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PULSES OF WIND AND WATER IN CALIFORNIA'S DESERTS: AN EXAMINATION OF PRECIPITATION PULSE DYNAMICS OF PHOTOSYNTHESIS IN YUCCA BREVIFOLIA (ENGLM.) AND DUST STORMS IN THE SALTON SEA REGION

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by

Daniel Oren Hastings

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ABSTRACT

PULSES OF WIND AND WATER IN CALIFORNIA'S DESERTS: AN EXAMINATION OF PRECIPITATION PULSE DYNAMICS OF PHOTOSYNTHESIS IN YUCCA BREVIFOLIA (ENGLM.) AND DUST STORMS IN THE SALTON SEA REGION

Daniel Oren Hastings

Many ecological phenomena occur in response to pulses. In desert ecosystems, pulses of moisture drive many ecosystem processes, and without this moisture, pulses of wind can lead to large pulses of dust. These pulses can have different effects depending on antecedent conditions. The first two chapters concern the long-, medium- and short-term effects of soil moisture pulses on the health of the Western Joshua Tree (*Yucca brevifolia* Engelm.), a foundational and landmark species of the Mojave Desert. The species has been protected under California's Western Joshua Tree Protection Act. Joshua trees face an uncertain future because of climate change, extreme drought, invasive species, and wildland fire. I found that Joshua trees in the field can respond to precipitation events within a few days even at the hottest and driest time of the year, however, the magnitude of their response is related to the amount of water received in the previous winter. In greenhouse experiments, I found that medium-term changes to the antecedent water conditions of Joshua trees affected their photosynthetic upregulation following rehydration. These experiments show that Joshua trees can quickly respond to summer water pulses, which could open the door to more effective adaptive management of this climate-sensitive iconic species in the face of climate change. Next, I review the effects of pulses of wind and dust on human communities living near the Salton Sea. I analyzed regional air quality and health data and found that there is not yet evidence that the exposed lakebed of the shrinking sea is the major source of particulate matter pollution in the region. Finally, I provide recommendations about how to mitigate the threat of dust to communities in the region.

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Chapter 1

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INTRODUCTION

Pulses are a convenient way of conceptualizing transient phenomena in ecological systems. Pulses have been defined as "occasional and brief events of dramatically increased resource availability" (Yang & Naeem, 2008, p. 619). Fires in forest systems can cause a pulse of nutrients in soils that lead to a pulse in plant growth and the sudden addition of heat and smoke can cause many plant species to germinate. The emergence of millions of cicadas can lead to a pulse of nutrients in soils as the insects complete their life cycles. In marine systems, temporary changes in ocean currents can cause upwelling events that lead to massive algal blooms.

Being resource poor, deserts are particularly pulse driven systems, with many ecological phenomena tied to pulses of moisture as opposed to seasonal rhythms. As rainfall is sporadic in the desert, it is more like a pulse than in systems where rainfall is more regular. In the dry desert, many soils are easily aerosolized by occasional powerful windstorms, causing large dust storms. This movement of sediment affects plant, animal and soil communities, and the human communities that live in their vicinity.

The first two chapters of this dissertation focus on the physiology of Joshua trees in response to pulses of water, the first in the field, the second in the greenhouse. The third chapter concerns the air quality in the Salton Sea region and the dust storms that cause PM_{10} pollution in the area. These pulses shape the human and ecological communities in California's deserts.

CHAPTER 1: SUMMER PRECIPITATION PULSE RESPONSE VARIES WITH ANTECEDENT WATER CONDITIONS IN WESTERN JOSHUA TREE (*YUCCA BREVIFOLIA* ENGLM.)

Abstract:

The western Joshua tree (*Yucca brevifolia* Englm.) is a culturally and ecologically important species of the Mojave Desert that is threatened by climate change. The North American summer monsoon provides rainfall during an otherwise dry period, and some scenarios envision a 40% decrease in monsoon rainfall by 2100. We used summer water additions and the record-setting storm, Tropical Storm Hilary, to address the following questions: 1) Can Joshua trees use summer water pulses to improve water status, photosystem health, and carbon gain? and 2) Do antecedent water conditions impact pre-watering physiology? Measurement campaigns occurred in August of 2021 and 2023, which were dry (53 mm precipitation) and wet (383 mm precipitation) water years respectively. We measured leaf water potential, photosynthetic gas exchange, and chlorophyll *a* fluorescence of Joshua trees near Pioneertown, CA. Net leaf level CO_2 assimilation (A_{net}) for *Y. brevifolia* saw an average increase of 1.7 µmol CO_2 m^{-2} s^{-1} five days after the precipitation pulse in 2023, showing that Joshua trees can upregulate photosynthesis in response to summer precipitation. Stomatal conductance to water vapor increased in both years, by 80% in 2021 and by 500% in 2023. Results show that some but not all aspects of photosynthesis were upregulated by *Yucca brevifolia* following summer pulses in both dry and wet years. Pre-watering differences between years for five out of six measured parameters show ecological memory of antecedent precipitation conditions. Predicted decreases in monsoon rainfall may influence future summertime carbon gain by Joshua trees in the Mojave Desert.

KEYWORDS: chlorophyll fluorescence, photosynthesis, gas exchange, water potential, Mojave Desert

Introduction

In arid landscapes, precipitation occurs as distinct pulses (Noy-Meir, 1973), by contrast to more hydric systems where rainfall frequently occurs. Pulse size generally determines the degree of the ecological response, but some magnitudes of precipitation are not biologically significant (Ogle & Reynolds, 2004; Reynolds et al., 2004). In arid systems, like the Mojave Desert, pulses of biologically significant soil moisture may be months apart (Western Regional Climate Center). As a result, plants will employ various strategies to weather the dry months. At first, photosynthesis will be limited by stomatal closure, but after a time limitation will shift to other processes (Limousin et al., 2010), such as root shedding (Brunner et al., 2015), decreased production of the D1 protein leading to breakdown in PSII (Giardi et al., 1996), negative effects of reactive oxygen species on photochemistry (Muhammad et al., 2021), buildup of abscisic acid impeding the opening of stomata (Daszkowska-Golec & Szarejko, 2013). Once rainfall returns, wet soils lead to growth of root hairs and upregulation of photosynthetic enzymes (Chadha et al., 2018). Many of these processes require some time to unwind, so plants may be less responsive to soil moisture pulses following longer periods of dry conditions than shorter ones.

Although this pulse-dynamics model (Collins et al., 2014) captures the large-scale dynamics of arid systems, individual soil moisture pulses do not fully account for the effect of prior soil moisture conditions on physiological processes in plants. A better model would consider prior soil wetting events and their magnitude and temporal pattern (Reynolds et al., 2004). Ecological memory is a term that describes the effect of prior conditions on plant responses to current conditions (Ogle et al., 2015; Padisak, 1992). This memory can have different qualities such as length, temporal pattern and strength of the effect (Ogle et al., 2015). A large magnitude soil moisture pulse may have different effects on a plant that had been in dry conditions for six months than on one that had been dry for only a week. Likewise, a series of small moisture pulses may have a different effect than one large pulse of the same volume (Loik et al., 2004; Reynolds et al., 2004; Schwinning & Sala, 2004). It is currently unclear how widespread ecological memory is across plant species that are native to highly pulsed precipitation environments. Moreover, there is little known about the role of antecedent conditions on plant survival of drought as climate change makes meteorological variability more pronounced.

Climate change will possibly lead to increases in temperature of 4 to 7 °C by 2100 (Hopkins, 2018), and alter the timing and magnitude of precipitation events in the Mojave Desert. Precipitation during the winter months is likely to become more variable, with a higher frequency of very large events, but also higher frequency of drought. Summer precipitation in the Mojave Desert is typically delivered from the North American Monsoon pattern and may decrease by 40% (Hopkins, 2018). Summer rain follows a period of at least 4 months of little-to-no precipitation (Western Regional Climate Center). This combination of higher temperatures and lower rainfall leads to droughts that are more difficult for plants to withstand (Allen et al., 2010; K. E. King et al., 2024). Many species in the Mojave Desert use summer precipitation to alleviate water stress, and as the climate changes plant reliance on summer rainfall may increase (Snyder et al., 2004).

The Mojave Desert is home to the iconic western Joshua Tree (*Yucca brevifolia* Englm.), which faces threats from development, a changed wildfire regime due to invasive plants, and climate changes (Wilkening et al., 2020). The Joshua tree is a woody monocot with rosettes of spine-tipped evergreen semi-succulent leaves at the end of each branch (Lenz, 2007). The leafy part of the branch is typically 50-100 cm in length. Full-grown trees are typically 6 - 9 m tall (Baldwin et al., 2012), making them often the tallest plant on the landscape. The roots are believed to be broad and shallow, although evidence remains anecdotal (Bowns, 1973). Like other narrow-leafed yucca species (Kemp & Gardetto, 1982), they use the C3 photosynthetic pathway (Smith et al., 1983). The average Joshua tree lives about 100 years, and their maximum longevity is about 400 years (Gilliland et al., 2006).

The largest threat to Joshua trees is climate change. In the late Pleistocene, the Joshua trees' range extended south to the Gulf of California (Cole et al., 2011). Warming at the start of the Holocene caused the range of Joshua trees to contract from the south to its current boundaries, but there was no concurrent expansion to the north (Cole et al., 2011). A series of models of future Joshua tree distribution suggest that they may be extirpated from Joshua Tree National Park (JOTR) by 2100, except for small refugia (Barrows & Murphy-Mariscal, 2012; Cole et al., 2011; Dole et al., 2003; Shafer et al., 2001; Sweet et al., 2019). Decreased recruitment has been observed in the southern areas of JOTR for the past 20 years (Cole et al., 2011; DeFalco et al., 2010; Sweet et al., 2019). While Joshua trees are estimated to uptake the majority of their yearly carbon between January and May (Smith et al., 1983), it is not known if Joshua trees try to take advantage of summer precipitation pulses to decrease water stress, as many Mojave Desert shrubs do (Snyder et al., 2004).

This research seeks to understand the effect of summer water pulses and antecedent conditions on Joshua tree photosynthesis using a water addition experiment and taking advantage of a record-setting storm, Tropical Storm Hilary, the largest storm summer storm in 80 years. Specifically, we address the following questions:

1. Do Joshua trees take advantage of summer soil moisture pulses by upregulating photosynthesis?

2. Is the baseline level of photosynthesis of Joshua trees in summer affected by antecedent water conditions?

Methods

Field Site

Field experiments were conducted at Burns Pinon Ridge UC Natural Reserve located approximately 2 km north of Yucca Valley, California (34° 9’ N, 116° 27’ W) at approximately 1200 m elevation (Figure 1). Vegetation is predominantly *Yucca brevifolia* Woodland Alliance (Sawyer et al., 2008), with *Lycium* spp., *Erioginum* *fasciculatum, Pinus monophylla*, *Juniperus californica*, Cylindropuntia *echinocarpa*, *Cercocarpus betuloides*, *Prunus* spp., *Coleogyne ramosissima*, *Ephedra californica*, *Yucca schidigera*. The site has a granite-origin xerorthent coarse loam soil (California Soil Resources Lab, n.d.).

Figure 1: The field site at Burns Pinon Ridge Reserve (indicated with a star) near Pioneertown, California, USA. 34° 9' N, 116° 27' W. Elevation 1200 m.

Meteorological Measurements

Air temperature, rainfall, photosynthetically active radiation (photon flux density), and soil moisture data were collected from the University of California Natural Reserve System meteorological station at Burns Pinon Ridge (data access and equipment specifications available at www.dendra.science). Historical climate data were acquired from the Western Regional Climate Center (data available at https://wrcc.dri.edu/).

Plants

Ten unbranched Joshua trees between 0.4 m and 2 m tall were selected in pairs based on similar slope, aspect, soil type, and plant size. The plants grow in a generally flat alluvial plain between two hills with a deep sandy soil. For plants used in photosynthetic measurements, an individual leaf was haphazardly selected on the west side of each plant at chest height. Leaves of Joshua trees stay green for at least 4 years (Smith et al., 1983), so the leaves of each plant were marked with a non-toxic permanent marker (Sharpie; Newell Brands, Atlanta, GA) for return visits. Leaf length ranged from 18-27 cm.

Experimental Design

In August 2021, one plant of each pair was randomly assigned to be watered with a 10 mm pulse of water applied to a 1 m radius around each plant. The 10 mm pulse magnitude was chosen to approximate the average precipitation pulse (8.5 mm) for the months July, August and September at Kee Ranch in Pioneertown, California (approximately 3 km from the field site) for the period 1948-1979 (Western Regional Climate Center).

On August 20 - 21, 2023, Tropical Storm Hilary traversed southern California, the first Pacific cyclone to arrive in the mainland US since 1939. The storm brought extreme rain and wind to southern California and Baja California, with some areas receiving an entire year's average rainfall in one day (Cangialosi & Berg, 2024). Burns Pinon Ridge Reserve received 83 mm of rainfall from this storm. All plants were measured before and after the storm, and no additional water pulse was added.

Soil Moisture

Soil moisture was measured as volumetric water content for five plants at depths of five cm and 25 cm using horizontally inserted dielectric soil moisture probes (EC-5 and 5TM sensors, Meter Group Inc., Pullman, WA). These probes are 5 cm long and have a 200 mL soil measurement volume. The data were averaged every 15 minutes in a data logger (Zentra ZL-6, Meter Group Inc., Pullman, WA).

Leaf Water Potential

In 2021, leaves from each of the plants were collected between 08:00 and 09:00 h. The leaf samples were 8 – 12 cm long and were clipped from the east side of each plant and then immediately wrapped in Parafilm, put in a Ziplock bag, and placed in a cooler until used in measurements, usually after about 30 minutes. Water potential was measured using a Scholander-type pressure chamber (PMS Instrument

Company, Albany, OR) with a modified stopper for accommodating the shape of the Joshua tree leaves.

