

WESTERN PLANNER DOUBLE-BLIND ARTICLE REVIEW

TITLE: Green Stormwater Infrastructure in a Semi-arid Climate: The Influence of Rain Gardens on Soil Moisture Over Seven Years

YES **NO**

Mark an "X"

Content – is it applicable to our audience?	X	
Substance – is it timely, relevant and useful?	X	
Accuracy – is it verifiable, cited, or credible?	X	
Fluency – is it easy readable and understandable?	X	
Suggested content categories (separate with commas): e.g., affordable housing, apartments, mixed use		
Additional comments illustrations and graphics are incredibly helpful and help frame the article nicely. Legend in Daily Fluctuation in VWC chart needs to be cleaned up a bit Thoroughly researched Information in this article is incredibly useful for our western communities		

Abstract

Trees planted around rain gardens present an opportunity to remediate stormwater pollutants, diversify habitat, and cool impervious surfaces in municipalities. In semi-arid regions where water resources are scarce however, it is unclear whether stormwater captured in these basins is sufficient to sustain urban trees without supplemental irrigation. This seven-year study examined whether soil moisture could be significantly improved at parking lot curb cuts with rain gardens compared to curb cuts without rain gardens. Hourly volumetric water content (VWC) was measured at 6-inch depth intervals down to 30 inches in a soil profile predominantly composed of clay loam textures. Results indicate that average

VWC in rain garden soils was significantly higher at four out of five measured depths and when averaged across the full 30-inch profile compared to sites without rain gardens. Rain gardens also regularly replenished and retained soil moisture above an irrigation threshold across seasons and during periods of drought.

Keywords

Green stormwater infrastructure, Rhizosphere soil moisture, Rain gardens, Urban water conservation

Introduction

Throughout municipalities there is increasing documentation that trees in urban settings provide numerous social and environmental benefits (1). For example, trees are known to offset urban heat islands by lowering soil and other underlying surface temperatures (2, 3), sequester carbon (4), and positively influence consumer behavior by improving the aesthetics of commercial exteriors (5). These benefits, among others, have led researchers to value urban forests in the trillions of dollars (6), however urban tree cover is being lost in municipalities across the United States (7).

Maintaining and increasing urban tree cover has many challenges such as proximity to utilities, insufficient space to grow, soil quality, etc. (8). In semi-arid climates obstacles to increased tree canopy could be water scarcity during drought or due to rising costs of irrigation. Pitting trees against water resources can be particularly difficult in municipalities because urban trees might utilize more water than trees in less urban settings. Higher water consumption by urban trees could be due to non-native species selection, more challenging growing conditions caused by limited soil volumes, or increased stress resulting from reduced infiltration and warmer temperatures created by impervious surroundings (9, 10, 11).

One potential method foresters might employ to conserve water resources and offset the cost of irrigating urban trees is to utilize Green Stormwater Infrastructure (GSI) such as rain gardens. Traditional (i.e. “gray”) stormwater infrastructure such as gutters, drains, and pipes convey stormwater away from an area while GSI “is designed to mimic nature and capture rainwater where it falls” (12). Rain gardens, which are shallow retention basins aimed at capturing runoff from adjacent impervious surfaces, have been used in many communities to reduce stormwater pollutant transport and provide passive irrigation for vegetation (13). Stormwater in rain gardens is slowed, pooled, and allowed to infiltrate soils where it can be filtered, stored, and utilized by vegetation between precipitation events. Passive irrigation from impervious surfaces has been recommended to support urban tree growth (9), however research about the degree to which soil moisture can be improved and retained with GSI in semi-arid climates is still limited.

One technique to assess soil moisture is through in-situ probes that measure volumetric water content (VWC). VWC is the proportion of a volume of soil composed of water and is often presented as a percentage. A study in the semi-arid community of Tucson, AZ found that VWC at passively irrigated sites that received runoff from impervious areas (i.e. streets) compared favorably to actively irrigated sites at approximately 12-inch depths (14). The study did not examine depths in the soil profile below 12 inches where deeper rooted plants might be able to take advantage of soil moisture less influenced by evaporation. A separate study in Santa Fe, NM provided comparisons of VWC at sites with and without rain gardens down to 30 inches in the soil profile, but the study only lasted one year (15).

Continued monitoring of VWC across a deeper rhizosphere (i.e. root zone) profile during prolonged periods without precipitation and over multiple years could provide more clarity about the degree to which VWC fluctuates and how it might affect urban trees. The intention of this study was to expound on the Santa Fe research with results from seven total years of measurements.

Methods

Study Area: Santa Fe, New Mexico is a high elevation (7,000ft), semi-arid community (pop. 80,000) in the southwestern part of the United States. Between 1981-2010 average annual high and low temperatures for the area were 65°F and 35°F and mean precipitation was 14.18 inches/year at the “Santa Fe 2” weather station ([16](#)) (Note: While the precipitation record from the “Santa Fe 2” gauge did not overlap with the period of study—the gauge was discontinued in 2010—it was chosen due to its proximity of only 1.6 miles northeast of the study site. The next closest official National Weather Service Cooperative weather station is over 4.7 miles away). The city has four primary potable water resources including the Santa Fe River reservoirs (i.e. Nichols and McClure) and city well fields, as well as the more distant Buckman well fields and Buckman Direct Diversion (BDD) on the Rio Grande (i.e. San Juan-Chama Project). During dry years, the BDD can account for over half of Santa Fe’s potable water consumption, however increasing demand by growing regional populations, less reliable snowpack, and earlier spring runoff has led to future water availability concerns among communities dependent upon surface water from the Rio Grande ([17](#), [18](#)). After exceeding seasonal threshold water consumption quantities and associated delivery charges, the city of Santa Fe charges approximately \$0.02/gallon (\$21.72/1,000gallons) to customers for water produced from the City’s four water sources ([19](#)).

This study was conducted at the Kids’ Campus parking lot located at the Santa Fe Community College (SFCC). The parking lot has curb cuts along the western edge that each drain about 3,500ft² of asphalt surface. Historically, stormwater exited the curb cuts onto mild slopes (less than 5 percent) with a mixture of native grasses. Soils in the area are generally described as Alire loam; a classification predominantly composed of clay loam textures in the top 35 inches of a typical profile ([20](#)). To analyze soil moisture at the site, two of the curb cuts were treated with rain gardens and two curb cuts were left untouched as controls (Figure 1).

