.

Because wind speed was recorded within the arroyo channel 1 m above the surface, a conversion given by the following equation was necessary (FAO-56 Method).

$$u_2 = u_h \frac{4.87}{\ln(67.8\,h - 5.42)}$$

Where, u2 = wind speed 2 m above the ground surface, m s-1; uz = measured wind speed 2 m above the ground surface, m s-1; h = height of the measurement above the ground surface, m.

Δ, or the slope of the saturation vapor pressure curve and temperature, is produced using the following formula (FAO-56 Method):

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27 * T_{mean}}{T_{mean} + 237.3}\right)\right]}{(T_{mean} + 237.3)^2}$$

Net radiation is defined as the difference between incoming net shortwave radiation and the outgoing net longwave radiation expressed as MJ m² d-1. This is a function of extraterrestrial radiation, the solar constant, the inverse relative Earth-Sun distance, sunset hour angle, latitude, solar declination, clear sky radiation, elevation above sea level, albedo, the Stefan-Boltzman constant and actual vapor pressure. After calculating net radiation, the amount of inherent variability suggests that an alternative method of observing radiation might be that of solar insolation incorporated in photovoltaics measured at the earth's surface.

The calculation for the psychrometric constant γ is given by the following equation (FAO-56 Method).

$$\gamma = \frac{C_p P}{\varepsilon \lambda} = 0.000665\, P$$

Where: P = atmospheric pressure kPa, λ = latent heat of vaporization, 2.45, MJ kg-1; cp = specific heat at constant pressure, 1.013 10-3, MJ kg-1 °C-1; μ = ratio molecular weight of water vapor/dry air = 0.622. It is important to note that at 2000m above sea level atmospheric pressure deceases from 101.3kPa to 79.8kPa increasing the potential evapotranspiration losses.

$$ET_{sz} = \frac{0.408\Delta\,(R_n - G) \,+\, \gamma \frac{C_n}{T + 273} u_2 (e_s^o - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

The above equation expresses evapotranspiration losses in mm day-1 the equivalent of 1,000 m³/ha/day-1 which can then be converted into gallons/acre/day-1 (Fig. 12).

One limitation in using this equation for this context is that the equation was developed for use in the State of Florida for stations positioned 2 m above a well vegetated surface not short of water. In our scenario, the measurements were recorded closer to the ground to make use of microclimatic observations on a sparsely vegetated surface that was water limited at various times throughout the study. This methodology probably underestimates the actual differences between the arroyo and upland areas and the overall water loss.

Statistics

Data were processed through the SPSS program for mean comparison amongst sites and analysis of soil temperature, matric potential, air temperature, wind and humidity. Soil moisture retention correlations were also developed as they display the natural water retention characteristics of the soil. The data (Fig. 13) are then displayed according to volumetric water content (x-axis) and water retention rates or matric potential (y-axis).

Data Analysis

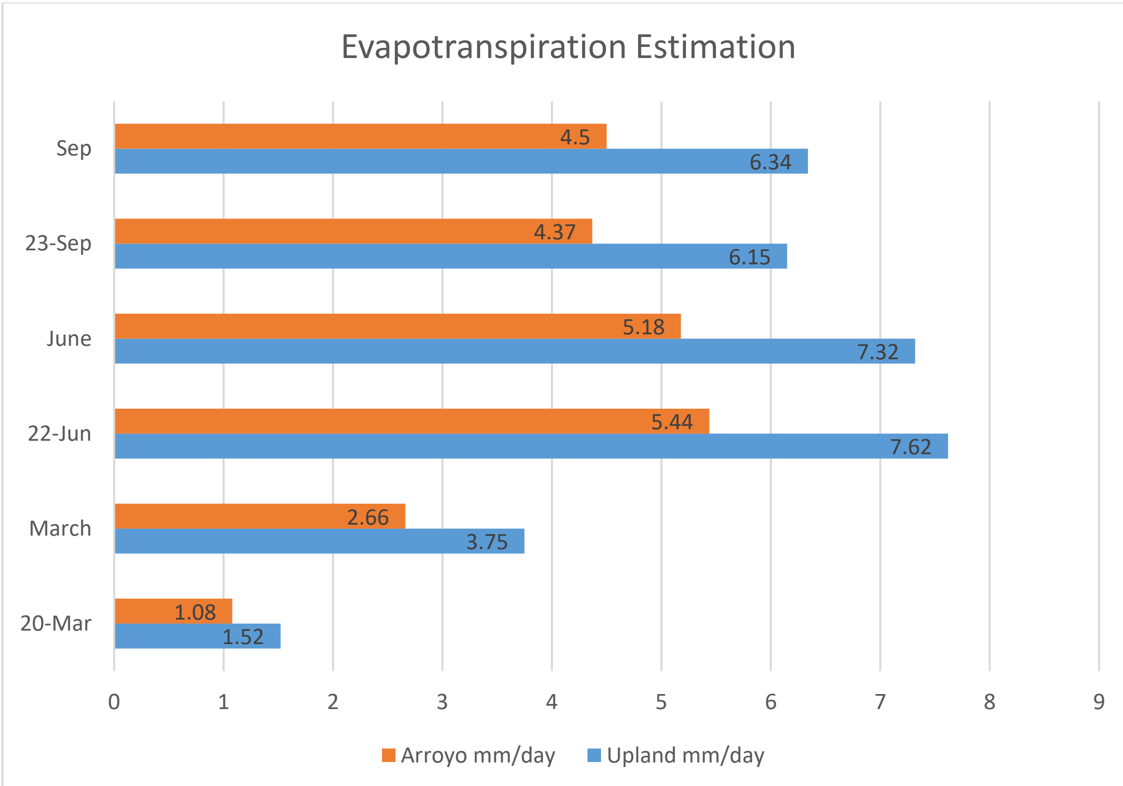

Figure 12. Graph representing estimated differences in evapotranspiration throughout 2015.