In 2023, the samples were collected in the same manner, then taken to the refrigerator in the field station and removed one by one to be measured. The epidermis of each sample was removed just prior to measurement, the tissues shredded longitudinally with a razor blade and put into a steel sample cup of a dewpoint potentiometer (WP4 and WP4C, Meter Group, Pullman, WA). The steel sample cups were filled halfway with paraffin wax to decrease the air volume in the chamber to decrease equilibration time. Measurements were taken on a continual basis until they achieved stability, usually 45 to 75 mins (Baer, 2018; Baer et al., 2021). All samples were measured the same day they were collected.

Photosynthetic Gas Exchange

In 2021, photosynthetic gas exchange measurements were made between 06:00 and 08:00 h each day for six days. The measurements started on the morning of August 15, 2021, and the 10 mm water pulse was applied that afternoon. The last measurement was on the morning of August 20, 2021. Gas exchange measurements were made using an open-path portable photosynthesis system (LI-COR LI-6400 portable photosynthesis, LI-COR, Lincoln, NE) at 415 ppm CO_2 concentration with a light source (6400-02B LED) emitting 1500 μmol photons m^{-2} s^{-1} photosynthetically active radiation in a 2 cm by 3 cm chamber. The instrument was allowed to warm up for 30 minutes prior to sampling, then infrared gas analyzer zeros were checked and calibrated. After closing the leaf chamber on the leaf, a non-toxic poster putty (Blu-Tack; Bostik Company, Wauwatosa, WI) was put over air gaps in the gasket material, as per manufacturer recommendation, to ensure there was no leakage due to the irregular shape of Joshua tree leaves. The infrared gas analyzers were then matched at every plant with the same flow of air prior to making measurements. Data were logged three times on each leaf three seconds apart after the measurements had attained stability, and the mean of those measurements was used in analysis. Measurements were taken on the same leaf on the west side of each plant at each sampling time.

In 2023, photosynthetic gas exchange measurements of ten plants were taken every day from August 16-25 between 07:00 and 08:00 h and between 21:00 and 22:00 h, except for days when it was not possible due to rain or equipment problems. Thereafter, measurements were taken on alternate days at four different times of day until September 1st, 2023. Gas exchange measurements were also made at six times (04:00, 07:00, 09:00, 12:00, 15:30, and 18:00) during the day three days prior to Tropical Storm Hillary and four days after. Photosynthetic gas exchange measurements in 2023 were made as described above but using an Li-6800 system (LI-COR, Lincoln, NE) with built-in 3 second data averaging.

The leaves of the Joshua trees were nearly flat on top and had a convex V-shaped underside. Leaf area for the gas exchange calculations was independently estimated for each leaf as the area of the top flat side (idealized as a trapezoid), plus the area of two idealized flat panels on the bottom of the leaf (also trapezoids). These measurements were approximated using 2 measurements of leaf width and two measurements of leaf thickness collected ~30 mm apart, which is the length of the leaf chamber used. These were summed and divided by 2 to get an estimate of one-side leaf area.

Chlorophyll *a* Fluorescence

In 2021, daytime chlorophyll *a* fluorescence was measured on August 18th, between 12:30 and 13:00 h. Daytime fluorescence measurements were compared between watered and un-watered plants in pairs.

In 2023, daytime chlorophyll *a* fluorescence measurements in 2023 were made on August 16th prior to the pulse and then every other day from August 21st to 27th between 13:00 and 15:00 h. Pre-dawn chlorophyll *a* fluorescence measurements were taken pre-storm on August 16th, and after the storm pulse on August 22nd and September 1st.

Fluorescence parameters were assessed using a pulse-amplitude-modulated fluorometer (LI-COR LI-6400 Leaf Fluorometer). The effective quantum yield of Photosystem II (PSII) was calculated as:

$$\frac{F_{m'} - F_s}{F_{m'}} = \frac{F}{F_{m'}} = \Phi_{PSII}$$

Where F_m' is the maximal fluorescence of the light-adapted leaf and F_s is the steady-state fluorescence. Dark-adapted chlorophyll fluorescence measurements used a rectangular saturating flash of 5000 µmol photons m^{-2} s^{-1} modulated at 20 kHz with a 50 Hz filter. Measurements were taken at 0.25 kHz modulation with a 1 Hz filter.

The light-adapted maximum quantum yield of PSII (F_v'/F_m') was calculated as:

$$\frac{F_v'}{F_m'} = \frac{F_m' - F_o'}{F_m'}$$

Where F_o' is the minimal fluorescence of the light-adapted leaf.

The dark-adapted maximum quantum yield of (PSII) (F_v/F_m) was calculated as:

$$\frac{F_m - F_o}{F_m} = \frac{F_v}{F_m}$$

Where F_m is the maximal fluorescence of the dark-adapted leaf and F_o is the minimal fluorescence of the dark-adapted leaf. Daytime chlorophyll *a* fluorescence was measured with 1500 µmol photons m^{-2} s^{-1} actinic light. After attaching the instrument to the leaf, fluorescence was allowed to stabilize prior to the flash routine. The saturating flash was 5000 µmol photons m^{-2} s^{-1} modulated at 20kHz with a 50 Hz filter. The fluorescence was measured with a measuring LED intensity of 7 of 10, modulation at 20 kHz, filter of 1 Hz, and a gain factor of 10. The dark phase of the flash was 6 seconds long and used a 0.25 kHz modulation and a 5 Hz filter.

Statistical Analysis

For the question testing the effect of summertime rainfall on Western Joshua tree photosynthesis, two-way analysis of variance (ANOVA) was used with the formula:

$$Y_{ijk} = \mu + \beta_{1Year_i} + \beta_{2Treatment_j} + \epsilon_{ijk}$$

to determine if summer pulses were a significant predictor of the photosynthetic response variable.

For the question testing the effect of antecedent water conditions on pre-pulse photosynthetic rate, Welch's t-test was used to compare the pre-watering parameter levels. Significance was assessed at the level $p < 0.05$. For between-year gas exchange and chlorophyll fluorescence comparisons, five unwatered plants and five watered plants measured on the same day five days after watering were used from 2021 and in 2023 ten plants were measured prior to the storm and five days after the storm.

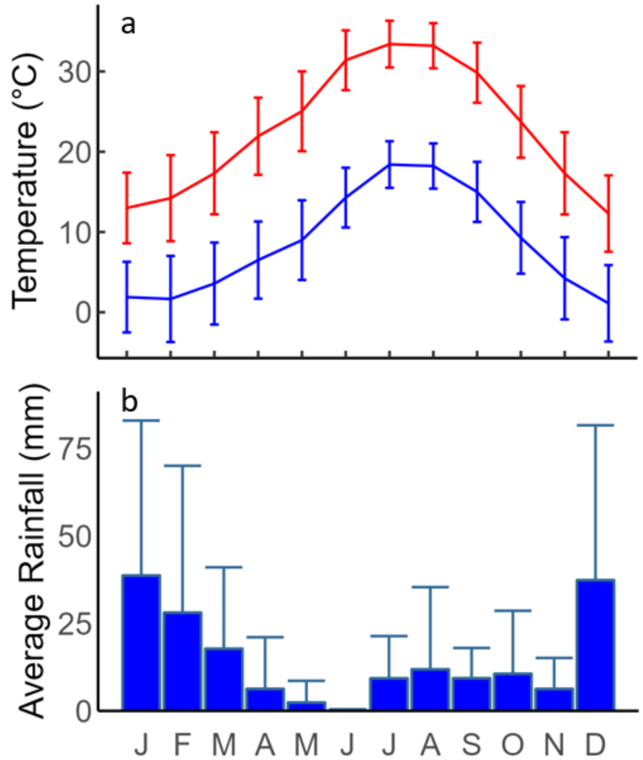

Figure 2: Climate data at Burns Pinon Ridge Reserve from 2010-2023. A) Mean daily minimum (blue) and maximum (red) temperatures in °C and standard deviation. B) Monthly precipitation; data are means and standard deviation.

Results

Climate & Meteorology

Burns Pinon Ridge Reserve had an average annual precipitation of 16.6 ±7.6 cm per year (coefficient of variation = 0.46) for the period 2010-2023. Seventy-eight percent of this precipitation fell in fall and winter, 5% fell in the months April, May, and June, and 17**%** fell in July, August, and September. It rarely rained between March and the end of June (Figure 2). In Water year 2021, 5.3 cm of rain fell on the field site prior to the experiment, whereas in water year 2023 28.8 cm of rain fell on the field site before field sampling (Figure 3). The average maximum temperature in July is 35°C and average minimum temperature in January is -1°C (Western Regional Climate Center**).**

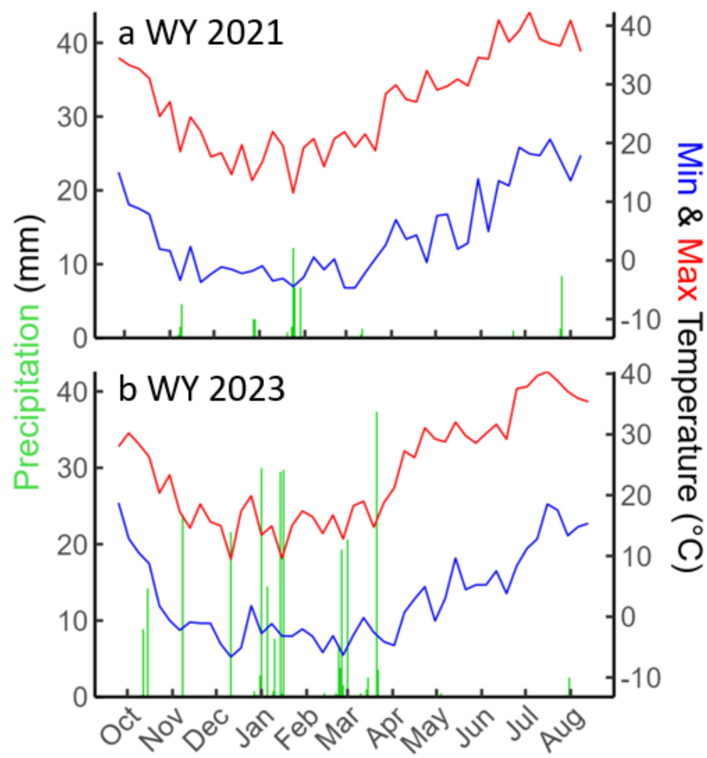

Figure 3:Daily total precipitation (mm, green vertical bars) and mean temperature (red, blue lines, °C) at Burns Pinon Ridge UC Reserve for water years (WY) a) 2021 and b) 2023.

There were 79 precipitation events recorded during the monsoon months of July, August, and September between 2010 and 2023 at the field site (data from DENDRA, www.dendra.science). Of these 79 events, 21% were between 0.1 and 2 mm, 55% were less than 5 mm, 15% were greater than or equal to 5 mm and less than

10 mm, and 29% were more than 10 mm. The mean monsoon precipitation event was 5.9 ±9.6 mm, and the maximum event size was 67 mm.

Tropical Storm Hilary made landfall in Baja California, Mexico on August 20, 2023 at 10:00 h local time and proceeded north, reaching Los Angeles County at 16:00 h (Cangialosi & Berg, 2024) and tracking west of the field site. Tropical Storm Hilary dropped 83 mm of rainfall on Burns Pinon Ridge Reserve over 36 hours. Wind speed had a maximum gust of 20 m/s and an average of 11.5 m/s during the peak of the storm, predominantly from the south.

For the days after the storm, the average daily maximum was 31°C and the average daily minimum temperature was 18°C during the measurement period. During the storm, the daily high temperature fell to 18°C, and then increased back to previous levels of 30°C or higher by August 23, two days afterwards (Figure 3).

Soil Moisture

In 2021, soil volumetric water content (VWC) for unwatered plants averaged 0.017 m^3/m^3 at 5 cm depth and 0.056 m^3/m^3 at 25 cm depth. For the watered plants, the soil volumetric water content at 5 cm depth was 0.079 m^3/m^3 and 0.054 m^3/m^3 at 25 cm depth (Figure 4).

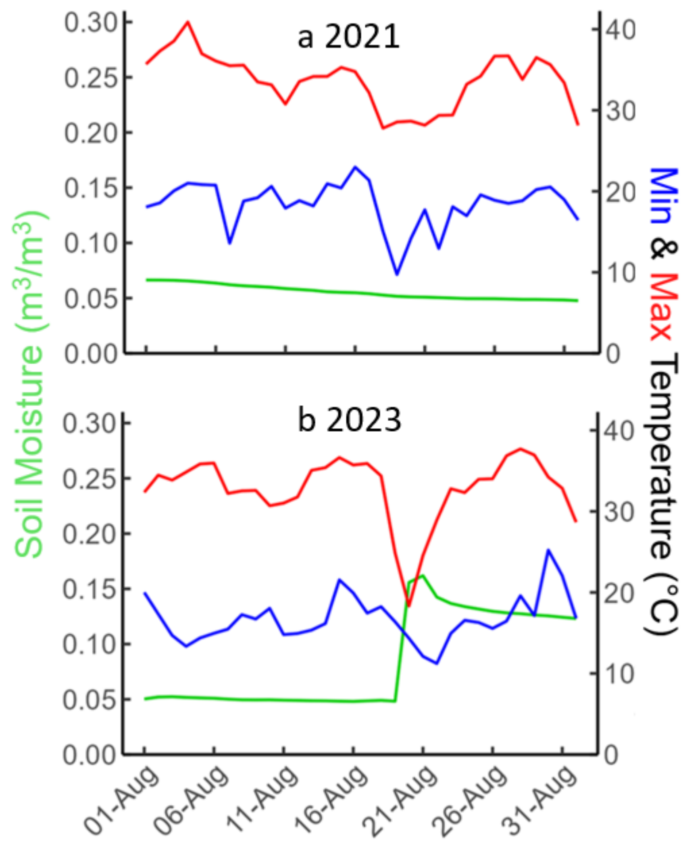

Figure 4: Air temperature and soil moisture at Burns Pinon UC Ridge in August of a) 2021 and b) 2023.