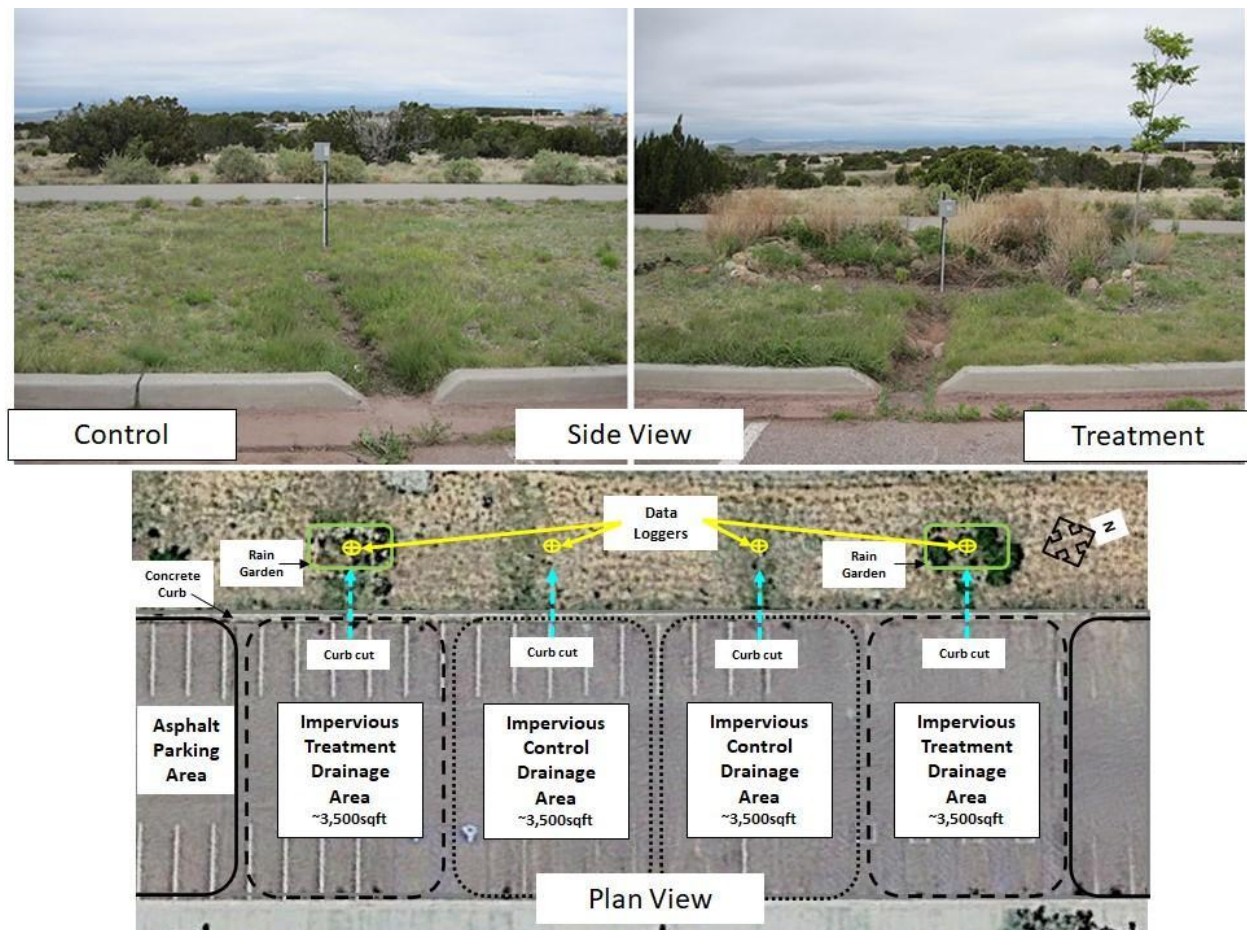


Figure 1. Example of curb cut without (i.e. Control) and with (i.e. Treatment) a rain garden as well as a plan view diagram of a section of parking lot that drains through four curb cuts (i.e. two controls, two treatments).

In October of 2012 and April 2013 rain gardens were excavated approximately 6-inches deep by high school students to capture stormwater from two of the parking lot curb cuts. Excavated soil was placed around the sides and downslope perimeter of the rain gardens as a berm to retain stormwater. The berms were shaped to 3:1 slopes before being walked on for compaction, seeded with wildflowers and grasses, and mulched with 4-8 inch rounded cobble. The berm perimeters left an interior stormwater pooling area roughly 15ft x 10ft x 1ft for a maximum open volume catchment (i.e. not including soil porosity) of 1,122 gallons. Over the course of a year with an average of 14.18 inches of precipitation and a runoff coefficient of 0.8, it is expected that each curb cut would drain approximately 24,750 gallons of stormwater.

The interior of the two rain gardens where water pools was mulched with 3 inches of woodchips lightly mixed with composted soil. The basin depressions were planted with six 1-gallon plugs of little bluestem (*Schizachyrium scoparium*) and sacaton (*Sporobolus* spp.) grasses tolerant to temporary inundation by water. Berm slopes were planted with 1-gallon shrubs including three-leaf sumac (*Rhus trilobata*), false indigo (*Amorpha fruticosa*), and New Mexico Privet (*Forestiera neomexicana*). The northeastern berm of each basin also received a 15-gallon container, 1.5-inch caliper Patmore green ash (*Fraxinus pennsylvanica* 'Patmore') or honey locust (*Gleditsia triacanthos*) tree. Plant species were selected because they are known to be drought tolerant, provide pollinator habitat, have demonstrated the ability to remediate common stormwater pollutants, and are native or adapted to the region without

being invasive. The two control sites consisted of curb cuts that received comparable volumes of runoff to the treated sites but without depressions where stormwater could pool. The controls were maintained with existing plant cover such as blue grama (*Bouteloua gracilis*) and other drought tolerant grasses and forbs. Supplemental irrigation was not provided to plants at the control or treatment sites during the period of measurement (i.e. September 2014-August 2021).