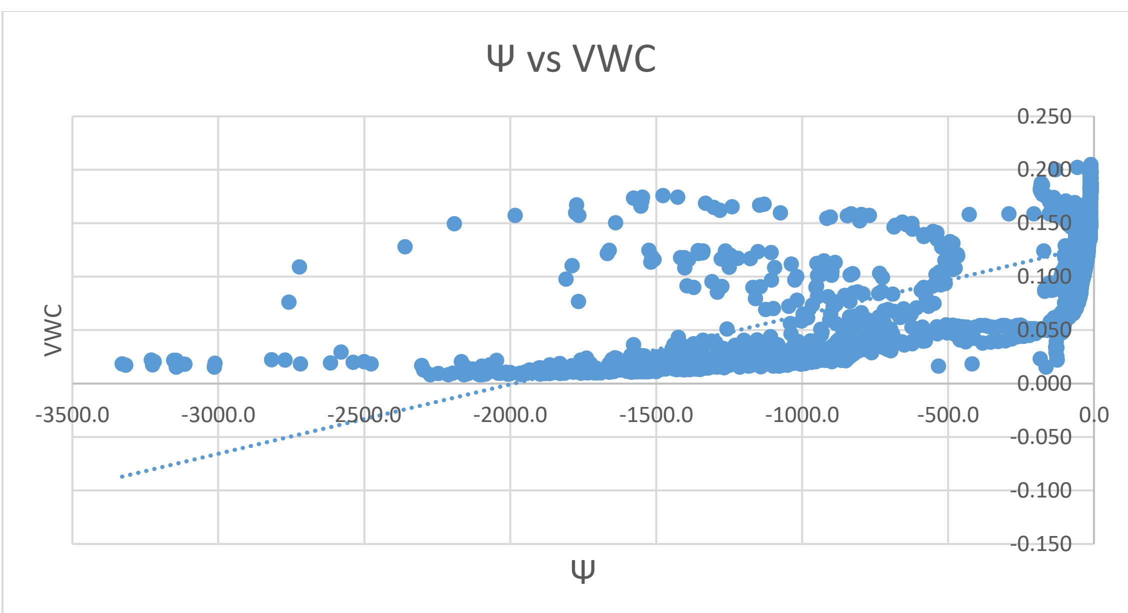

Figure 13. Graph representing correlation between matric potential and volumetric water content for 1 year on control site A. Permanent wilting point occurs when Ψ equals -1500kPa. Plant available water occurs between -15kPa and -1500kPa.

Meteorological Data

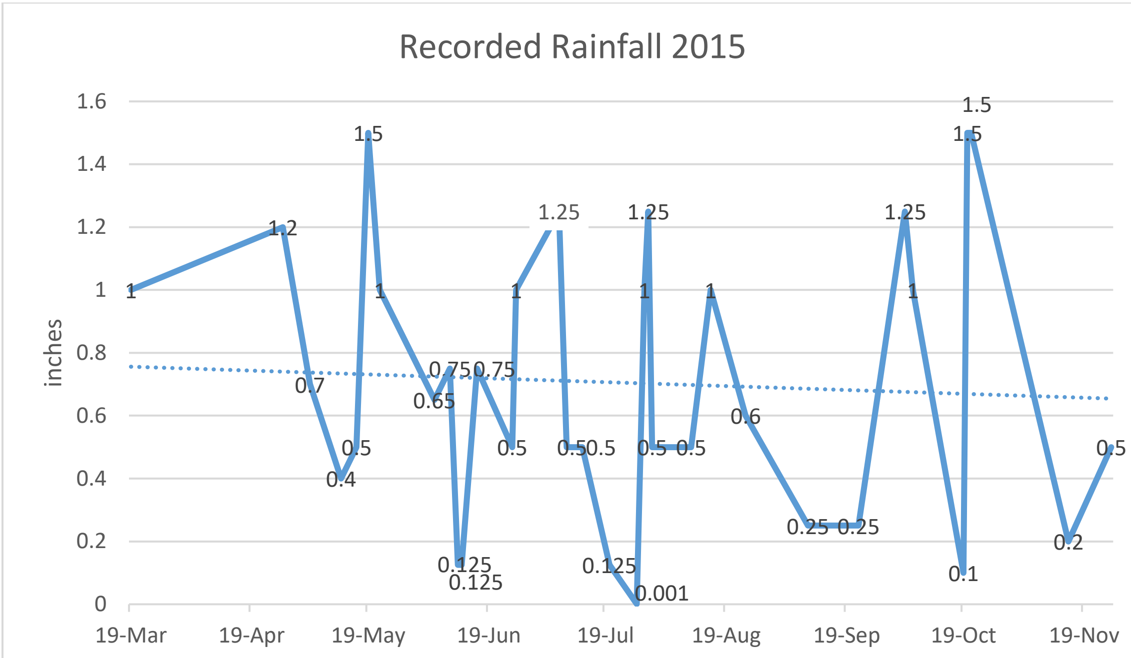

Figure 14. Line graph representing rainfall amount (in) and date for the year 2015.