In 2023, soil VWC averaged 0.027 m^3/m^3 at 5 cm depth underneath Joshua trees and 0.063 m^3/m^3 at 25 cm depth before the pulse. The pulse caused a maximum VWC of 0.261 m^3/m^3 at 5 cm depth and 0.334 m^3/m^3 at 25 cm depth. Following the peak, soil moisture settled at an average of 0.121 m^3/m^3 at 5 cm depth and 0.170 m^3/m^3 at 25 cm depth. Soil moisture stayed relatively stable at both depths from the storm to the end of measurements on September 1. Soil moisture sensors detected the effects of this precipitation pulse into October 2023.

Leaf Water Potential

In 2021, leaf water potential (Ψ_{leaf}) ranged from -1.50 MPa to -3.00 MPa. There were no days in which there was a significant difference between the watered and unwatered plants, but there was some day-to-day variability (Figure 5).

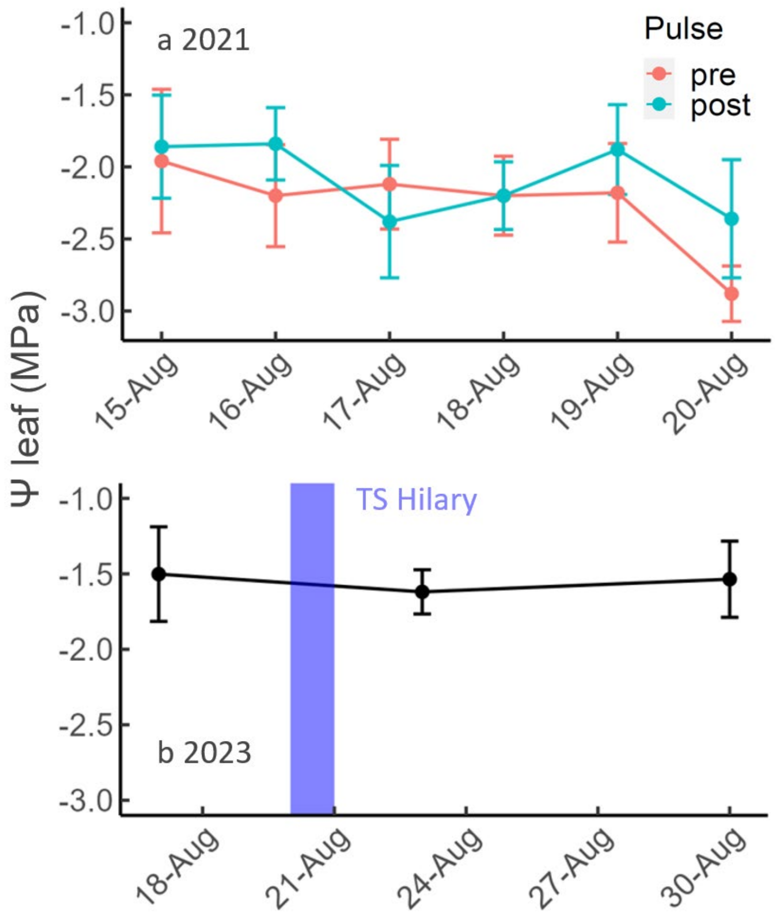

Figure 5: Leaf Water Potential (MPa) from leaves collected at 8 AM. a) 2021 b) 2023.

In 2023, Ψ_{leaf} showed no significant change from pre-storm levels two days or nine days after the storm. Mean Ψ_{leaf} was -1.50 MPa ± 0.087 pre-pulse, -1.62 MPa ± 0.042 two days after the storm, and -1.54 MPa ± 0.076 nine days after the storm.

Combining the two years, there was a small but statistically significant difference in Ψ_{leaf} between the watered and unwatered plants (Table 1; ($\hat{\beta}$ = -0.22 MPa; t = 2.4, p = 0.027). There was also a significant difference in the mean pre-watering Ψ_{leaf} (Table 2; μ1- μ2 = 0.40, t = -2.5, p = 0.02).

Table 1: ANOVA results for response variables using the formula $Y_{ijk}=\mu+\beta_{1iYear}+\beta_{2jTreatment}+\epsilon_{ijk}$, where 2021 is the base level of the factor Year and unwatered is the base level of the factor Treatment. P-values are for the P > |t|. P-values for coefficients statistically significant at the 0.05 level are in bold.

	Intercept (μ)	Effect of Year	Effect of Treatment
	$\hat{\beta}$ (SE) t-value p-value	$\hat{\beta}$ (SE) t-value p-value	$\hat{\beta}$ (SE) t-value p-value
Ψ_{leaf}	-1.97 (±0.086) t = -22.9 **p = 5.96 × 10^{-25}**	0.517 (±0.097) t = -2.3 **p = 3.6 × 10^{-6}**	-0.221(±0.096) t = 5.4 **p = 0.027**
g_s	0.019 (±0.012) t = -1.5 p = 0.14	0.051(±0.013) t = 3.8 **p = 7.00 × 10^{-4}**	0.054 (±0.013) t = 4.3 **p = 2.0 ×10-4**
A_{net}	-0.116 (±0.733) t = -0.2 p = 0.875	1.61 (±0.781) t = 2.1 **p = 0.048**	1.77 (±0.743) t = 2.4 **p = 0.025**
F_v/F_m	0.721 (±0.027) t = 26.5 **p = 2.95 × 10^{-15}**	0.084 (±0.031) t = 0.7 **p = 0.016**	0.232 (±0.031) t = 2.7 p = 0.469
F_v'/F_m'	0.286 (±0.040) t = 7.2 **p = 1.42 × 10^{-6}**	0.048 (±0.046) t = 1.0 p = 0.31	0.16 (±0.046) t = 3.5 **p = 0.0026**
ϕ_{PSII}	0.281 (±0.055) t = 5.2 **p = 7.9 × 10^{-5}**	-0.109 (±0.063) t = -1.7 p = 0.102	0.176 (±0.063) t = 2.8 **p = 0.012**

Table 2: Table of Welch's T-test results comparing 2021 and 2023 pre-watering physiological parameters. P-values for difference in means (μ_1- μ_2) statistically significant at the 0.05 level are in bold. P-values marginally significant are indicated with a period (.).

	Welch's t-test				
	μ_1- μ_2	95% CI Lower	95% CI Upper	t-value	p-value
Ψ_{leaf}	-0.403	-0.740	-0.066	-2.5	**0.022**
g_s	-0.014	-0.030	0.002	-1.9	0.082 **.**
A_{net}	-0.971	-2.773	0.831	-1.1	0.261
F_v/F_m	-0.139	-0.230	-0.048	-3.9	**0.011**
F_v'/F_m'	0.033	-0.073	0.139	0.7	0.491
ϕ_{PSII}	0.264	0.155	0.374	5.7	**0.0007**

Stomatal Conductance

In 2021, mean stomatal conductance to water vapor (g_s) nearly doubled from 0.006 ± 0.003 mol H_2O m^{-2} s^{-1} before water addition to 0.011 ± 0.003 mol H_2O m^{-2} s^{-1} after water addition, although this is a relatively small increase (Figure 6).

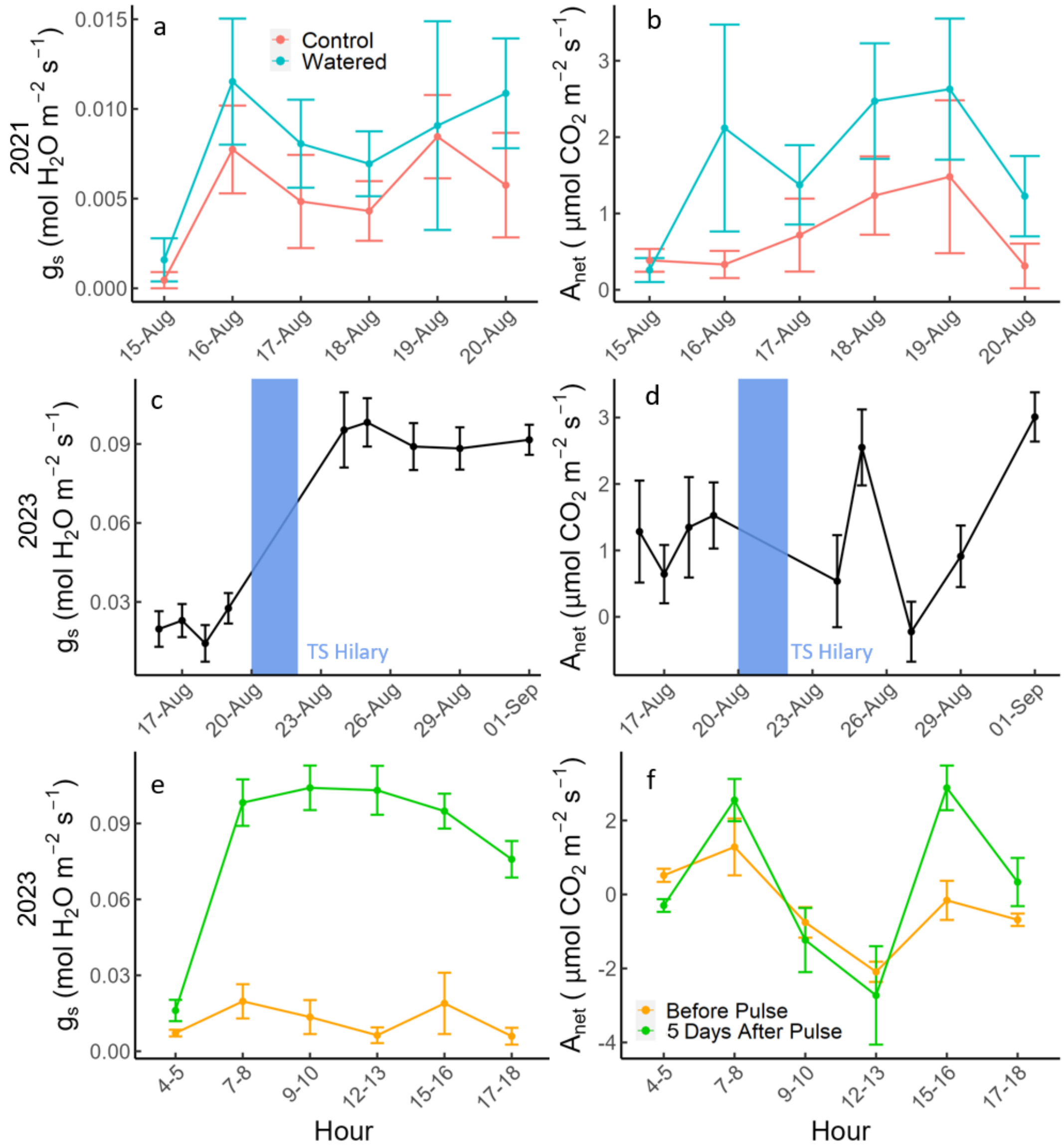

Figure 6: Joshua tree gas exchange response to water additions. a) gs and b) Anet of watered and unwatered plants on August 20, 2021, 5 days after an experimental water addition. c) gs and d) Anet in the three weeks surrounding Tropical Storm Hilary in August 2023. e) g_s and f) A_{net} at different times of day before and 5 days after Tropical Storm Hilary.

In 2023, g_s was elevated between the pre-pulse measurements and the post-pulse measurements at all times of day. Pre-pulse, the mean stomatal conductance during the early morning measurement was 0.020 ± 0.007 mol H_2O m^{-2} s^{-1}, four days after the pulse it was 0.100 ± 0.015 mol H_2O m^{-2} s^{-1}. By nine days after the pulse, stomatal conductance had begun to drop versus the peak level to 0.088 ± 0.008 mol H_2O m^{-2} s^{-1} but was still significantly elevated versus pre-pulse. All times of day followed this pattern.

The response of g_s to watering was significant ($\hat{\beta}$ = 0.054 mol H_2O m^{-2} s^{-1}; t = 2.4, p = 0.0002) across years. The baseline level of g_s in 2023 appears to be higher than in 2021, but this trend was marginally significant (Figure 7; μ_1-μ_2 = -0.014, t = -1.9, p = 0.082). Some pre-dawn stomatal opening was observed for Western Joshua trees.