Soil Moisture and Precipitation: The maximum VWC a soil texture will hold against gravity is referred to as field capacity (FC), while the point at which common annual agricultural crops (e.g. sunflowers) begin to struggle to extract water from a given texture is called permanent wilting point (PWP). While shrubs and trees might be resilient to dips below PWP, the assumption in this study was that if VWC remained above PWP, then urban trees would be expected to withstand drought conditions (i.e. periods of time with below normal precipitation). Field capacity for a clay loam soil similar to the textures found at the study site is 30.9% and permanent wilting point is 18.4% (21). The median VWC of FC and PWP (i.e. 24.7% in a clay loam texture) is often used by landscapers and farmers as a threshold to begin irrigating plants to avoid vegetation stress and maximize growth.

To monitor soil moisture a 5-inch diameter auger was used to drill holes in the soil profile 13ft from the curb edge at each of the control and treatment plots. Decagon 5TM soil moisture probes were placed in the soil profile to measure VWC in the rhizosphere. Probes were inserted into the profile at 6, 12, 18, 24, and 30 inches below the soil surface at each plot for a total of 20 probes (i.e. four sample plots with five probes each) (Figure 2). After installing the probes, the open soil profile column was refilled with excavated soil to a comparable bulk density prior to digging. Probes below 12 inches were expected to account for soil moisture at depths less influenced by evaporation and potentially available for deeper rooted shrubs and trees. Hourly VWC was recorded for each probe on Decagon EM50 data loggers at each treatment and control plot. An Onset tipping bucket rain gauge, with a precision of 0.01-inch, was also installed at the site to provide estimates of soil moisture responses to daily precipitation events, total precipitation depth by season, and for comparison to the 30-year precipitation average (1981-2010) provided by the “Santa Fe 2” gauge.

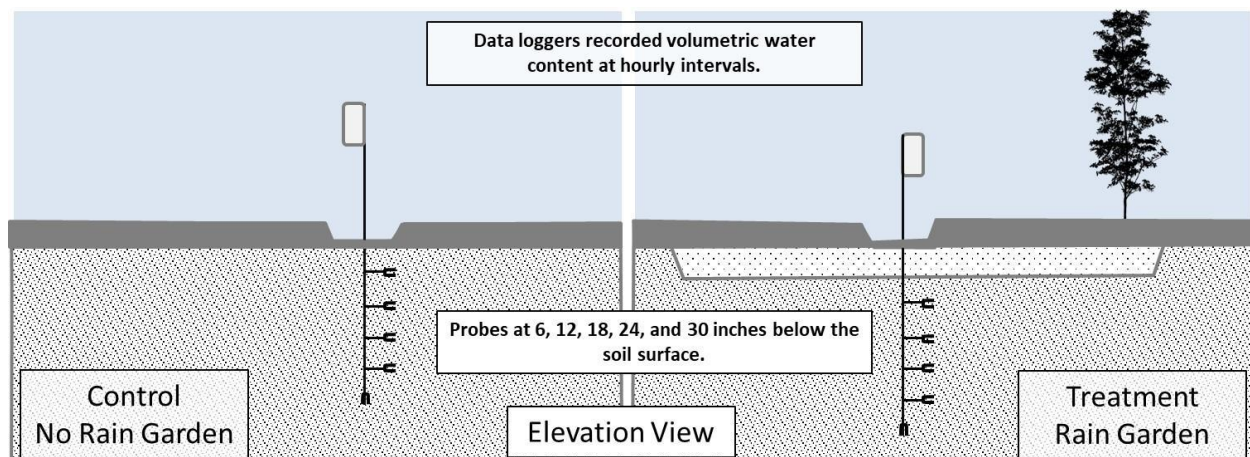


Figure 2. General schematic showing where soil moisture probes were placed in the soil profiles for controls and treatments.

Data Analysis: It is presumed that fluctuations or differences in VWC could exist due to a lag time in response to precipitation events, seasonal evapotranspiration rates, or other factors. Therefore, hourly VWC for each probe (61,368 measurements/probe over seven years) was averaged into different units of

time (e.g. full seven-year period, season, and date) before further analysis was performed. To assess whether significant differences existed by treatment (rain garden or control), depth, or if an interaction was present, data was averaged for each probe at each depth before a general linear model (two-way ANOVA with replication) was performed ($\alpha=0.10$). A post-hoc Tukey HSD test was used to assess differences by corresponding depths.

Measurements of VWC by treatment for the full 30-inch profile were subsequently averaged into three-month seasonal blocks. The seasonal blocks were of interest due to the likelihood of variations in water availability and demand by vegetation. The seasonal blocks included plant dormancy periods (Winter: December-February), typically dry and warming periods (Spring: March-May), primary growing periods with hot temperatures and potential for high intensity monsoons (Summer: June-August), and cooler periods prior to the onset of plant dormancy (Fall: September-November). Corresponding precipitation data for seasonal periods was also compiled into percentages versus the 30-year average from the "Santa Fe 2" gauge for comparative purposes.

Finally, average daily VWC across the 30-inch soil profiles for treatments and controls was charted with daily precipitation totals to better understand the extremes and frequency of soil moisture replenishment and depletion during and between storm events. Refining data by date provided information about the duration that vegetation might be required to endure moderate to severe periods of insufficient soil moisture in the absence of active irrigation. Examining soil moisture responses to precipitation events also allowed for assessment of precipitation depths that resulted in average VWC across the 30-inch profile to become saturated (i.e. exceed field capacity).