Table 3. Precipitation dates, type and amount from December 2014 – January 2016.

Date	Type	Amount (in)	Date	Type	Amount (in)	Date	Type	Amount (in)
26 Dec	Snow	2.0	19 May	Rain	1.5	30 July	Rain	1.25
2 Jan	Frost	0.2	22 May	Rain	1.0	31 Jul	Rain	.5
6 Jan	Frost	0.2	5 Jun	Rain	.65	10 Aug	Rain	.5
14 Jan	Snow	3.0	9 Jun	Rain	.75	15 Aug	Rain	1
21 Jan	Snow	5.0	11 Jun	Rain	.125	24 Aug	Rain	.6
30 Jan	Snow	3.0	12 Jun	Rain	.125	9 Sep	Rain	.25
11 Feb	Snow	1.0	16 Jun	Rain	.75	22 Sep	Rain	.25
16 Feb	Snow	1.0	25 Jun	Rain	.5	4 Oct	Rain	1.25
22 Feb	Snow	1.0	26 June	Rain	1	6 Oct	Rain	1
25 Feb	Snow	16.0	7 July	Rain	1.25	19 Oct	Rain	.1
19 Mar	Rain	1.0	9 July	Rain	.5	20 Oct	Rain	1.5
27 Apr	Rain	1.2	13 July	Rain	.5	21 Oct	Rain	1.5
4 May	Rain	.7	20 July	Rain	.125	15 Nov	Rain	.2
12 May	Rain	.4	27 July	Rain	.001	26 Nov	Rain	.5
16 May	Rain	.5	29 July	Rain	1	12 Dec	Snow	6

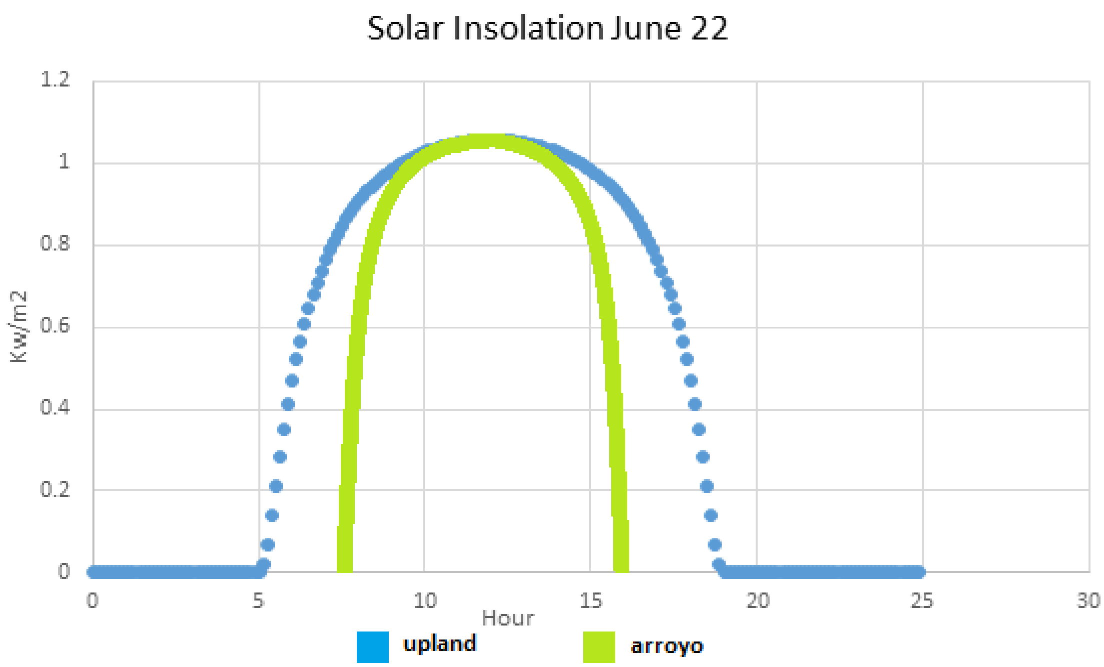

Figure 15. Graph representing the amount of power that would be received by a tracking concentrator in the absence of a cloud for 35° N during the solstice (Brownson 2013).

Table 4. Descriptive statistics for six soil moisture sensors employed for 1 year expressed as m^3/m^3.

	A	B	C1	C2	D1	D2
N	2340	2340	2340	2340	2340	2340
Mean	.09929	.18805	.15151	.12432	.16902	.14756
Std. Error of Mean	.001210	.000851	.000731	.000912	.000678	.000344
Median	.11600	.19500	.15700	.14100	.17400	.14900
Mode	.157	.203	.153	.145	.110	.154
Std. Deviation	.058538	.041184	.035369	.044109	.032793	.016664
Variance	.003	.002	.001	.002	.001	.000
Range	.197	.302	.215	.190	.214	.107
Minimum	.008	.071	.066	.035	.106	.114
Maximum	.205	.373	.281	.225	.320	.221