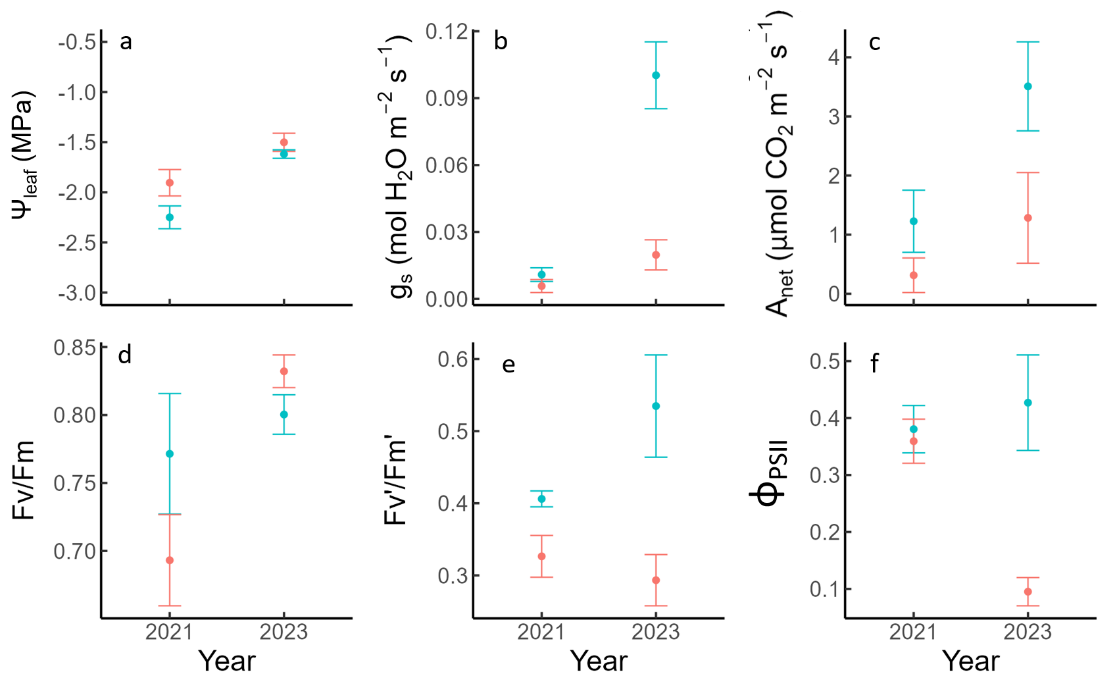

Figure 7:Leaf-level responses of Western Joshua trees to watering in 2021 and 2023. a) Leaf water potential b) net leaf-level CO2 Assimilation c) Stomatal conductance to water vapor, d) maximum quantum efficiency of Photosystem II under dark adapted conditions, e) maximum quantum efficiency of Photosystem II under light-saturated conditions, f) Effective quantum yield of PSII. Data are means ± S.E. (n = 5).

CO_2 Assimilation

In 2021, net leaf-level CO_2 assimilation rate (A_{net}) in the early morning increased after watering. Notably, A_{net} increased from 0.31 ± 0.29 µmol CO_2 m^{-2} s^{-1} to 1.23 ± 0.52 µmol CO_2 m^{-2} s^{-1} after water addition. In 2023, A_{net} in the early morning measurement was higher for post- than pre-pulse measurements, increasing from a mean of 1.28 ± 0.77 µmol CO_2 m^{-2} s^{-1} to 3.51 ± 0.75 µmol CO_2 m^{-2} s^{-1}. The noon, afternoon and evening measurements were all significantly higher than pre-pulse measurements. Nine days after the pulse, the early morning photosynthetic rate had returned to pre-pulse levels, but the late morning, noon, afternoon, and evening measurements all remained significantly elevated over pre-pulse levels.

The pre-watering A_{net} was not significantly different between the years (μ_1-μ_2 = -0.971, t = -1.1, p = 0.26), but there was a positive effect of watering on A_{net} ($\hat{\beta}$ = 1.77 µmol CO_2 m^{-2} s^{-1}; t = 0.025, p = 0.025).

Chlorophyll *a* Fluorescence

In 2021, maximum quantum efficiency at night following several hours of darkness (F_v/F_m) increased from 0.69 ± 0.03 before watering to 0.77 ± 0.04 after watering. In 2023, F_v/F_m was 0.83 ± 0.01 before watering and 0.80 ± 0.01 after watering. There was a statistically significant effect of watering on F_v/F_m, but because the 2023 values are at or approaching the theoretical maximum of 0.83 (Maxwell & Johnson, 2000a), the effect is likely not meaningful. An ANOVA fit on only the 2021 data shows no significant effect of watering on F_v/F_m (μ_1-μ_2 = 0.08, t = -1.4, p = 0.19).

There is a statistically significant difference between the pre-watering means (μ_1-μ_2=-0.14, t = -3.9, $p < 0.05$), indicating slight stress to photosynthetic light processing in 2021 prior to watering.

In 2021, F_v'/F_m' was 0.33 ± 0.03 before watering and 0.40 ± 0.01 after watering. In 2023, F_v'/F_m' was 0.29 ± 0.036 before watering and 0.53 ± 0.07 after watering. There was a statistically significant effect of watering on F_v'/F_m' ($\hat{\beta}$ = 0.16, t = 3.5, p = 0.003), but no difference in the pre watering values (μ_1- μ_2= 0.03, t = 0.7, p = 0.49),

By contrast with other trends, in 2021, the maximum quantum yield of light-adapted leaves (ϕ_{PSII}) was largely unchanged by the pulse in 2021 (0.36 ± 0.04 before watering and 0.38 ± 0.04 after watering). Despite this, there was a statistically significant effect of watering ($\hat{\beta}$ = 0.176; t = 2.8, p = 0.012) highlighting the large magnitude of the response to summer rainfall in 2023 (from 0.10 ± 0.02 before watering to 0.43 ± 0.08 after watering).

Discussion

Photosynthetic and water relations parameters of *Yucca brevifolia* were measured *in situ* following an experimental watering addition in 2021 and a summer storm in 2023. Joshua trees upregulated multiple aspects of photosynthesis in response to summer soil moisture pulses of different sizes even at the hottest time of the year. In 2021, A_{net}, F_v'/F_m', and F_v/F_m increased following watering and in 2023, A_{net}, g_s, F_v'/F_m', and ϕ_{PSII} increased after Tropical Storm Hilary, while F_v/F_m remained near its theoretical maximum. These increases occurred within a few days of the watering pulses, which indicates that Joshua trees can rapidly respond to summer precipitation pulses. Although the chlorophyll fluorescence data show that summer soil moisture pulses improved the photosynthetic efficiency of the plants in both years, the size of the effect suggests that the health of Photosystem II in both years was not a major hinderance to photosynthesis. This is consistent with the findings of Barker et al. (2002), who find that Joshua trees retain very high levels of photoprotective zeaxanthin and antheraxanthin overnight during summer, indicating high levels of thermal energy dissipation.

The soils were equally dry before water additions in both 2021 and 2023, but the plants had significantly different levels of photosynthesis and stomatal conductance between years. Summer of 2021 followed a dry winter when plants received only 53 mm rain since the start of the water year (1 October 2020). By contrast, 2023 was a wet water year when plants had received 288 mm of rainfall prior to Tropical Storm Hilary. The Joshua trees had different pre-watering levels of A_{net} and g_s that corresponded with their antecedent water conditions. Previous work by Smith et al. (1983) recorded the highest measurement for A_{net} as 8.5 μmol CO_2 m^{-2} s^{-1} in hot temperatures and 12 μmol CO_2 m^{-2} s^{-1} in the cooler months. Our results are similar; the highest observed A_{net} in August was 8.9 μmol CO_2 m^{-2} s^{-1} and highest in winter was 17 μmol CO_2 m^{-2} s^{-1} (data not shown). These different rates of baseline photosynthesis suggest that antecedent water conditions influenced the ability of plants to photosynthesize, even 4 months after the last rainfall (as in 2023). This underlines importance of incorporating a longer history of precipitation in ecological studies as opposed to studies of single events (Loik, 2007; Ogle & Reynolds, 2004) to account for this ecological memory effect. It also suggests that the ecological memory of water for Joshua trees in this arid system extends at least 4 months.

Leaf Water Potential (Ψ_{leaf}) did not significantly change in response to TS Hilary, which could be evidence that Joshua trees employ an isohydric water relations strategy (McDowell et al., 2008). Ψ_{leaf} varied more in 2021 than 2023 and showed a significant difference between pre- and post- watering, but the effect size of -0.22 MPa is relatively small. Other arid-lands species like *Artemisia tridentata* (Nutt.) have been observed to change by ~2.00 MPa in a pulse watering experiment (Loik, 2007). There was a small decrease in water potential for Joshua trees following watering, which could be due to transpiration following stomatal opening. Strong stomatal control may be a primary mechanism for resisting drought. The anatomical adaptations of Joshua trees support strong stomatal control, including a thick waxy cuticle, recessed stomata (Wilkening et al., 2020), and increased wax deposition around the stomata (Anna Jacobsen, unpublished data). Our observations are consistent with Smith et al. (1983) who observed water potential in Joshua trees ranging from -1.00 to -3.00 MPa at the extremes at a nearby site with similar elevation.

In 2023, water potential and chlorophyll *a* fluorescence measurements as well as leaf-level stomatal conductance and CO_2 assimilation responses to watering showed that Joshua trees were not highly stressed despite not having received rainfall in 3.5 months. Joshua trees in August did not require precipitation to maintain turgor pressure and photosynthetic health. The next precipitation event was on September 2, 2023, a monsoon type storm. After that, the next precipitation event was in November 2023, a 10 mm pulse. It could be that the sizable precipitation event associated with Tropical Storm Hilary would decrease the stress on the plant in October and November.

The ability to quickly respond to summer rainfall may provide Joshua trees with a momentary opportunity to obtain carbon during the dry months. Desert plants do not respond equally to all forms of rainfall, but the magnitude of summer rainfall events and past history of rainfall matters for Western Joshua trees.

CHAPTER 2: ANTECEDENT WATER YIELDS MORE RAPID PHOTOSYNTHETIC UPREGULATION IN *YUCCA BREVIFOLIA* (ENGLM.) AFTER REHYDRATION FOLLOWING A DRY PERIOD

Droughts are becoming more common throughout the world as global temperatures increase, especially in already arid regions of the world (Allan & Douville, 2024). In many more regions, the annual mean soil moisture will decrease by one standard deviation or more in all warming scenarios (Calvin et al., 2023), causing additional water stress outside of droughts. This decreased moisture availability combined with increased temperatures and consequent vapor pressure deficits will increase the stress on plants in the already harsh conditions of arid systems (Breshears et al., 2013; Eamus et al., 2013; K. E. King et al., 2024).

Rainfall in arid systems can be conceptualized as distinct pulses of precipitation (Noy-Meir, 1973), but understanding these rainfall pulses in isolation misses much of the variation caused by antecedent effects from prior rainfall pulses and soil moisture conditions (Ogle et al., 2015). The effects of these prior conditions constitute ecological memory, which can have different strength, length, and temporal patterns (i.e., hysteresis) depending on the magnitude and timing of these prior events (Ogle et al., 2015; Ogle & Reynolds, 2004; Schwinning et al., 2004). Consequently, the effects of a current precipitation event interact with effects from prior precipitation events, thereby magnifying their impact. As precipitation events become more variable and less frequent (Hopkins, 2018), understanding the interacting effects of prior precipitation events on plant physiology takes on greater importance.

Plants respond to water stress in a variety of ways, including stomatal closure, desiccation of root hairs, reduction of gas-phase CO_2 conductance, the breakdown of Photosystem II, downregulation of ribulose 1,5-bisphosphate carboxylase/oxygenase (RuBisCo), decrease in xylem conductivity, decrease in chlorophyll, and buildup of abscisic acid that prevents stomatal opening (Flexas et al., 2006, 2013; Galmés et al., 2007; Nobel, 2009). Upregulation upon rewatering requires coordinated genetic, physiological, and anatomical changes in the plant (Schwinning & Ehleringer, 2001). Many of these drought responses take time to reverse when plants are watered following a period of dry conditions, impeding plants from taking advantage of transient soil moisture pulses.

The western Mojave Desert is a system of very sparse and highly unpredictable rainfall, where many plants use water storage as a buffer against drought (Snyder et al., 2004). The western Mojave Desert receives most of its rainfall in winter, although the timing is highly variable (Western Regional Climate Center). About 20% of annual precipitation falls in the monsoon season (July, August, September; Western Regional Climate Center). While climate models envision that total annual precipitation may not change appreciably in the Mojave, it is expected that monsoon rainfall will decrease by 40% (Hopkins, 2018). Monsoon rain fall punctuates a long dry period between winter rains. In fact, for the months of April, May, and June the western Mojave Desert sees only 8% of its average annual rainfall (Western Regional Climate Center). Monsoon rains are utilized by some desert shrubs (Snyder et al., 2004) and desert grasses (Potts et al., 2006), to improve water status and carbon gain. For some species, monsoon rain may be a crucial buffer between heavy winter rain seasons. In the Mojave Desert, an understanding of the interactive effects of consecutive precipitation pulses is especially important because precipitation events are typically clustered, occurring within ten days of each other both during the monsoon and in the winter (Reynolds et al., 2004). Because of this, understanding how the timing of precipitation may vary plant physiological response may give valuable insight into plant carbon budgets.

The western Joshua tree (*Yucca brevifolia* Englm.) is an endemic keystone species of the Mojave Desert and a cultural touchstone of the desert southwest. Its range largely defines the boundaries of the Mojave Desert, where it provides crucial vertical structure for avifauna in vegetation communities that otherwise lack height (St Clair & Hoines, 2018). The Joshua tree's fame is largely due to its unusual growth habit, which features rosettes of spine-tipped semi-succulent leaves at the end of long branches. An arborescent monocot, it grows to 6 – 9 m tall (Aedo et al., 2012) and lives to a maximum of about 400 years (Gilliland et al., 2006). It uses the C3 photosynthetic pathway, like the other thin-leaved yucca species, and the leaves stay green for a minimum of 4 years (Smith et al., 1983). Joshua trees also face threats from exotic species due to altered fire regimes, development, and climate change (Wilkening et al., 2020). Changes in climate are expected to be extirpate Joshua trees from Joshua Tree National Park by 2100 (Barrows & Murphy-Mariscal, 2012; Cole et al., 2011; Dole et al., 2003; Shafer et al., 2001; Sweet et al., 2019), except for small refugia. In response to this, the western Joshua tree has been protected from take under California law under the Western Joshua Tree Conservation Act (The Western Joshua Tree Conservation Act, 2023), although they were rejected as an endangered species under the federal Endangered Species Act (US Fish and Wildlife Service, 2023). If Joshua tree populations decline, it will be important to understand how Joshua trees respond to water availability for restoration and potential assisted migration efforts.