Results and Discussion

Volumetric Water Content by Depth and Treatment: Comparisons of volumetric water content revealed a significant interaction ($F(4, 10) = 3.8, p = 0.039$) meaning that differences in soil moisture in rain gardens compared to controls is dependent on soil depth. Average VWC in rain gardens was significantly elevated above controls when averaged across the entire 30-inch profile ($F(1, 10) = 31.3, p < 0.001$) and at each corresponding 6-inch depth except 12 inches ($F(4, 10) = 1.7, p = 0.233$) (Figure 3). Increases in soil moisture in rain gardens at 6 inches could have been caused by improved soil structure brought about by decomposing organic matter (i.e. woodchips) similar to a study in Tucson that found organic mulch increased gravimetric soil moisture over sites mulched with rock ([22](#)). Differences in water holding capacity across the greater soil profile, however, is believed to be a result of increased residence time (i.e. ponding) of stormwater in the rain gardens compared to sites where stormwater runs off the landscape (i.e. controls). Allowing stormwater to slow and pool in basins likely provided opportunities for water to infiltrate the soil surface and percolate to lower depths. Average VWC was above the irrigation threshold at each depth and across the 30-inch profile for rain garden soils, but fell below 24.7% in controls at 6, 12, 18, and 30-inch depths (Figure 3).

Volumetric water content was particularly enhanced at 18, 24, and 30 inches in the rain garden soil profile (29.9%, 28.9%, and 30.0% respectively). Plant available water content (PAWC) (i.e. the VWC between field capacity and permanent wilting point where roots can easily extract water) at these depths was almost maximized (i.e. near FC) during the period of study. VWC levels at these lower depths suggest that a reservoir of soil moisture could be accessible for deeper rooted vegetation to utilize as plants mature and/or experience periods of dry conditions. In the case of the control sites, seven-year average VWC across the full 30-inch soil profile was below the median point for initiating irrigation and fell below PWP at 30 inches.

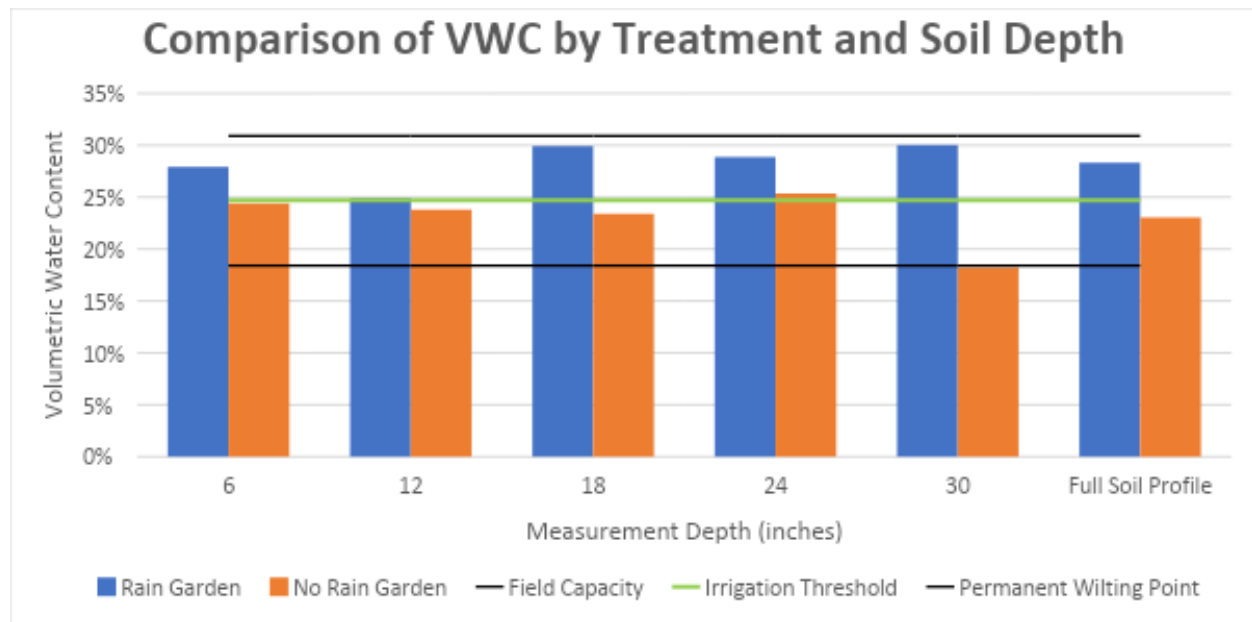


Figure 3. Average VWC by depth and treatment over seven years. Field capacity (top black line), recommended irrigation threshold for a clay loam soil texture (green line), and permanent wilting point (bottom black line) are represented for comparison. Rain gardens resulted in significantly higher VWC than controls across the full 30-inch profile and at each corresponding depth except at 12 inches.

Increases in VWC found in rain gardens could lead to improved growing conditions for plants, but the changes appear to be random across the soil profile when compared to controls. Assuming soil horizons were spatially uniform across the study area, excavating the rain gardens 6 inches in depth prior to implementing soil moisture probes could have resulted in soil probes being located in disparate soil textures from the control sites (i.e. the rain garden probes inserted 6 inches below the soil surface in basins already excavated 6 inches would lead to that probe being closer to 12 inches deep in control areas). Comparisons of soil moisture probes offset by depth and overlaid on a diagram with a typical Alire loam soil profile resulted in more symmetrical VWC lines as seen in Figure 4. At 24 and 30 inches VWC in rain gardens appears to rapidly diverge/increase compared to controls. In addition to PAWC, this result is also encouraging in the context of vadose zone soil moisture (i.e. groundwater recharge). By maintaining higher antecedent moisture in the soil profile, gravitational movement of water to deeper parts of the soil profile could more easily occur during storm events.