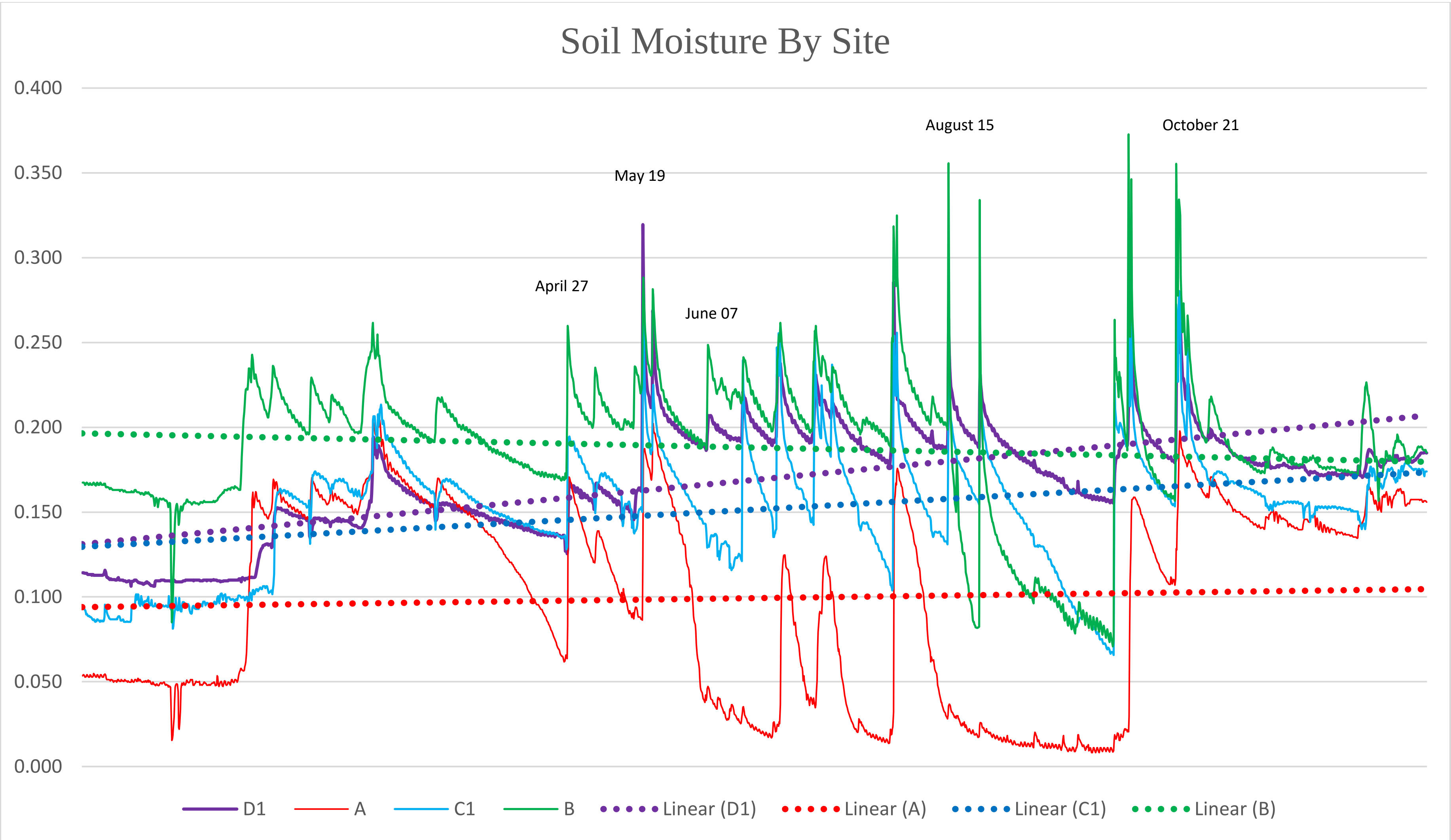

Figure 16. Graph representing soil moisture, reference dates, and trend lines for the year 2015. A (upland control no mulch), B (arroyo without ORD), C1 (upland with rock mulch), and D1 (arroyo with ORD).

Table 5. Descriptive statistics for annual air temperature °C (2015).

	N	Range	Minimum	Maximum	Mean	Std. Dev.
Soil °C A	2301	29.8	.10	29.90	14.0263	8.59011
Soil °C B	2301	24.9	1.60	26.50	12.4742	7.08317
Soil °C C	2301	26.4	1.20	27.60	13.9354	8.12093
Soil °C D	2301	21.1	2.50	23.60	12.1533	6.16687

Table 6. Descriptive statistics for annual soil temperature °C (2015).

	N	Range	Minimum	Maximum	Mean	Mode	Std. Deviation
Temp °C A	2301	54.40	-17.70	36.70	10.9511	13.10	10.21509
Temp °C B	2301	51.50	-14.20	37.30	10.8432	13.60	9.91364
Temp °C C	2301	53.80	-17.50	36.30	10.8531	16.30	10.09331
Temp °C D	2301	51.80	-16.70	35.10	10.5499	11.70	9.48362