While many thousands of studies have looked at the effects of dry periods on the physiology plants (Cui et al., 2022), only some have looked at the effects of rewatering following a dry period (Duan et al., 2015; Jia et al., 2020; Taylor et al., 2014; Xu et al., 2010). This period of recovery following water stress is a key window into survival strategies of plants, especially in arid systems where sustained dry periods followed by soil rewetting are more common. We investigated this effect *in situ* at a site at University of California Irvine Burns Piñon Ridge Reserve and found that precipitation levels from the previous winter were related to the ability of plants to upregulate photosynthesis in response to summer precipitation pulses (Hastings & Loik, *in press*). This research intends to expand our knowledge of the effects of antecedent water conditions on the scale of several weeks instead of several months. Specifically, this paper addresses the questions:

Do plants with favorable antecedent water conditions upregulate photosynthesis more quickly than those with drier antecedent water conditions?

Does Photosystem II upregulate more rapidly than photosynthetic gas exchange upon re-watering, and how does antecedent water affect this response?

Methods

Plant Material

Yucca brevifolia plants were grown from seed freshly collected from near Pearblossom, CA starting in 1998. Seedlings were grown in a general-purpose peat-vermiculite growing medium (PROMIX BX; Premier Tech Ltd., Quakertown, PA) in 4 by 20 cm Ray Leach Cone-tainer plastic pots (Stuewe and Sons, Tangent, OR). Plants were kept in ambient outdoor conditions of a rooftop greenhouse at the University of California, Santa Cruz. After five years they were repotted into 1-gallon pots (Nursery Supplies Inc., Orange, CA). Four months prior to the experiment, the plants were repotted into 3-gallon pots (The Lerio Corporation, Mobile, AL) with decomposed granite soil obtained from a local builder's supply. The plants were between 30 and 60 cm tall at the start of experiments.

Plants were transferred to a glasshouse facility on the roof of the Interdisciplinary Sciences Building at UC Santa Cruz three months prior to experiment start. Plants were randomly assigned to a new position in the greenhouse every two weeks prior to the experimental watering treatment, and weekly thereafter. Lights in the greenhouse were programmed to turn on when incoming solar radiation on the glasshouse roof decreased below 500 W m^{-2} between 07:00 and 19:00 h.

Experimental Design

Eighteen plants of similar size and vigor were selected and then divided randomly into treatments, a Drought group, which would be watered only at the end of the experiment, a Pulse group, which would be watered once halfway through the experiment and again at the end, and one Control group which was watered every 5 days throughout (Figure 8). The experimental treatment was 32 days long, with a mid-point watering for the Pulse group on the 16th day. Plants were watered with 1.7 L of distilled water at each watering, calculated from the 0.16 m^3 m^{-3} water holding capacity of the decomposed granite growing medium. Pots were weighed weekly to determine volumetric water content. As the plants have few leaves and water potential measurements are destructive, we used g_s as an indicator of plant water stress (Duan et al., 2014).

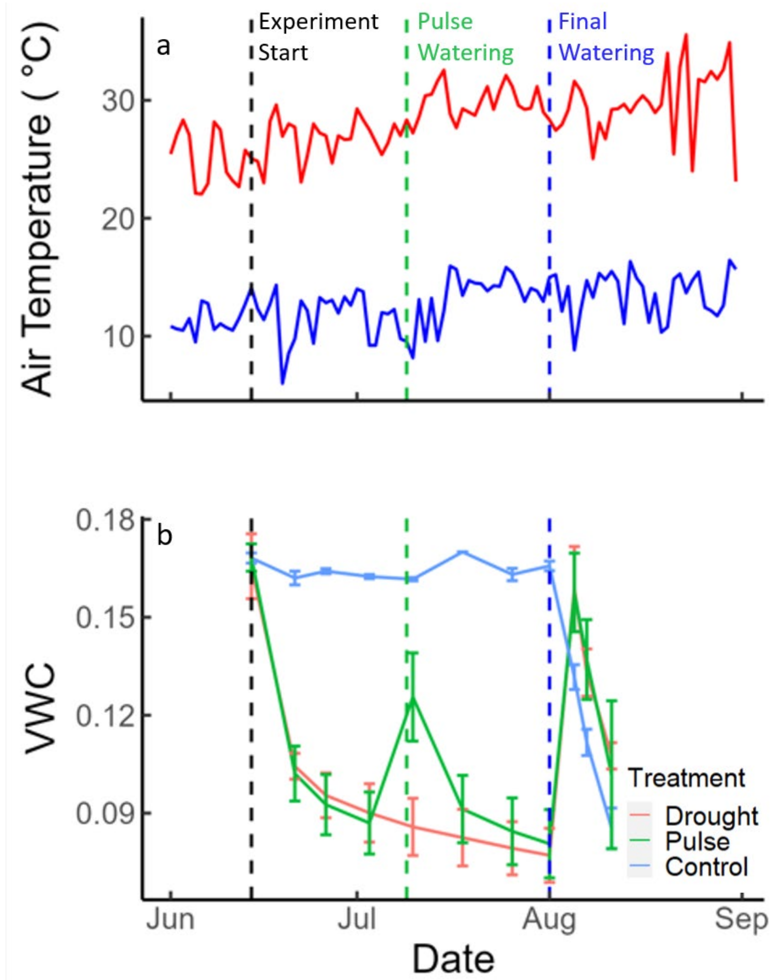

Figure 8:a) Ambient air temperature in the greenhouse during the period of study. Daily maximum temperature is depicted in red, daily minimum temperature is depicted in blue. The dashed vertical lines depict experiment start (black), watering of the pulse treatment (green), and final watering of all plants (blue). b) Change in volumetric water content during the greenhouse experiment due to soil drying.

Photosynthetic Gas Exchange

Photosynthetic gas exchange was measured between 11:00 and 13:00 h every four days during the experimental treatment prior to final watering to monitor plant stress levels. Preliminary measurements at various times of day showed that plants were most active at midday. Photosynthetic gas exchange measurements were taken daily following final watering. Photosynthetic gas exchange measurements were made using an open-path portable photosynthesis system (Model LI-6800, LI-COR, Lincoln, NE) at 415 ppm CO_2 concentration and internal lighting set to 1500 μmol photons m^{-2} s^{-1} photosynthetically active radiation. The instrument was allowed to warm up for 30 minutes prior to sampling, infrared gas analyzer zeros were checked and calibrated. After closing the leaf chamber on the leaf, a non-toxic poster putty (Blu-Tack; Bostik Company, Wauwatosa, WI) was put over air gaps in the gasket material caused by the thickness of the leaves, as per advice from Li-COR, to ensure there was no leakage due to the irregular shape of Joshua tree leaves. Plants were measured by block group. The infrared gas analyzers were then matched at every plant with the same flow of air prior to making measurements.

One leaf on each plant was marked with permanent marker (Sharpie; Newell Brands, Atlanta, GA) for repeat measurements. The leaves of these Joshua trees were nearly flat on top and had a convex V-shaped underside. Leaf area for the gas exchange calculations was independently estimated for each leaf as the area of the top flat side (idealized as a trapezoid) plus the area of the two idealized flat panels on the bottom of the leaf (also trapezoids). These measurements were approximated using two measurements of leaf width and two measurements of leaf height taken ~30 mm apart, which is the length of the gas exchange chamber used. These were summed and divided in half estimate of one-side leaf area.

Chlorophyll *a* Fluorescence

Chlorophyll *a* fluorescence was measured between 11:30 and 13:30 h each day for the first six days following final watering on each plant (except the fifth day, when there was an equipment error), and then again on the 9th day. Measurements were made using a pulse-amplitude-modulated fluorometer of a LI-COR model LI-6400 Leaf Fluorometer, on the same leaf used for gas exchange measurements. Fluorescence was allowed to stabilize under 1500 μmol photons m^{-2} s^{-1} actinic light prior to the flash routine, typically about 5 minutes. The saturating flash was 4200 μmol photons m^{-2} s^{-1}. The fluorescence was measured with a measuring LED intensity of 5, modulation at 10kHz, filter of 1Hz, and a gain factor of 10. The dark phase of the flash was 6 seconds long and used a 0.25 kHz modulation and a 5Hz filter. The effective quantum yield of Photosystem II (PSII) was calculated as:

$$\frac{F_{m'} - F_s}{F_{m'}} = \frac{F}{F_{m'}} = \boldsymbol{\Phi}_{PSII}$$

Where F_m' is the maximal fluorescence of the light-adapted leaf and F_s is the steady-state fluorescence.

The light-adapted maximum quantum yield of PSII (F_v'/F_m') was calculated as:

$$\frac{F_v'}{F_m'} = \frac{F_m' - F_o'}{F_m'}$$

Where F_o' is the minimal fluorescence of the light-adapted leaf.

Statistics

Chlorophyll *a* fluorescence and gas exchange parameters following the final rewatering were idealized as sigmoid functions. The Pulse and Drought plant data following the final rewatering were fit using non-linear least-squares regression to the parameterized sigmoid function:

$$\frac{a}{1 + e^{-c \cdot (Time - b + d \cdot Treatment)}}$$

Where *a*, *c*, and *b* are shape parameters, *Time* is the time since final watering in integer days, *b* is a shape parameter that corresponds to the x location of the increase in the response variable and *Treatment* is a binary variable where zero represents the droughted group and one represents the pulse group, and *d* represents the difference in *b* between the droughted and pulse groups. Differences in the onset of photosynthetic upregulation were assessed at the 0.05 significance level for Pr(>|t|) for the variable *d*.

Results

Greenhouse conditions

Greenhouse temperatures averaged 19.8°C ± 1.2 (S.D.), with average daily minimum temperatures of 12.7°C ± 2.2 and average daily maximum temperatures of 28.2°C ± 2.1 (Figure 8a). The highest temperature observed during the study period was 32.5°C and the lowest temperature was 6.0°C. Daily maximum temperatures warmed slightly over the study period at a rate of 0.07°C per day.

Volumetric water content decreased rapidly at the cessation of watering of the two treatment groups from 0.165 ± 0.007 m^3 H_2O / m^3 soil to 0.103 ± 0.006 m^3 H_2O / m^3 soil. Four days prior to the mid-experiment pulse watering, the Pulse group mean VWC was 0.084 ± 0.010 m^3 H_2O / m^3 soil and Drought group mean VWC was 0.079 ± 0.008 m^3 H_2O / m^3 soil (Figure 8b). VWC increased in the pulse group to a maximum of 0.158 ± 0.013 m^3 H_2O / m^3 soil one day after the pulse, while the VWC in the drought group continued to decline. In the last measurement prior to final watering, the VWC of the Pulse group had decreased to 0.080 ± 0.010 m^3 H_2O / m^3 soil compared to the drought group at 0.077 ± 0.008 m^3 H_2O / m^3 soil and were not statistically different (Welch's t-test, t = 0.650, df=9.5, p=0.053). Mean volumetric water content in the treatment groups was 0.151 ± 0.022 one day after the final watering.

Photosynthetic Gas Exchange

At the start of the experiment, stomatal conductance (g_s) and net leaf-level CO_2 assimilation (A_{net}) were not significantly different between treatment groups (g_s: ANOVA, F = 0.52, p = 0.60; A_{net}: ANOVA, F = 0.17, p = 0.85). Mean g_s at the start of the experiment was 0.024 ± 0.006 mol H_2O m^{-2} s^{-1} and mean A_{net} was 3.33 ± 0.60 µmol CO_2 m^{-2} s^{-1} (Figure 9). By six days from experiment start, the Drought and Pulse groups had significantly diverged from the Controls (g_s: ANOVA, F = 3.93, p = 0.04; A_{net}: ANOVA, F = 3.70, p = 0.01). Just before the mid-point watering, stomatal conductance of drought and pulse plants were equivalent (Welch's T-Test, t=1.08, df =

6.3, p=0.32). Following the mid-point watering, g_s for the plants in the Pulse group increased from 0.005 ± 0.001 to a maximum of 0.023 ±0.007 mol H_2O m^{-2} s^{-1} approximately 6 days afterwards. Stomatal conductance then decreased to 0.013 ± 0.002 mol H_2O m^{-2} s^{-1} prior to the final watering.

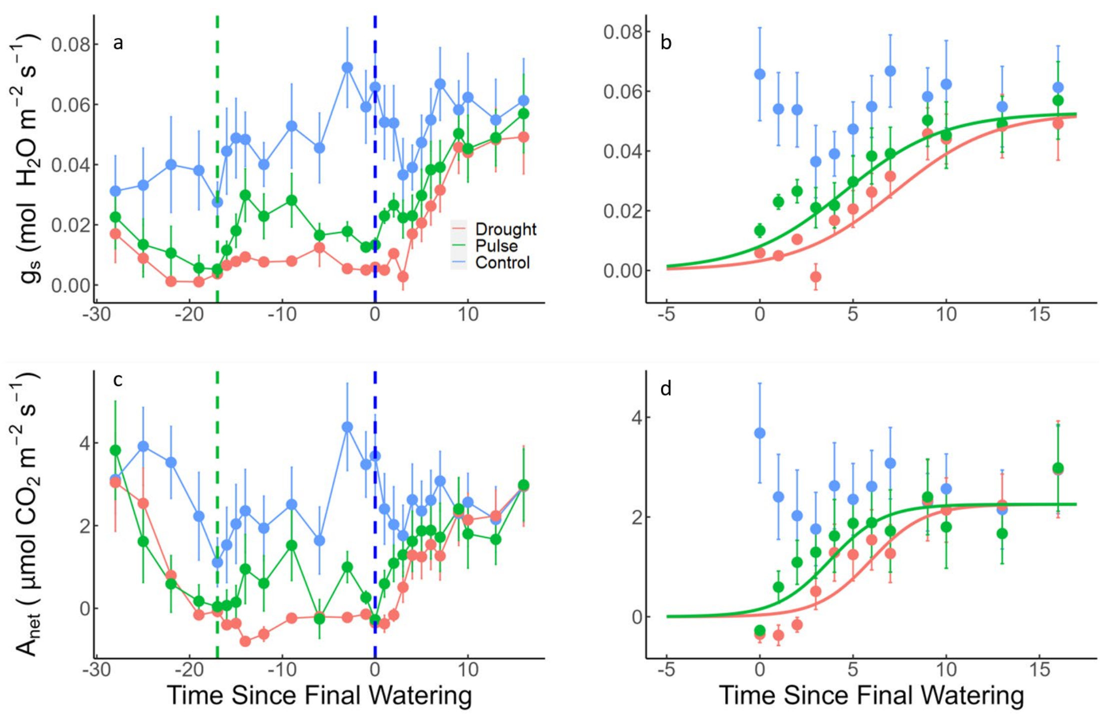

Figure 9:Gas exchange data for the length of the experiment (a&c) and since the final watering (c&d). Vertical dashed lines indicate watering of pulse treatment (green) and watering of all plants (blue). In c) and d) thick curved lines represent fitted models.