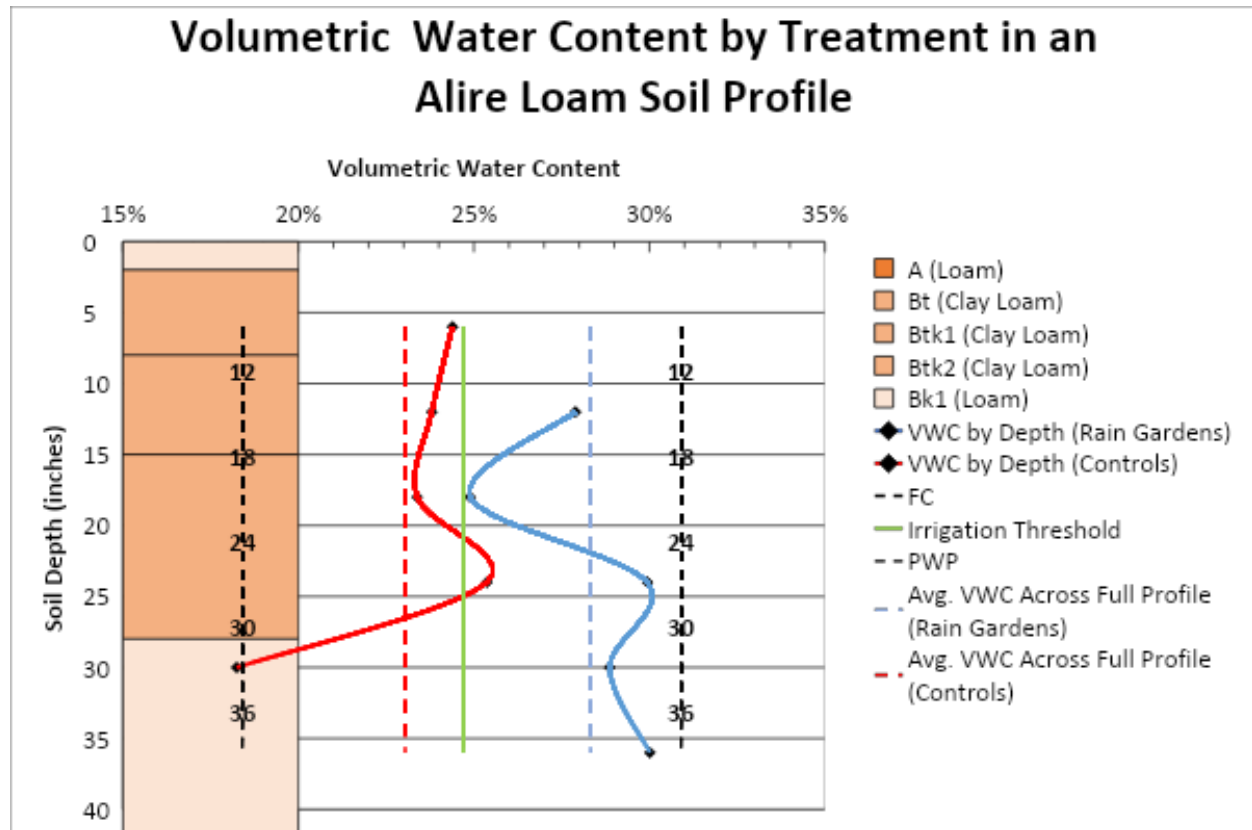


Figure 4. Alire loam soil profile (textures color coded) with average VWC for curb cuts with and without rain gardens. The VWC measurements for rain gardens are based on where the probes would have been placed in the soil profile after 6 inches of excavation.

Volumetric Water Content by Season: The timing and intensity of precipitation as well as evapotranspiration rates are known to differ by season in Santa Fe. Between 1981-2010 average precipitation was highest during the warm summer months of June-August (5.85 inches) and lowest during the cool winter months of December-February (1.96 inches) ([16](#)). This means that some seasons might provide opportunities for soil moisture recharge (e.g. cool or wet months), while others could be periods of soil water depletion (e.g. warm or dry months). As can be seen in the four left-hand columns in Figure 5, seasonal precipitation at the site was below average during all four seasons of the seven-year study (number in parentheses denotes 1981-2010 average precipitation depth in inches from the “Santa Fe 2” weather station).