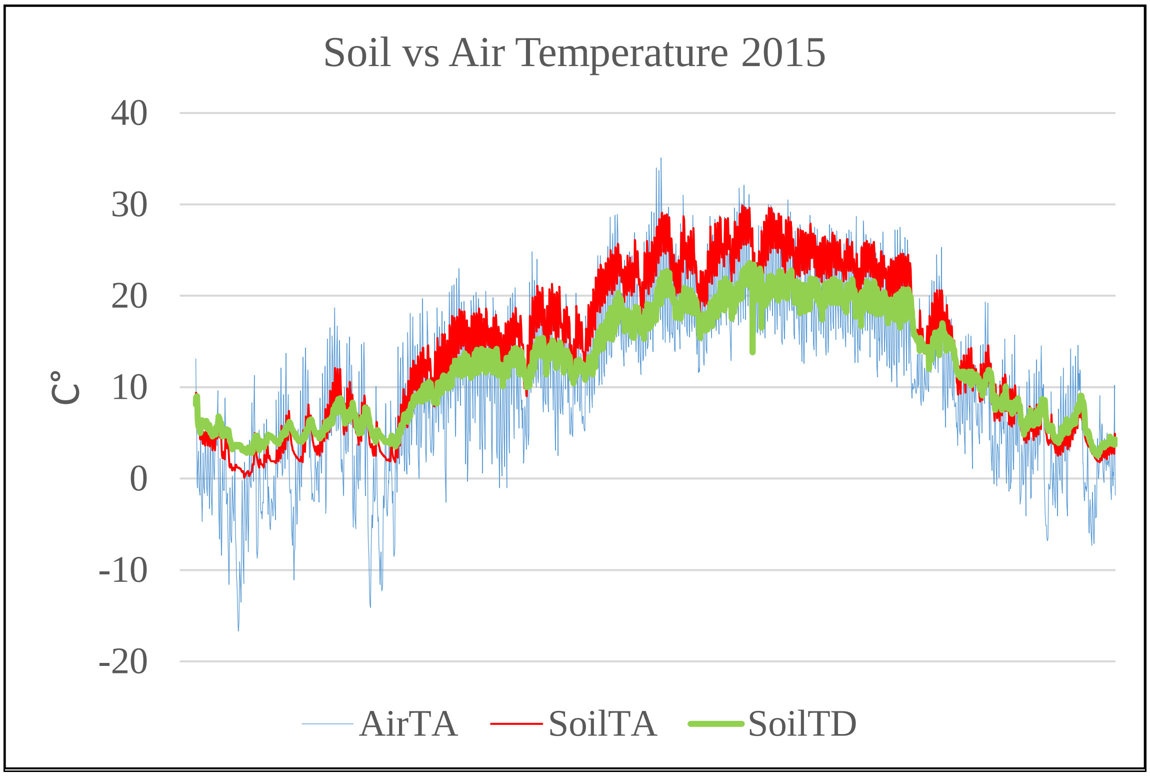

Figure 17. Soil and air temperature readings; site A (upland control) vs. site D [1] (arroyo with ORD) for the dates April 1 – September 30.

Table 7. Descriptive statistics for annual wind speeds in m/s (2015).

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Wind C	2340	5.80	.00	5.80	1.2248	.84488
Wind D	2340	3.70	.00	3.70	.8282	.61039

Table 8. Descriptive statistics for annual (2015) percent humidity 0.3m above sites A-D.

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Humidity A	2304	.96	.09	1.05	.5773	.25883
Humidity B	2304	.97	.09	1.05	.5733	.25494
Humidity C	2304	.96	.09	1.05	.5852	.26000
Humidity D	2304	.96	.10	1.05	.5770	.24706

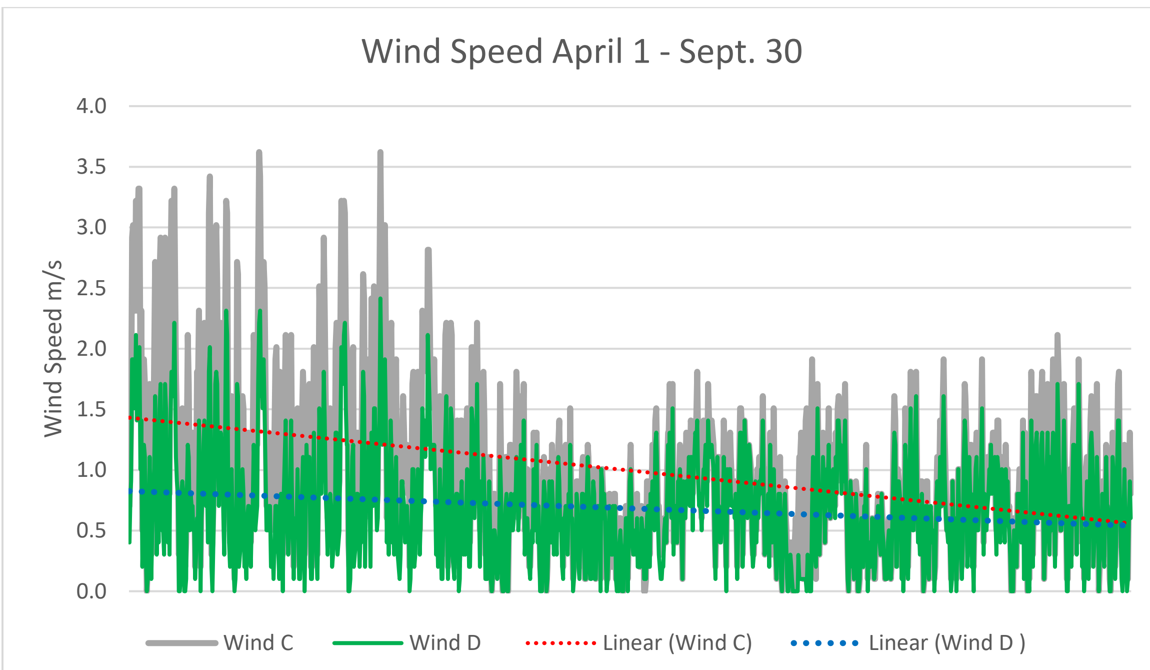

Figure 18. Graph representing wind speeds at Site C and D from April 1 – September 30.