Differences in g_s and A_{net} upregulation were assessed between the drought and pulse groups by comparing their responses to the final watering. The upregulation of g_s was significantly different between pulse and droughted groups with an estimate effect size of 2.7 ± 0.89 days (non-linear least squares regression (NLS), t = -3.06, p = 0.003), while the upregulation difference for A_{net} was similar , 2.20 ± 1.1 days (NLS, t = -1.97, p = 0.051). Fifteen days after final rewatering, all plants had returned to pre-experimental photosynthetic gas exchange levels.

Chlorophyll *a* fluorescence

The effective quantum yield of light-adapted leaves (ϕ_{PSII}) just prior to final watering was significantly different between the control and treatment groups (Tukey's Honest Significance Difference (THSD) for ANOVA, D-C: p = 0.00002, P-C: p = 0.0002 P-D: p = 0.42). ϕ_{PSII} increased significantly faster in the pulse group than in the drought group (NLS, d = -1.02 ± 0.4, p = 0.02), with an effect size of about one day (Figure 10).

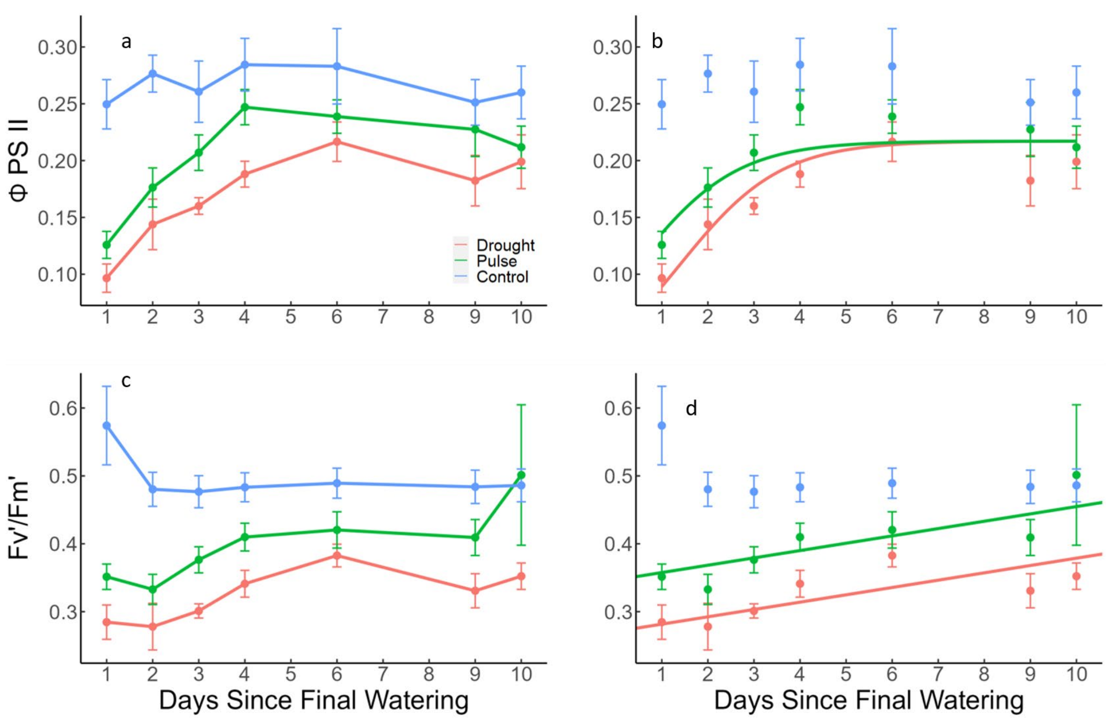

Figure 10: Chlorophyll a fluorescence data from the final watering to the end of the experiment. Figures b) and d) show the fitted models.

The light-adapted maximum quantum yield of PSII (F_v'/F_m') was significantly different for the control and treatment groups at the time of final watering, but not from each other (THSD for ANOVA, D-C: p = 0.0002, P-C: p = 0.002, P-D: p = 0.45). F_v'/F_m' did not behave in a sigmoid fashion in response to watering and we were unable to obtain a meaningful model fit. However, by the end of the experiment, the Pulse group was not significantly different from the Control group, while the Drought group remained significantly lower than the Controls (THSD for ANOVA, D-C: p = 0.002, P-C: p = 0.13, P-D: p = 0.10). A linear model including the two treatment groups and the days since watering shows a significant difference in the y-intercept of two groups of 0.08 $\pm$0.018, indicating that the value for F_v'/F_m' was on average 0.08 higher in the pulse group than in the control group (least squares regression, $Y_{ijk} = \mu + \beta_{1Timei} + \beta_{2Treatmentj} + \epsilon_{ijk}$, F = 15.64, p = 0.000002).

Discussion

We found significant differences in the onset of response to watering in all photosynthetic chlorophyll *a* fluorescence and gas exchange parameters, indicating that precipitation pulses as many as 16 days apart can impact a plant's ability to upregulate photosynthesis and gain carbon.

Photosynthetic gas exchange upregulated more quickly in plants with that had a mid-treatment watering than those without. The difference in onset of increase in these parameters began was similar 2.7 days in g_s and 2.2 days in A_{net}. The increases in photosynthesis and g_s were visible within the first day after watering in the Pulse group. This is similar timing to *Bouteloua gracilis* ((Kunth) Lag. ex Griffiths), an herbaceous species with a shallow fibrous root system, which also upregulated g_s within one day following rewatering (Sala & Lauenroth, 1982). In Big Bend National Park, Patrick et al. (2007) observed an eight-fold increase in $A_{net,}$ including for a related semi-succulent *Dasylirion wheeleri* (S. Watson; Asparagaceae) in response to a 25% increase in monsoon precipitation. Changes in precipitation timing may have similar non-linear effects on photosynthesis. Soil moisture pulses in desert soils can dissipate quickly due to high evaporative demand and low water holding capacity (Reynolds et al., 2004). Turning these transient pulses of water into carbon gain is a critical survival tool in these arid systems, so an advancement by two days may be significant in the carbon budget of these plants.

The increased upregulation speed of the Pulse group plants also occurred at the biochemical level in the chloroplasts. Chlorophyll *a* fluorescence measurements show that extended dry periods can decrease the efficiency of Photosystem II, and that favorable antecedent water conditions slightly improve the rate at which plants can repair any damage to or protective downregulation of PSII caused by the dry period. Increases in ϕ_{PSII} show that the plants can allocate more incoming light to photochemistry as the plant water status improves following watering (Maxwell & Johnson, 2000b). The values for ϕ_{PSII} we observed were on the lower end of the values observed by Huxman et al. (1998), but are largely consistent with the values observed in our field study (Hastings & Loik, *in prep*) and another field study (Barker et al., 2002). Our plants were given one large pulse of fertilizer 3 months before and 1 week before the experiment, whereas Huxman et al. fertilized their plants every 4 days for 8 months. It may be that decreased nitrogen availability in our study lowered the efficiency of Photosystem II (Mu et al., 2017; Shangguan et al., 2000; X. Wang et al., 2016). That our results are consistent between the greenhouse and the field study suggest that the nitrogen poor soils at the field site (data not shown) may be a key limiting factor in photosynthetic efficiency for Joshua trees.

The light-adapted maximum quantum yield of PSII did not show a pronounced saturation effect with a sigmoid response to watering, like the other photosynthetic parameters, suggesting that the action of watering on maximum quantum yield may occur over a longer time scale than the period of this experiment. Despite this, there was a significant difference in F_v'/F_m' across all days between the Pulse and Drought groups, suggested that plants exposed to antecedent soil water have a slightly more resilient photosynthetic apparatus than those in the drought group. Jia et al. (2020) observed that quantum yield and quenching coefficients (e.g. F_v/F_m & qP) in *Zea mays* droughted for 15 days did not recover to pre-drought levels even ten days after rewatering. Thus desert plants show considerable variability in the lengths of water stress that affect Photosystem II and the time required to restore function (Fanglin et al., 2021).

These effects constitute a short-term ecological memory effect of prior precipitation on this desert system, which can be thought of as having qualities of strength, length, and temporal pattern (Ogle et al., 2015). For Western Joshua trees raised in pots, ecological memory would have a strength of ~2.5 in photosynthetic gas exchange (based on effect size) and a length of at least 16 days. Further study using a variety of pulse timings could help determine the thresholds of this temporal pattern. As physiological processes follow a regular pattern of downregulation during water stress beginning with stomatal closure and proceeding through photoprotective changes to Photosystem II (Galmés et al., 2007), it may be that there are temporal thresholds governed by these physiological processes that influence the strength of this memory.

Joshua trees continue to be threatened by warming temperatures and increased risk of drought under climate change. The ability to quickly respond to changes in soil moisture may provide some resilience to changes in the precipitation patterns in the Mojave Desert. The interaction effects between serial precipitation events influence the ability of Joshua trees to respond to these transient pulses of soil moisture. Understanding these effects can give us a better picture of the health of Joshua tree communities and help design watering regimes for restoration and assisted migration efforts.

CHAPTER 3: WILL PLAYA DUST SUPPRESSION REDUCE INCIDENCE OF ASTHMA IN THE SALTON SEA BASIN?

All over the world, terminal lakes are drying up. Climate change, increased water usage, and other factors are diverting or decreasing inflows to these lakes, and causing myriad problems including runaway salinity, concentration of pollutants and metals, and exposure of dry lakebed, which can be a source for giant dust storms (Seltenrich, 2023). The Aral Sea, located between Kazakhstan and Uzbekistan in Central Asia, lost 90% of its area after the Amu Darya and the Syr Darya Rivers, the major rivers feeding the Aral Sea, were overdrawn (X. Wang et al., 2023). The result has been the exposure of hundreds of thousands of hectares of dry lakebed that can cause plumes of dust to blow for 500 km downwind. Seltenrich (2023) presents case studies from nearly every continent, starting with California's Salton Sea. His study focuses on connections between the Salton Sea drying up, particulate matter rising from the dried seabed, and regional cases of childhood pulmonary disease (p. 2):

> [The Salton Sea's] dust is carried from vast areas of exposed playa [exposed lakebed] into communities nearby, especially south of the lake in the Imperial Valley. This region has California's second-highest rates of pediatric hospitalizations and emergency department visits for asthma.

Parents in the Imperial Valley are very concerned about the pulmonary health of their children. These quotations from residents (Cheney et al. 2023, pp. 9&11) illustrate this:

> “When he was six months old, well, he got really sick. We took him to Mexicali, and they told me to put a nebulizer on him and pat him on the back every 15 min to get rid of all the phlegm.”

> “[My son’s chronic health condition] is related to the Salton Sea’s dust. Because my child has a lot of nosebleeds. It is something that is very worrisome. The doctors tell me that there is no medicine to stop the bleeding. I have noticed that in the month of February, this is when my son’s nose bleeds the most. I’ve already taken him to the doctor: ‘Why does my child have a nosebleed in the seasons when it’s windy?’ When we went to the Central Valley, they did not have nosebleeds. Nor did my little girl who has asthma have breathing problems or asthma attacks”.

Another resident echoes Seltenrich’s explanation of the cause of childhood illness in the region (Cheney et al., 2023, p. 9):

> [The Salton Sea] is drying up because they no longer supply it with the water that they used to supply it with. Everything [agricultural toxins] is left on the lake’s shores. When it’s windy, all this dust goes into our lungs.

News agencies have also reported on the Salton Sea crisis. ABC News (Griswold et al., 2024), NBC News (Sandusky, 2023), and the Guardian (Singh, 2021) have described concerned families with asthmatic children, as well as the toxic dust that appears to be causing this health crisis. In the Guardian's coverage, Salton Sea resident Noemi Vasquez describes the night that she nearly died in her sleep, unable to breathe due to her asthma and a major dust storm. She says that she keeps inhalers in every room of the house and that her young grandchild always keeps a Trolls-themed nebulizer kit with her to deal with emergency asthma attacks.

Citizens in the Imperial Valley have responded to this by establishing their own air quality monitoring network. The Identifying Violations Affecting Neighborhoods (IVAN) Community Air Monitoring Network was started in the early 2010s by non-profit Comité Civico Del Valle, the California Environmental Health Tracking Program, the University of Washington School of Public Health, and several other collaborators. It was funded by the National Institute of Environmental Health Sciences. The IVAN air monitoring program has 40 air quality sensors in the Imperial Valley that measure $PM_{2.5}$ and PM_{10} (Carvlin et al., 2017). This network arose in response to residents' concerns about air quality and the feeling that there was inadequate data about air quality in the places that mattered to them (Carvlin et al., 2019). Sensors are located at elementary schools and other areas of interest to the residents. It is the largest community-based air quality monitoring system in the US.