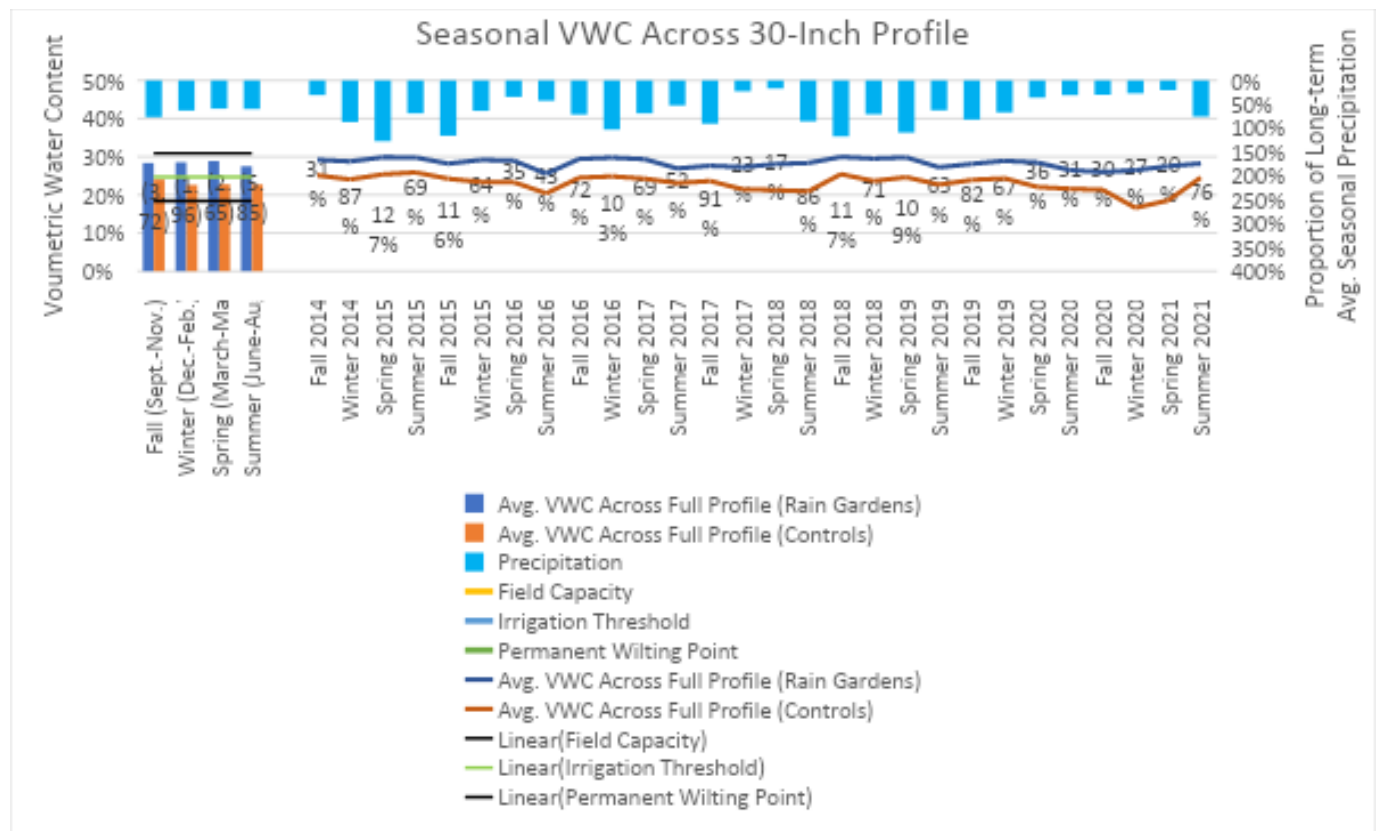


Figure 5. Seasonal fluctuations in VWC for sites with and without rain gardens. Precipitation measurements are based on the percentage of long-term average for each season (i.e. number in parenthesis is in inches from “Santa Fe 2” gauge). Field capacity, irrigation threshold, and permanent wilting point are depicted as the upper, middle, and lower horizontal black and green lines respectively.

Despite the generally drier conditions during the period of study, seasonal VWC averaged across the 30-inch profile in rain gardens was consistently maintained above the irrigation threshold for a clay loam soil while controls were even with or fell below the threshold. By retaining soil moisture close to field capacity in the winter and spring (i.e. periods of plant dormancy or reduced evapotranspiration), it could be argued that rain gardens were replenishing and holding soil moisture prior to periods with increased water losses in summer due to higher temperatures and transpiration rates. Sites without rain gardens failed to maintain seasonal soil moisture levels that might help plants maximize growth potential and might have caused plant stress from insufficient water.

Evidence of differences in VWC by treatment and the benefits of rain gardens is more apparent when individual seasonal fluctuations are examined. During the study, there were only five (18%) 3-month seasonal periods when precipitation was equal or above the long-term average, however average VWC across the 30-inch profile in the rain gardens never dipped below the irrigation threshold. There were only five out of 28 seasonal blocks when soil moisture in the profile met or exceeded the irrigation threshold at sites without rain gardens.

Daily Volumetric Water Content Fluctuations and Response to Precipitation Events: As noted in Figure 3, VWC across the 30-inch profiles over seven years was 28.3% in rain gardens and 23.0% in controls. These soil moisture levels would not have remained static, however. Instead, the timing and magnitude

of precipitation events likely influenced stormwater runoff and soil moisture replenishment. Over the course of study there were 498 dates with measurable precipitation ranging from 0.01-1.76 inches. Daily VWC and corresponding precipitation depth was plotted during the seven-year period in Figure 6 to better understand the extremes of soil moisture replenishment and depletion during and between storm events. Table 1 adds clarity to the spikes and dips by highlighting the percentage of time that soils were below PWP and the irrigation threshold, as well as above field capacity.

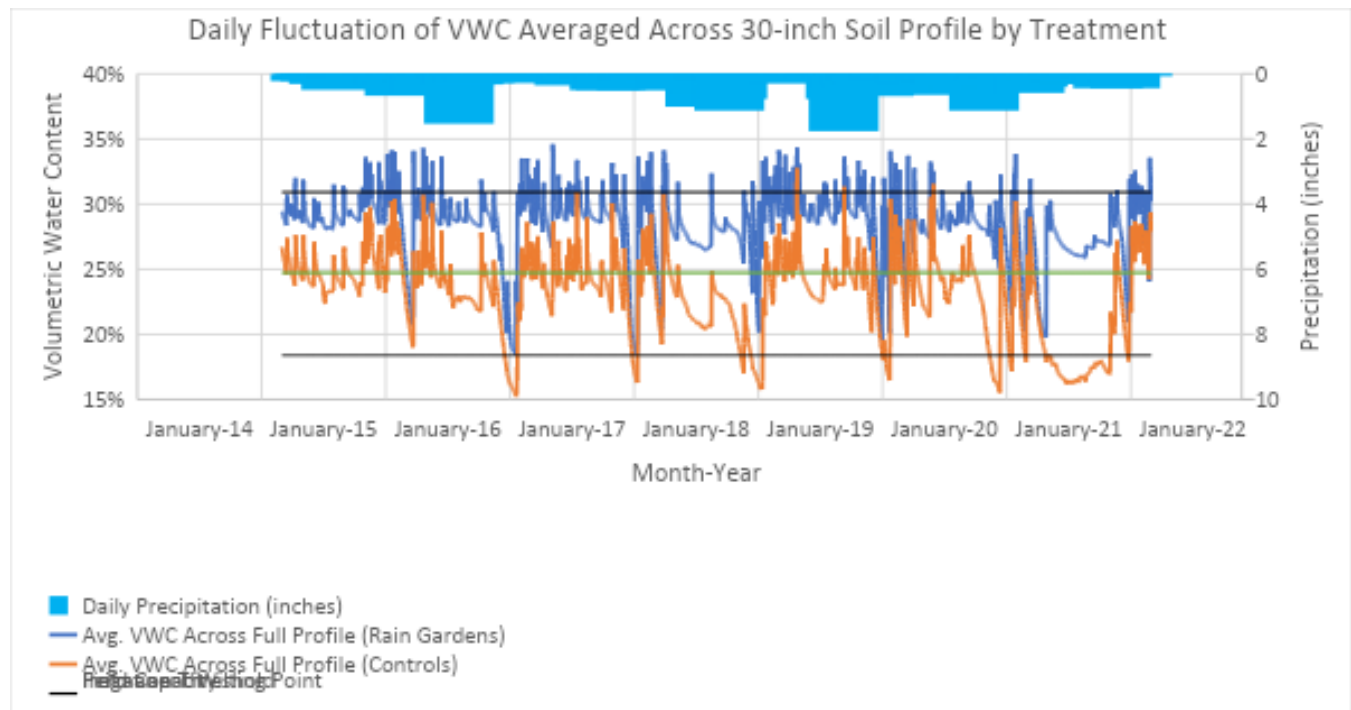


Figure 6. Daily precipitation and corresponding volumetric water content averaged across the 30-inch soil profiles over seven years for each treatment. Field capacity, irrigation threshold, and permanent wilting point are depicted as the upper, middle, and lower horizontal black and green lines respectively.