Discussion

Channel and Site Characteristics

The dimensions of the studied arroyo (length 300 m) provide insight into further applications along similar gradients averaging a slope of 7 % with comparable surroundings of woody species encroachment, reduced grass cover, and catchment sizes between 15 and 30 acres. The semi-arid setting of nearly 2000 m above sea level and at 35° N latitude incorporates both a reduced atmospheric pressure leading to increased potential evaporation and an increase in solar intensity which also increases evaporation and transpiration. Cross sections of the arroyo demonstrate the level of incision and consequent floodplain disconnection while highlighting a reduced solar and wind exposure. Deposition from sandstone and fractions of caliche provide a well-drained, slightly alkaline, sandy loam rich in silt. Soil along and within the arroyo is well suited for supporting both native vegetation and crops. This soft, well aerated soil also contributes to its erodibility. Although some arroyo channels may differ in length, width and depths, they are all influenced by local weather and maintain the potential to be restored to a more stable state increasing local ecological values.

Meteorological Data – Precipitation

2015 was a relatively moist year (Fig. 14, Table 3) characteristic of El Niño weather patterns in the Southwest. Because precipitation amounts were recorded using a basic rain gauge and a tape measure during snowfall events, there is some inherent error. The amounts recorded are relatively high and the nearest climate center in Pecos, NM (30 miles north) recorded only 43.7 cm of precipitation (US climate data) for the year.

Additionally, precipitation date and amounts were recorded as a peripheral measure of soil moisture and not used in the ET evapotranspiration calculations. Future climate models, however, predict contrastingly different yearly averages as minimal as 30 cm of precipitation along with the likelihood of extended drought. The wettest months recorded were July (13cm) and October (13.6 cm). The abundance of vegetation produced through late spring and early summer included seed growth of plants that did not germinate in previous years which helped dampen the intensity of two late season storms in October of 3.8 cm each. These late season storms were associated with increased low pressure tropical activity and highlight the need for additional moisture storing areas throughout the landscape not only to dampen intense storm effects but to increase retention of winter moisture that will be available to plants the following spring.

Solar Insolation

During the solstice at 35°N latitude with minimal cloud cover, solar insolation (Fig. 15) can be quite high >11 $kW/m^2/day$. However, direct sunlight exposure can be reduced within a deep arroyo anywhere from 33-40 % effectively reducing ET while still providing diffuse light utilized by lower story plant species. The consequent reduction of early morning sunlight prolongs the duration of dew on leaf surfaces that eventually adds to moisture retained within the soil. During the evening hours, which tend to be much warmer, arroyo sections cool down earlier allowing them to retain a significantly larger amount of soil moisture than the adjacent upland. The banks along the sides of the arroyo become less steep due to restoration efforts; however, the shadowing early and later in the day remains an important factor in reducing solar exposure. Vegetation growing along these banks also contributes to increased humidity and soil moisture retention along the arroyo channel.

Soil Moisture

Soil moisture readings (Fig. 16, Table 4) were largely affected by location, restoration method, and available precipitation. Soil moisture infiltration and retention were greatest beneath the treated upland site C^1 (avg. 0.15/m^3) and the treated arroyo section D^1 (avg. 0.17/m^3) attributable to the use of an upland rock mulch in Site C^1 and a reduced solar insolation and wind exposure along with an ORD emplaced at site D^1.

Through the 2015 year, site C^1 (upland with rock mulch) stored abundant moisture through retention of snow and rainfall. The rounded river stone used to protect site C^1, proved highly effective as moisture was able to travel beneath the stones and into the soil where it was lost to evapotranspiration slowly over time evident in the more gradual wave segments (blue). Beginning at less than 0.09 m^3/m^3, the available soil moisture at site C^1 increased dramatically to 0.17 m^3/m^3 one year later in spite of a downward precipitation trend and exhibited a saturation value of 0.281 m^3/m^3. The lowest value recorded at site C^1 was 0.066 m^3/m^3 which only developed after two months without appreciable summer moisture. Furthermore, a soil moisture sensor at C^2 located 3 m upslope from C^1 indicated that the rock mulch had a substantial influence on the surrounding soil moisture. The sensor at C^2 recorded an average of 0.12/m^3 and closely represented the influence of its downslope C^1 counterpart.

Even more impressive were the results from sites D^1 (arroyo with ORD) and D^2 (3 m upstream). Not only was increased soil moisture retained between precipitation events compared to all other sites, the values recorded were substantially greater as moisture was lost much slower over time providing consistent and significant storage between rains expressing the most gradual wave pulses (purple). At site D^1 the average value of 0.17 m^3/m^3 meant soil moisture retention and vegetative stress were not issues, with the lowest value recorded being 0.10 m^3/m^3 and a saturation value of 0.32/m^3. Although the earliest measurement at site D^1 was 0.11 m^3/m^3, following the spring rains in April, soil moisture remained above 0.16 m^3/m^3 for the remainder of the year. This was especially important during a period of two months (August – October) without appreciable summer moisture, and in spite of a downward precipitation trend, greater than any other site. Soil moisture at D^2, designed to represent the influence of localized soil moisture provided by the ORD located 3 m downstream, averaged 0.148 m^3/m^3 exhibiting a minimum value of 0.114 m^3/m^3. These values occurred within the arroyo system and substantiate the importance of restoration efforts that compound over time and appear to function regardless of temperature extremes.