The State of California and the Imperial Irrigation District (IID; the major owner of water rights in the Imperial Valley) are committed to spending hundreds of millions of dollars (The State of California, 2003) remediating the playa to suppress dust and mitigate the health crisis, with the possibility of investing billions more (M. J. Cohen et al., 1999). Control measures, which as of 2022 have been implemented on

5665 hectares of the highest emissions playa types (Imperial Irrigation District & Formation Environmental LLC, 2022), aim either to reduce the wind velocity over the surface of the playa and decrease the amount of dust that is aerosolized, or to submerge the playa in water again to both mitigate air quality problems and provide habitat for fish and birds (Imperial Irrigation District & Formation Environmental LLC, 2016a). The fundamental justification for potentially spending several billion dollars is to protect public health from the risk of airborne pollution arising from exposed Salton Sea playa.

In this chapter, I examine the fundamental linkages that dominate public discussions of the Salton Sea: the three-part connection between the sea shrinking, toxic dust being aerosolized from recently exposed playa, and the incidence of pulmonary disease in the region's children. I begin by summarizing the Salton Sea's history, the asthma crisis at the Salton Sea, and results of interviews with health professionals in the Salton Sea region. I then examine the available data about the air quality, including providing new analyses. My general findings are that problems with asthma in the region pre-date expanded emissions from the playa, and that existing data do not conclusively demonstrate a correlation between expanding exposed playa and incidence of asthma in the region. Based on these findings, I conclude with recommendations for policy re-orientation and further research.

The Rise and Fall of the Salton Sea

The Salton Sea is the largest lake ever created by accident. In the late 19^{th} century, the efforts to use the water of the Colorado River to irrigate the Imperial Valley's crops were well underway (Farr, 1918). In 1905 the levees controlling that water broke, and for one and a half years the entire contents of the Colorado River emptied into and filled the depression called the Salton Sink, creating what is now called the Salton Sea (deBuys, 2001). The Salton Sink had periodically flooded with water over the millennia since its formation; the most recent iteration, Lake Cahuilla, disappeared in the 17^{th} century.

The Salton Sea, despite its name, is the largest lake in California (California Natural Resources Agency, 2017). It holds 900 billion cubic meters of water and has a maximum surface area of about 96,000 hectares (Cohen & Hyun, 2006). It is situated mostly in Imperial County, with a small portion of the north end of the lake in Riverside County. Water flows into the sea from the Whitewater River to the north, and from the New and Alamo Rivers to the south. By the time the water reaches the Sea, it has been used to irrigate several fields, and thus the Salton Sea is also classified as an agricultural sump (Audubon Society, n.d.). As a terminal or endorheic lake, the Salton Sea has no outflows for its inflowing water and accumulated agricultural byproducts, but the Salton Sea loses approximately 1.6 billion cubic meters of water per year to the dry desert air (Salton Sea Ecosystem Restoration Program, 2006).

The Salton Sea is situated in the Sonoran Desert, where the temperatures regularly reach 45°C in the summer. After its formation and through most of the 20^{th} century, the Salton Sea was an oasis in the dry desert, attracting hundreds of species of birds on their annual migrations (Fogel et al., 2021). As wetlands were being filled in and dried up across the United States, the Salton Sea became a vital stopover point, replete with food to sustain these animals on their cross-continental journeys (Fogel et al., 2021).

During this period, the lake drew the attention of tourists and entered its heyday. The desert oasis was an ideal place for fishermen, water-sports enthusiasts, and beach vacations. Being close to Los Angeles, it attracted celebrities like Guy Lombardo, Jerry Lewis, Dean Martin, and Frank Sinatra, all of whom vacationed there in the 1950s. In the 60s, acts like the Beach Boys and the Pointer Sisters performed at venues near the sea (Gottberg & Cichocki, 2016). Vacation towns sprang up on the water's edge and the region enjoyed a period of expansion and economic prosperity.

This golden era was short lived, however, as the constantly increasing salinity and pollution began to degrade the quality of the ecosystem. By 1985, the sea had reached the salinity of ocean water. Selenium build-up in the lake prompted the state to issue warnings to fishermen the following year (Associated Press, 1986). In the 1990s, mass die-offs of birds began as outbreaks of avian botulism and selenium poisoning claimed the lives of tens of thousands of birds (Audubon Society, n.d.). By the late 1990s, the fish die-offs worsened as agricultural eutrophication caused massive algal blooms that made large portions of the lake anoxic, killing over 7.9 million fish in one day (Marcom, 1999). The death of a dog swimming in the Salton Sea in 2021 caused authorities to issue warnings against entering or touching the water due to the presence of harmful cyanobacteria (State Water Resources Control Board, 2021).

Problems were compounded for this already-shrinking lake in 2003 when the Quantification Settlement Agreement (QSA), a reapportioning of California's allocation of Colorado River water, resulted in the diversion of 370 million cubic meters of water from IID's allotment to San Diego (Quantification Settlement Agreement and Related Agreements and Documents, 2003). IID's water allotment feeds the fields in the Imperial Valley to the south of the Salton Sea, the surplus of which eventually drains into the sea. In exchange for the water transfer, recipient agencies would improve water efficiency in the Imperial Valley by lining hundreds of miles of canals. This further decreased inflows to the sea, as water that seeps into the aquifer is another inflow to the sea. Recognizing that the QSA would decrease inflows to the sea, a further deal was struck wherein IID would institute a field fallowing program that would create mitigation flows intended to keep the inflows to the sea static while a solution was found. Farmers were paid to not use their water allocation, allowing it to flow into the Salton Sea. IID, the Coachella Valley Water District, and the San Diego County Water Authority agreed to pay for the first $133 million dollars in mitigation efforts for problems that a shrinking Salton Sea might cause, and the State of California agreed to cover any costs above that amount (M. J.

Cohen et al., 1999; The State of California, 2003). The mitigation flows slowed the decrease in sea level, but the Salton Sea began to shrink, slowly at first, and then more rapidly at the end of the mitigation flow period (USGS). As it did, thousands of hectares of former lakebed, known locally as playa, became exposed, raising concerns that this loose substrate could raise dust storms much like those seen at the dry Owen's Lake (National Academies of Sciences Engineering and Medecine, 2020). The shrinking sea turned attention to the respiratory health of communities living near the sea.

Asthma at the Salton Sea

Imperial County is synonymous with agriculture. Enjoying over 300 days of sunshine annually and warm temperatures throughout the year, Imperial County is an important supplier of wintertime green vegetables on an immense scale, each year producing $400 million dollars' worth of lettuce alone (Ortiz, 2021). Imperial County had a population of 178,000 in 2023 (US Census Bureau) and 50% of workers are employed in agriculture. The community around the Salton Sea is 86% Hispanic (US Census Bureau 2023), predominantly Mexican and Central American immigrant farm workers. Spanish is the most-spoken language—between 2018 and 2022, the US Census Bureau reported that 75% of households in the Imperial Valley spoke a language other than English at home. There is also a large community of indigenous Purépecha people from the Mexican state of Michoacan, and many of them do not speak Spanish or English (Cheney et al., 2023). Poverty is common in Imperial

County. Over 20% of residents in Imperial County live in poverty, and the median average income per capita was $22,000, 40% below the national average (US Census Bureau). Imperial County has been classified as a medically underserved area since 1994 (US Health Resources & Service Administration, accessed 4/23/2024).

The communities on the north side of the sea in Riverside County are similar to those to the south in Imperial County (Cheney et al., 2023).The census tracts just to the north of the sea all have poverty rates above 20% (US Census Bureau) and are demographically comparable to communities in Imperial County (US Census Bureau; Cheney et al., 2023). The north side of the lake is also home to the Torres Martinez Desert Cahuilla Indians, a Native American tribe with 3,000 members.

While there is ample anecdotal evidence of respiratory ailments in the Salton Basin (Cheney et al. 2023), there is little publicly available data. The California Department of Public Health's (CDPH) California Breathing program has compiled county-level data on asthma prevalence (Lifetime Incidence of Asthma and Current Incidence of Asthma) and contact with emergency medical care (emergency department visits and hospitalizations) and asthma related deaths. I have reproduced the data on asthma prevalence and contact with emergency medical care in Appendix A (data on asthma related deaths were not available for Imperial County). As Riverside County is heterogeneous, and many of its largest population centers far from the sea, I have not included those data because a signal related to the Salton Sea is unlikely to be discernable.

Several things are striking about these data. First, the rates of emergency department visits for children are consistently among the highest in California and are often double the average. Second, the trend in emergency department visits is not mirrored in the asthma prevalence data, where Imperial County typically ranks near the state average. Third, the data are only available between the years of 2015 and 2020, offering a narrow window into the asthma crisis.

These data are difficult to interpret because of several confounding factors. In a medically underserved area like Imperial County, emergency departments see higher utilization (Weisz et al., 2015), as many people do not have primary care providers (PCPs) and use emergency departments for all of their medical needs. It is unclear how much of the signal in these high levels of emergency department comes from this effect or an underlying asthma crisis (Biddle et al., 2023). There are also several factors which could deflate the asthma prevalence data. In a county where the community is medically underserved, there may be many more people suffering from asthma than have had access to a physician for diagnosis. And with strong community ties and proximity to Mexico, residents can acquire inhalers in Mexico without contact with health providers in Imperial County, and at a lower cost, which might depress the reported number of asthma sufferers compared to actual sufferers.

Farzan et al. (2019) surveyed the parents of 357 children in northern Imperial Valley to better understand the prevalence of asthma in the region. The overall rate of asthma reported was 22.4%. Rates of asthma symptoms were higher than the reported cases of asthma, suggesting it may be more prevalent than indicated by surveys or government data. These data come with their own complications. As parents self-selected into the survey, the authors concede, “It is possible that parents/guardians of asthmatics or those who were concerned about their child’s respiratory health were more likely to complete the survey than parents of non-asthmatic children” (Farzan et al., 2019, p. 3828). Others have written papers that assess the problem, but their analysis relies on the same limited CDPH county-level data (Jones & Fleck, 2020).

Despite these confounding issues, these data and the additional qualitative reports from community groups (e.g. Comité Civico del Valle), media accounts (Griswold et al., 2024; Sandusky, 2023; Singh, 2021), and qualitative studies (Cheney et al., 2023) are enough to raise major concerns about respiratory health in the area.

Interviews at Medical Facilities

In an effort to better understand the asthma problem in the Salton Sea region, I visited nine health care facilities and conducted substantive informal interviews at five of them between June 27 and July 1, 2022. The five facilities included two urgent care facilities (All-Valley Urgent Care, Brawley, CA; Premier Urgent Care, Coachella, CA), two full-service clinics (Innercare, Mecca, CA; Innercare, Brawley, CA), and one hospital (John F. Kennedy Hospital Emergency Department, Indio, CA).[1] I interviewed nurses and administrators at these clinics about the asthma crisis,

[1] Other facilities visited were Eisenhower Medical Center Emergency Department, Rancho Mirage, CA; Pioneers Memorial Hospital, Brawley, CA; Innercare Salton City, Salton City, CA; All Valley Urgent Care, El Centro, CA. Employees at these facilities either declined to comment or were unavailable at the time of the visit.

the reasons for the discrepancy between asthma prevalence, and what they perceived as the biggest health issues residents were facing. A few key points that emerged from these interviews.

The clearest point was that the communities were medically underserved and faced many barriers to healthcare access. Several medical professionals and administrators said that patient non-compliance and lack of PCPs were reasons for elevated emergency room visits. The language of "patient non-compliance," a common term in the medical field to describe patients who do not follow a doctor's plan for their care, implies that patients are acting irrationally, when in fact many patients may be carrying out a cost-benefit analysis that accounts for social and economic realities, in addition to the perceived benefits of treatment (Donovan & Blake, 1992). For patients in the Salton Sea region, factors such as the cost of care, the cost of transportation to medical facilities, loss of income due to missed work, need for childcare during medical visits, and need for language interpreters may decrease the perceived benefit of follow up care. One interviewee also mentioned that many of their patients belonged to migrant families and follow up care was difficult as they moved frequently, following crop harvests. One nurse pointed to a "culture of medication" among patients that she typically sees wherein they were only interested in getting medication for their ailments and not interested in "solving the problem" or receiving regular (e.g. follow-up) treatment. Another nurse mentioned that most of the patients she sees suffering from asthma attacks don't have any daily maintenance medication that would normally be prescribed during an appointment with a primary care physician. This could lead to more acute asthma attacks.

Further, the healthcare workers interviewed did not seem to be particularly focused on asthma. An administrator at one clinic reported that asthma was not a major concern at the clinic and that obesity, diabetes, mental health, and colorectal cancer were some of the top medical problems in the area. She also later noted that during a recent audit of patients, five out of the ten patients had persistent asthma and were taking corticosteroid inhalers to treat it. One nurse interviewed at All Valley Urgent Care in Brawley said that she thought that the problem of asthma was significant, and that there was a seasonality to the asthma attack visits, with most of them occurring in March and April. She believed that especially bad allergens in the area were to blame, along with dust storms and agricultural dust.

Interview subjects also corroborated that the region's lack of primary care providers increased the number of emergency department and urgent care visits.

Air Quality at the Salton Sea

Air pollution from dry lake beds is not new. The exposed lakebed of California's Owen's Lake, notoriously appropriated by Los Angeles in the 1910s, became one of the biggest polluters on the continent after the Los Angeles Department of Power and Water drained the lake (Reisner, 1993). Pollution from dried lake beds is primarily in the form of particulate matter, which is regulated as part of the National Ambient Air Quality Standards (NAAQS). Particulate matter is a concern as it is comprised of small particles of dust that can be inhaled and cause damage to respiratory health (Johnston et al., 2019). Particulate Matter, or PM, is divided into two main categories based on the diameter of the particles, $PM_{2.5}$, which is particles less than 2.5 microns, and PM_{10} which is particles less than 10 microns. $PM_{2.5}$ can penetrate deeper into the lungs, while PM_{10} tends to deposit higher in the lungs (California Air Resources Board et al., 2018). Windblown dust tends to be the larger PM_{10}, although the movement of PM_{10} will often stir smaller $PM_{2.5}$ particles into the wind (California Air Resources Board, n.d.). $PM_{2.5}$ often come from combustion, whether from vehicle engines or fires, while PM_{10} can contain endotoxins and fungal spores in addition to coarse dust (Johnston et al., 2019).