Soil moisture replenishment in rain gardens was remarkably better than sites without stormwater catchment basins. There were 224 days in which average VWC in rain gardens exceeded field capacity across the 30-inch profile versus only four days at the control sites. Of the 224 days during which VWC reached saturation, 166 days (74%) had a corresponding precipitation event. This outcome indicates that 166 out of the 498 total measured storm events (33%) contributed to the replenishment of soil moisture in the rain garden soil profile. Of storm events that resulted in field capacity being exceeded in rain gardens, the average storm depth was 0.19 inches. The average depth was as low as 0.18 inches in the winter and summer and as high as 0.28 inches in the fall. The regularity with which rain garden soil profiles exceeded field capacity compared to controls is probably a result of increased infiltration from ponding runoff as well as maintaining higher antecedent moisture in the profile between storms. Infiltration in rain gardens might also have been aided by better soil porosity due to deeper rooted shrubs and trees as well as improved soil structure from decomposed wood mulch. Reasons for smaller storm depths achieving saturation in rain gardens for summer and winter storms compared to spring and fall events is unknown. The differences could be a consequence of higher intensity precipitation easily discharged off impervious surfaces in summer and reduced evapotranspiration during cold months helping to maintain higher antecedent soil moisture. Average storm depth among the four storms (i.e. less than 1% of all storms) that caused saturation at control sites was 0.40 inches.

Table 1. Volumetric water content (averaged across the 30-inch profile) and storm events resulting in saturation over the course of study including dips below irrigation and permanent wilting point thresholds as well as above field capacity.

Season	Total Days During Study	Percent of Days Below Permanent Wilting Point		Percent of Days Below Irrigation Threshold		Percent of Days Above Field Capacity (i.e. Saturation)		Storm Events Resulting in Saturation Across Rain Garden Profile	
		Rain Gardens	Controls	Rain Gardens	Controls	Rain Gardens	Controls	Number of Storms	Average Storm Depth (inch)
Fall	637	0.0%	5.8%	12.1%	58.2%	9.6%	0.3%	45	0.28
Winter	632	0.0%	14.2%	0.0%	83.4%	4.0%	0.2%	19	0.18
Spring	644	0.0%	14.4%	0.0%	74.1%	7.0%	0.2%	33	0.20
Summer	644	0.0%	20.3%	22.4%	57.9%	14.4%	0.0%	69	0.18
Total	2557	0.0%	13.7%	8.6%	68.4%	8.8%	0.2%	166	0.19

During 2,557 days of monitoring, daily VWC averaged across the 30-inch profile in rain gardens fell below the irrigation threshold 9% of the time compared to 68% at sites without rain gardens. Rain gardens held VWC above the irrigation threshold throughout each winter (December-February) and spring (March-May) meaning soil moisture was replenished or retained at a level where plants could utilize the water as they emerged from dormancy. VWC in controls during those same seasons was consistently below the irrigation threshold (83% and 74% of days respectively). Soil moisture in rain gardens fell below the irrigation threshold during 22% of summer days (June-August) and 12% of fall days (September-November), possibly due to warmer and drier conditions with higher evapotranspiration rates. Control sites amounted to substantially more time below the irrigation threshold for comparative growing seasons including 58% of summer and fall days.

Deeper rooted shrubs and trees might be tolerant of periods when VWC falls below the irrigation threshold, but soil moisture depletion near permanent wilting point could compromise vegetation health and survival. Over the course of seven years there were ten occurrences during which there was no measurable precipitation at the site for at least 28 consecutive days (Table 2). By the end of each dry period, VWC averaged across the 30-inch profile for rain gardens only fell below the irrigation threshold three times and never dipped below permanent wilting point. In fact, VWC averaged across the 30-inch profile in rain gardens never reached or fell below PWP for a clay loam soil at any point during the seven-year study. At control sites, average VWC over the same profile depth at the end of the ten dry periods was always below the irrigation threshold and reached or fell below PWP four times. Soil moisture at sites without rain gardens equaled or fell below PWP 14% of the seven-year period of study, including 20% of days in summer. The last year of the study was particularly dry. Subsequent to the summer of 2020, which was the third driest summer in Santa Fe on record ([23](#)), VWC plunged at or below PWP 53% of the time at control sites from September 2020-August 2021 (Figure 6).

Table 2. Periods with at least 28 consecutive days without measurable precipitation and corresponding VWC across the 30-inch profiles for treatments and controls.

Beginning date without measurable precipitation	Ending date without measurable precipitation	Total consecutive days without measurable precipitation	Rain garden VWC at end of period without precipitation	Control VWC at end of period without precipitation
3/21/2015	4/17/2015	28	28.7%	22.9%
2/25/2016	4/7/2016	43	28.3%	21.8%
6/8/2017	7/5/2017	28	18.8%	16.9%
10/7/2017	11/6/2017	31	27.2%	22.8%
11/9/2017	1/9/2018	62	26.9%	20.9%
1/11/2018	2/10/2018	31	26.8%	20.7%
3/29/2018	5/1/2018	34	27.8%	19.9%
7/29/2020	8/26/2020	29	20.2%	18.3%
9/11/2020	10/24/2020	44	19.9%	18.4%
3/18/2021	4/28/2021	42	26.9%	17.1%

As evidenced by the enhanced and sustained improvements to soil moisture by rain gardens, semi-arid municipalities might be able to reduce the costs of irrigation by capturing stormwater runoff. In Santa Fe, treated water is often used to irrigate trees along streets and parking lots at a cost of \$0.02/gallon even though lower quality water (e.g. stormwater runoff) would suffice in many situations. The city irrigates trees in street medians with two 5-gallon/hr emitters twice per week for four hours during establishment and four hours every two weeks as they become older (personal communication). This would amount to \$6.40/tree/month and \$1.60/tree/month respectively. Once trees are established, they are irrigated manually if soil moisture drops below 23%; a value that might occur with regularity given the general absence of curb cuts along streets or medians to provide added passive irrigation. In contrast, each curb cut at the study site would drain roughly \$495/yr of equivalent water volume into a rain garden (i.e. 24,750 gallons/year x \$0.02/gallon). When considering the elevated VWC in rain gardens, even during periods of drought (Table 2), it becomes clear that the potential economic savings in irrigation costs to urban trees from rain gardens could be substantial. Based on earlier results from the SFCC study site, Santa Fe Public Schools and the City of Santa Fe Parks Department have started retrofitting parking spaces as rain gardens with comparable catchment volumes and areas of contributing runoff. Tree growth and health, as well as soil moisture are being monitored at one of the retrofitted sites for future comparison with drip irrigated vegetation at a nearby location.