Although site B (unrestored arroyo section) exhibited the greatest average soil moisture (avg.0.18 m^3/m^3), initial readings were relatively high 0.167 m^3/m^3 representing an enhanced soil moisture capacity in this section of the arroyo. Site B also expressed this enhancement until a storm flow event in late August eroded the unprotected bank above the soil moisture sensor. The flow event increased local evaporation, greatly reducing soil moisture to just 0.070 m^3/m^3 while site D^1 (downstream) remained an impressive 0.155 m^3/m^3. The summer activity also revealed large wave variation (green) in the arroyo section that was otherwise highly productive in terms of soil moisture retention. The next series of mild storms redeposited soil above the sensor restoring the original capacity of the arroyo section. Because the arroyo control site began with abundant soil moisture, in hindsight it may have been an ideal location for a grade control structure.

Beneath site A (avg. 0.010 m^3/m^3), which served as the adjacent upland control, direct solar exposure and strong gusts quickly deprived the site of moisture to a minimum of 0.008 m^3/m^3, the lowest of any recording in 2015 and well beyond the wilting point (Fig. 13) which caused increased plant stress and made it difficult for the site to reabsorb soil moisture. Site A (red) was often found to be below average in terms of available soil moisture and expressed the steepest drop among sites in terms of available moisture between precipitation events. Because site A was unprotected by a rock mulch or a walled arroyo, it never reached the strong moisture and storage capacity expressed by the other sites. Site A served as a proxy for landscape desertification and the inability of particular patches to retain moisture in spite of abundant precipitation.

The lack of appreciable rain in September (1.27 cm), reduced soil moisture content in almost all sites and dropped to 0.070 m^3/m^3 in site B (unrestored arroyo section) and C^{l} (mulched upland) and below 0.010 m^3/m^3 beneath control site A, while interestingly, the restored arroyo section in site D^{l}, augmented early in 2015, remained above 0.156 m^3/m^3 which would have not been possible without restoration efforts, highlighting the need for such moisture retaining areas on the landscape. Similar ORD structures built further along the drainage also retained a relatively high soil moisture content in and around their intended use which prompted increased restoration attempts for the ensuing season.

At least a full year of data was necessary in order to understand and interpret the dynamics of the system and how it responded during flow events as well as months without moisture. Ideally, multiple years of this same data would give a clearer idea of the behavior of the system in both wet and dry years. Initial quarterly data during the winter did not show the impact of restored vs. unrestored sites and it became apparent that data collected during the summer was most important as it revealed the soils' response to both storms and high temperatures. Rain events on all sites are easily recognized in the soil moisture graph; however, the soil response during instances of semi-drought meant that protected sites retained moisture and significantly less variability.

Air and Soil Temperatures

Air temperature extremes (Table 5, Fig. 17) were found to be greatest on site A (upland control) with a maximum recording of 36.7°C and a minimum of -17.7°C, averaging 10.95°C. Contrastingly, the restored arroyo section site D [1] expressed less extreme conditions with a maximum of 35.1°C a minimum of -16.7°C and an average of 10.55°C. Site B (arroyo control) and C [1] (upland with rock mulch) produced results within the extremes having maximum and minimum temperatures of 37.3°C; 36.3°C and -14.2°C; -17.5°C respectively. Air temperatures were a factor of warm or cool air and winds moving across the land's surface and were influenced by vegetation, and arroyo banks. Shadowing from arroyo banks likely had the largest effect on reducing temperatures.

Seasonal differences in soil temperature (Table 6, Fig. 17) reveal that the restored arroyo site D [1] exhibited the lowest maximum temperature (23.6°C) and the warmest minimum air temperature (2.5°C) when compared with the upland control site A (max. 29.9°C, min. 0.10°C). These differences accentuate both warmer soil temperatures in winter and cooler soil temperatures during summer months at restored site D^{1} when compared to control site A. This in turn could lead to reduced plant stress during temperature extremes, particularly in the root zone and is likely due to a higher soil moisture content in site D^{1} which provided insulation. Site B (arroyo control) and C^{1} (upland with rock mulch) exhibited temperatures between the two extremes with a maximum of 26.5°C; 27.6°C and a minimum of 1.60°C; 1.20°C, respectively.

Wind Speed

Generally, as temperatures warmed into the summer, wind speeds were reduced. Winds were strongest during spring months and were reduced during summer months evident in the data (Table 7, Fig. 18). The anemometer at site C^{1} (upland with mulch) revealed that the adjacent upland wind speeds were much higher with a maximum of 5.8 m/s and an average of 1.23 m/s. Alternately, Site D^{1} protected within the arroyo channel, experienced maximum wind speeds of only 3.7 m/s and averaged 0.83 m/s. Though there were times when winds stopped, the anemometer at site D^{1} recorded 0.0 m/s most often. Through 2015, wind speeds were dramatically reduced by 32.4% (0.4 m/s) within the studied arroyo section D^{1} compared to C^{1} on the upland, which can be very beneficial especially as warm winds on hot (37°C) days can lead to a very high evapotranspiration (ET) rate. Strong spring winds had significant impacts on evaporation of soil moisture stored over the winter that would have increased cool season plant production. Stored soil moisture from winter snows carries the system through the driest months of May and

June and this is evident in soil moisture readings on all sites with the exception of site A (upland control).

Humidity

Average humidity levels (Table 8) recorded throughout the year 2015 on all four sites were very similar expressing minimal differences with site C [1] (mulched upland) averaging only 0.01% higher at 0.58%. This may be attributable to the lack of well-defined canopies above the VP-3 sensors on all four sites. Although humidity differences do not appear in sensor outputs, frequent visits to the study site reveal the abundance of insects particularly mosquitos within the arroyo channel below tree canopies. Humidity differences are thus likely to occur at varying degrees, heights, and in specific locations which may have not been captured by the VP-3 sensors.

Evapotranspiration

On a typical 36°C day under light wind conditions (1.6 m/s), and a low humidity (0.15%), evapotranspiration (ET) can be as high as 7.26 mm/day or 7,765 gal/acre/day. Under similar conditions within a restored arroyo reach, ET may be as low as 5.44 mm/day or 5,800 gal/acre/day, a 25% reduction equivalent to -2000 gal/acre/day. The bed area of the studied arroyo is approximately 10,000 ft^2 or 0.23 acres. Conservative estimates indicate that over a 90-day period, as much as 20,000 additional gallons of moisture could be conserved in this system. This could dramatically reduce the amount of lost soil moisture storage lost making it available to vegetation and supporting native plant species thereby increasing biotic associations effectively restoring such systems (Fig. 19).

Figure 19. Restored arroyo highlighting the abundance of native grasses and shrubs within a juniper woodland. Photograph by Craig Conley.

Conclusion

The main findings of the study include both a reduced solar and wind exposure within similar arroyo systems and a consequent conservation of soil moisture within such restored sites. Because a relatively steep and confined arroyo system was used for this study, solar and wind exposure are likely to increase as restored arroyo systems widen and decrease in depth but are counterbalanced by reductions in slope which further promote increased infiltration especially in lower reaches often containing a deeper soil profile as sediments are deposited over time. With the incorporation of trees and wetland species on arroyo banks capable of tolerating flood, drought, and temperature extremes, the arroyo system can be developed into a significant swath of habitat both horizontally and vertically.

Although restoration efforts began in 2013, a number of failed restoration treatments resulted from underestimations in flow velocities and vegetative cover in the arroyo. A strong September storm in 2014 not only caused the failure of all but one ORD but also resulted in a more incised and disconnected channel and subsequent topsoil loss. Developments resulting from the storm included the use of much heavier rounded stones for ORD's as opposed to angular block. Also, [WL22]much larger sandstone boulders were used to reduce flow velocities in constructing permeable dam structures that required heavy machinery. In hindsight, the appropriate measure would have been to request a delivery of 10 yds^3 of 12" river stone. This would have reduced fuel costs and transport of materials, as well as trampling and compaction of roads leading to the study site. In replicating similar restoration efforts, greater consideration should be given to material use and type namely in structure build to ensure effectiveness and reduce site maintenance.

The robustness of the data loggers and sensors meant much fewer site visits were actually required. Site visitation may have affected surrounding vegetation and disturbed soils and banks that would have responded differently during precipitation events. Vapor pressure and humidity, which proved to have the highest contrast between the upland control site A and the restored arroyo section at site D^1 meant that perhaps only two VP-3 sensors were needed. Matric potential sensors also may have been affected in the same manner in that soil temperature was contrasted most in sites A and D^1 and that matric potential which represented well the soils textural capacity, was only reduced beyond the wilting point beneath site A when moisture was reduced below 0.05/m³. For these reasons the use of alternative soil moisture sensors and/or soil heat flux sensors in other locations may have benefited the study particularly when calculating ET. For recording precipitation, cylindrical rain gauges were less accurate than real time tipping bucket gauges would have been. Some evaporative losses between data monitoring visits may have affected the accuracy of the precipitation data and resulted in slightly lower rainfall estimates. This inaccuracy did not affect the final results, as these were based on micro meteorological conditions post precipitation event. The wind anemometers worked incredibly well and were crucial in ET estimation. Additionally, access to neighboring lands is crucial especially concerning the area contributing to the drainage. In this study, livestock grazing occurred on neighboring lands along the upper watershed and the adjacent fence line which may have altered or increased storm runoff by reducing vegetative cover.

In replicating the study, it is important to consider fewer site visits when possible. Instead, visit the location when flows are likely to occur. This may help to better understand system dynamics and structure placement. Although the study design was undertaken by only a few people, compensated undergraduate assistance with soil analyses, equipment and structure installation, and in site selection may have garnered a sufficiently greater amount of data. Also, while choosing to install the monitoring equipment for one year provided substantial data and longer intervals may have highlighted the soil moisture retention of structures after they had settled. Performing the analyses during a la Niña year may have also revealed the duration that restoration structures were truly effective in a real world scenario. Although the studied system had a southeast aspect, choosing to use both southwest and northeast facing systems in varying stream bottom types (sand, gravel) and slopes may reveal distinctions not present in this study.

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