Conclusion

Many communities have adopted rain gardens to reduce runoff and remediate stormwater pollutants. In semi-arid communities, rain gardens could also play a critical role in providing passive irrigation for roadside vegetation including urban trees. The degree to which soil moisture can be improved and sustained in rain gardens located in semiarid regions is understudied. In Santa Fe, New Mexico volumetric water content measured near curb cuts with rain gardens over seven years was found to be significantly higher at four out of five depths compared to soil profiles at curb cut sites without rain gardens. Despite periods of drought, VWC in rain gardens rarely fell below an irrigation threshold for a clay loam soil and never reached permanent wilting point. Average soil moisture measured across the

30-inch soil profile in rain gardens was also replenished to the point of saturation during 33% of storm events. The ease with which rain gardens refilled and maintained soil moisture bodes well for sustaining urban trees and offsetting irrigation costs in semi-arid climates with limited water resources.

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References

1. Dwyer, J.F.; McPherson, E.G.; Schroeder, H.W.; Rowntree, R.A. Assessing the benefits and costs of the urban forest. *Journal of Arboriculture*. **1992**, 18(5): 227-234.
2. Halverson, H. G.; Heisler, G. M. *Soil temperatures under urban trees and asphalt*. Research Paper NE-481; USDA Forest Service, Northeastern Forest Experiment Station: Broomall, PA, 1981; https://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/scanned/OCR/ne_rp481.pdf
3. Armson, D.; Rahman, M.A.; Ennos, R. A Comparison of the shading effectiveness of five different street tree species in Manchester, UK. *Journal of Arboriculture*. **2013**, 39(4). 157–164.
4. Nowak, D. J.; Greenfield, E. J.; Hoehn, R. E.; and Lapoint, E. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution*. **2013**, 178: 229-236.
5. Wolf, K. L. Business district streetscapes, trees and consumer response. *Journal of Forestry*. **2005**, 103(8):396-400.
6. Nowak, D. J.; Crane, D. E.; Dwyer, J. F. Compensatory value of urban trees in the United States. *Journal of Arboriculture*. **2002**, 28(4). 194-199.
7. Nowak, D. J.; Greenfield, E. J. Tree and impervious cover change in U.S. cities. *Urban Forestry & Urban Greening*. **2012**, 11(1): 21-30.
8. *Stormwater Trees*. Technical Memorandum. Great Lakes Restoration Initiative, US EPA-Great Lakes National Program Office; Chicago, IL, 2016;

https://www.epa.gov/sites/production/files/2016-11/documents/final_stormwater_trees_technical_memo_508.pdf

9. Halverson, H. G., Potts, D. F. 1981. *Water requirements of honeylocust (Gleditsia triacanthos f. inermis) in the urban forest*. Research Paper. NE-487; USDA Forest Service, Northeastern Forest Experiment Station: Broomall, PA, 1981;

https://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/scanned/OCR/ne_rp487.pdf

10. Lindsey, P.; Bassuk, N. Redesigning the urban forest from the ground below: A new approach to specifying adequate soil volumes for street trees. *Arboricultural Journal*. **1992**, 16, 25-39.

11. Pataki, D. E.; McCarty, H. R.; Litvak, E.; Pincetl, S. Transpiration of urban forests in the Los Angeles metropolitan area. *Ecological Applications*. **2001**, 21(3): 661-677.

12. Why you should consider Green Stormwater Infrastructure for your community. Environmental Protection Agency;

<https://www.epa.gov/G3/why-you-should-consider-green-stormwater-infrastructure-your-community>

13. Soak up the rain: Rain gardens. Environmental Protection Agency;

<https://www.epa.gov/soakuptherain/soak-rain-rain-gardens>

14. Luketich, A. M.; Papuga, S. A.; Crimmins, M. A. Ecohydrology of urban trees under passive and active irrigation in a semiarid city. *PLoS ONE*. **2019**, 14(11):e0224804

15. Kauffman, A. T.; Stropki, C. L.; Mundt, A. V. Stormwater irrigation: A comparison of soil moisture at curb cuts with and without rain gardens. *Stormwater: The Journal for Surface Water Quality Professionals*. **2017**, 18(3): 24-27.

16. US Climate Data, 1981–2010;

www.usclimatedata.com/climate/santa-fe/new-mexico/united-states/usnm0292

17. Elias, E. H.; Rango, A.; Steele, C. M.; Mejia, J. F.; Smith, R. Assessing climate change impacts on water availability of snowmelt-dominated basins of the Upper Rio Grande basin. *Journal of Hydrology: Regional Studies*. **2015**, 3. 525-546.

18. Rango, A. Snow: The real water supply for the Rio Grande basin. *New Mexico Journal of Science*. **2016**, 44: 99-118.

19. City of Santa Fe;

https://www.santafenm.gov/water_rates

20. USDA Natural Resources Conservation Service Web Soil Survey;

<http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>

21. Ratliff, L. F.; Ritchie, J. T.; Cassel, D. K. Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Science Society of America Journal*. **1983**, 47(4): 770–75.

22. Pavao-Zuckerman, M. A.; Sookhdeo, C. Nematode community response to green infrastructure design in a semiarid city. *Journal of Environmental Quality*. **2017**, 46: 687-694.

23. 2020 marked the City's third driest summer. Santa Fe New Mexican;
https://www.santafenewmexican.com/news/local_news/2020-marked-citys-third-driest-summer/article_806866d6-04d9-11eb-b6dd-0b014e8b84eb.html

Disclosures

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