The NAAQS are part of the Clean Air Act (1990) that require monitoring for six pollutants: carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter (both PM_{10} and $PM_{2.5}$). The NAAQS stipulate that PM_{10} must not exceed 150 $\mu g / m^3$ in a 24-hour period. The criterion for compliance with the NAAQS is the limit may not be exceeded more than once per year when averaged on a three-year basis. If these conditions are not met, the area may receive "non-attainment" status. Under the NAAQS, an exceedance day is a day when the PM_{10} exceeded the allowable levels. Exceedance days can be classified as exceptional events, which are defined as "unusual or naturally occurring events that can affect air quality but are not reasonably controllable using techniques that tribal, state, or local air agencies may implement to attain and maintain the National Ambient Air Quality Standards (NAAQS). Exceptional events may include wildfires, high wind dust events, prescribed fires, stratospheric ozone intrusions, and volcanic and seismic activities." (Environmental Protection Agency, n.d.). Events are only classified as "exceptional events" if the state applies for them to be flagged as an EE and the US EPA concurs with that classification. These applications will only be filed if a designation of exceptional event would be necessary for the state to meet NAAQS attainment status. For example, on September 13th and 14th, 2017, strong winds out of the west caused a large dust storm in the Imperial Valley and exceedance values in Brawley, El Centro, and Westmoreland. The state applied for exceptional event status for this dust storm, needing to prove that this event was a natural event that was not reasonably controllable and that anthropogenic sources of pollution were controlled using Best Available Control Measures (BACM).

The National Ambient Air Quality Standards rules for PM_{10} went into effect on August 22, 1994 (Environmental Protection Agency, 2004) and according the Ninth Circuit Court of Appeals in 2004, Imperial County did not meet the PM_{10} standards by the deadline of December 31 of that year and was designated a Serious Non-Attainment Area (Environmental Protection Agency, 2004). In 2018, the county applied for and received maintenance status, and is no longer classified as a non-attainment area (California Air Resources Board et al., 2018), showing that the air pollution control district had complied with federal standards except during officially designated exceptional events. The area received final approval of its redesignation to attainment status in October 2020 (Environmental Protection Agency, 2020).

The Salton Sea region's redesignation to maintenance status is due to two main factors. First, the Exceptional Events rule, promulgated in 2007, enabled the Air Pollution Control Board to exclude from consideration events that were beyond the control of the managing agency, such as large dust storms from the desert and the transmission of pollutants from the industrial facilities south of the international border in Mexicali. The second factor is that the Air Pollution Control Board demonstrated in their application that they had implemented "permanent and enforceable regulations" to curb PM_{10} emissions. Immediately following the designation as a non-attainment zone in 2004, the county developed Regulation VII rules that would curb these pollutants. They went into effect in January of 2006 and were updated again in 2010, going into effect in 2012 (California Air Resources Board et al., 2018). Rules 800-806 of Regulation VII govern sources of PM_{10} including: construction and earth moving activities, bulk materials transport, handling and outdoor storage, emissions from non-agricultural open areas, such as vacant lots (with an exemption for off-highway vehicle (OHV) areas), paved and unpaved roads, and agricultural operations over 16.1 hectares (California Air Resources Board et al., 2018).

PM_{10} events are correlated with high winds, and high winds are characteristic of the desert winters (Bach et al., 1996). In the Salton Sea basin, high winds tend to come from the west (D'Evelyn et al., 2021; Evan, 2019; Freedman et al., 2020). Air blown up over the Santa Ana mountains near the coast descends rapidly to the desert floor, picking up speed as it travels and creating a standing wave of high winds. These winds pick up sand and dust from the desert and spread it across the valley floor. Most high PM_{10} events occur from this pattern (Evan 2019). This pattern is also common during the fall and spring, the highest emission times in the desert (D'Evelyn et al., 2021).

Summer storms typically come from the south (Fogel et al., 2021). These storms are formed from monsoonal convection and form haboobs, dust storms that arise from the winds associated with thunderstorms (Amato Evan, personal communication, 2024). These storms drive north along the Imperial Valley and could send dust from the Salton Sea playa to northern residential areas, including Mecca and Indio.

The Playa as a PM_{10} Source

Several studies have attempted to quantify emissions from the playa directly using several methods. One method involves classifying landcover types and then using a portable wind tunnel to measure the amount of PM_{10} that is emitted given a certain velocity of wind (Cheng et al., 2022; Imperial Irrigation District & Formation Environmental LLC, 2016b; J. King et al., 2011; Sweeney et al., 2011). Other authors collected dust and conducted elemental analysis to compare the composition of dust to the composition of soils collected on the playa and elsewhere (Frie et al., 2017, 2019). Still others have attempted modeling (Jones & Fleck, 2020; Parajuli & Zender, 2018). Wind tunnel studies try to understand the dust from its source, elemental analysis studies try to study the dust in places where it is deposited, and modeling studies try to understand the regional scale dynamics. Each of these studies provide valuable insight into the dust dynamics in the region.

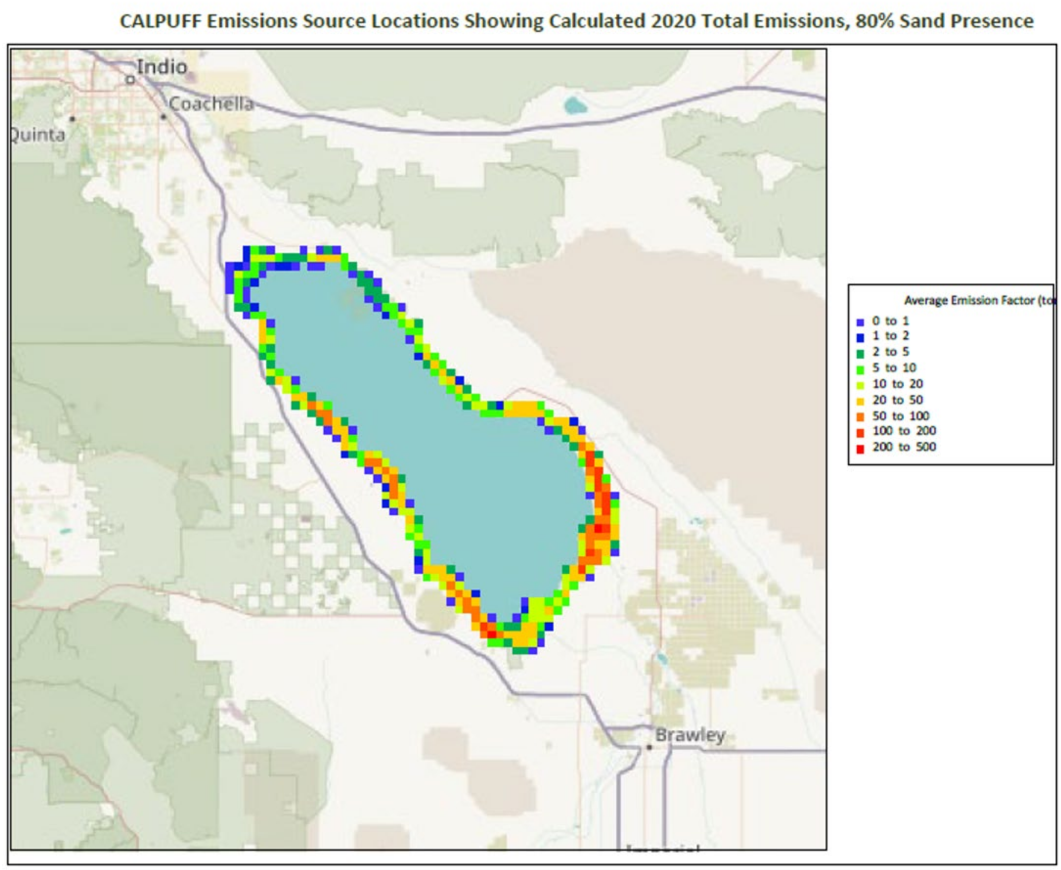

Figure 11: Map of emissivity of playa surfaces. From Salton Sea Long-Range Plan (Salton Sea Management Program, 2024).

These approaches have led to several conclusions. Playa emissions are variable depending on the crust type, position within the playa (margin or central), and wetness of the soil (Figure 11). Buck et al. (2011) characterize with a great degree of specificity the emissions potential of salt crusts with various compositions, finding that there is great heterogeneity in crust types and emissions potential on the playa.

Sweeney et al. (2011) found that playas with loose sand or soft crusts can be very high emitters, whereas playa with salt crust is one of the lowest emitters of PM_{10}. King et al. (2011) confirm this but add that salt crust playa can become much higher emitters, but only in the winter months when temperatures and humidity weaken the crust. The playa margins (i.e. portions of the exposed lakebed that were once the shores of the full lake) are more emissive than other areas of playa(Sweeney et al., 2011), and the areas with high water tables (often the playa closest to the receding lake) are not emissive to PM_{10} (Imperial Irrigation District & Formation Environmental LLC, 2016b). Sweeney et al. (2011, p. 31) go as far to say:

> *"Based on our comprehensive data set of dust emissions, we demonstrate that in the Mojave Desert alluvial sources such as dry washes and distal alluvial fans are much larger contributors to atmospheric dust loading compared to other landforms, particularly playas. Playas themselves are extremely heterogeneous with regards to dust emissions, with the highest emissions occurring on the coarser-grained playa margins that have been overlooked as a potentially large source of dust."*

Playa also seems to be the most temporally variable of the emissions sources (Frie et al. 2019, Sweeney et al. 2011). Frie et al. (2019) found that 36%-47% of emissions they captured were from the playa, and most of that mass came from a single dust event in April of 2018. In another study using elemental analysis, Frie et al. (2017) found that 9% of collected PM_{10} emissions were from the playa.

The Salton Sea Emissions Monitoring Program estimated the emissions from the playa and other sources every year since 2016 using a Portable In-Situ Wind

ERosion Lab (PI-SWERL; Formation Environmental LLC et al., 2020; Imperial Irrigation District et al., 2018; Imperial Irrigation District & Formation Environmental LLC, 2016b, 2019, 2021, 2022). IID classified ground cover in the study area based on soil type and soil crust type and then used emissivity estimates from the PI-SWERL measurements to extrapolate the emissions over the previous year. This analysis has consistently found that the emissions from the playa are much lower than from the deserts to the west of the Salton Sea, both in total and on a per unit area basis. Table 3 compares emissions from the playa and the desert to the west of the sea by mass and as a weighted average. IID found that the desert was more emissive by total mass with the playa only contributing an average of about 1% of total PM10 mass. They also found that the desert was more emissive on a per area basis, but the difference varied greatly between years.

Table 3: Absolute and relative contributions of the desert to the west of the Salton Sea and the Salton Sea playa to PM_{10} in the Salton Sea Region (from the yearly Salton Sea Air Quality Mitigation Program Reports published by the Imperial Irrigation District and Formation Environmental LLC).

Year	Playa Exposed (hectares)	Playa Emissivity tons/yr	Desert Emissivity tons/yr	Percent of emissions from Playa by mass	Playa weighted area average (tons/km2)	Desert weighted area average (tons/km2)
2016/17	6657	306.3	40,205.70	0.80%	5.6	15.37
2017/18	7137	447.2	45,280.80	1.00%	6.3	10.9
2018/19	8462	385.9	37,438.80	1.00%	4.7	9.02
2019/20	9678	35.0	15,218.00	0.20%	0.38	3.67
2020/21	10355	428.7	30,347.50	1.40%	4.14	7.3

Also notable is that 34,000 hectares of desert to the west of the Salton Sea are occupied by the Ocotillo Wells State Vehicle Recreation Area, an Off-Highway Vehicle (OHV) park that allows largely unrestricted vehicle travel. This activity can destroy soil crusts and destabilize otherwise non-emissive soil types (Imperial Irrigation District & Formation Environmental LLC, 2016a).

Air Quality Data Analysis

The official regulatory air quality monitoring stations designated by the EPA are the only long-term sources of calibrated, officially recognized air quality data in the region (Figure 12). Residents have criticized the EPA's data collection because the monitoring stations in the Salton Basin are not close to the shores of Salton Sea and the sensors may not capture dynamics in communities on the water's edge (Carvlin et al., 2019). Niland, Westmorland, Brawley to the south and Mecca to the north are the closest official monitoring stations to the sea.

MONITORING SITES IN AND AROUND IMPERIAL COUNTY

Figure 12: Monitoring Sites in and Around Imperial County. Reprinted from Salton Sea Air Quality Mitigation Program Annual Report 2016.

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Coverage of air quality sensors are not only sparsely distributed, but there are differences in the sampling frequency of the sensors. The minimum required sampling interval for PM_{10} is every six days. For each quarter's data to be considered for use, 75% of the six-day-interval measurements must be complete. (Title 40 Chapter I Subchapter C Part 58 Subpart B § 58.12). In the past 15 years, the number of days that data were collected increased dramatically, from an average of less than 100 days from 1990 to 2000 to 365 days a year of data coverage from 2019-2024 due to the advent of autonomous sensor technology. In years with less than 365 days of data coverage, the number of exceedance events are extrapolated linearly from the ratio of observation days to observed exceedance days (Title 40 Chapter I Subchapter C Part 50 Appendix K to Part 50).

The available data from the monitors closest to the sea can be analyzed for an upward trend in the number of exceedance days as the playa expanded (Figure 13). No increase in the number of exceedance days over that period can be observed. Playa area is therefore a poor predictor of the number of exceedance days (Robust Linear Model; df=74, t=0.316, p=0.75).

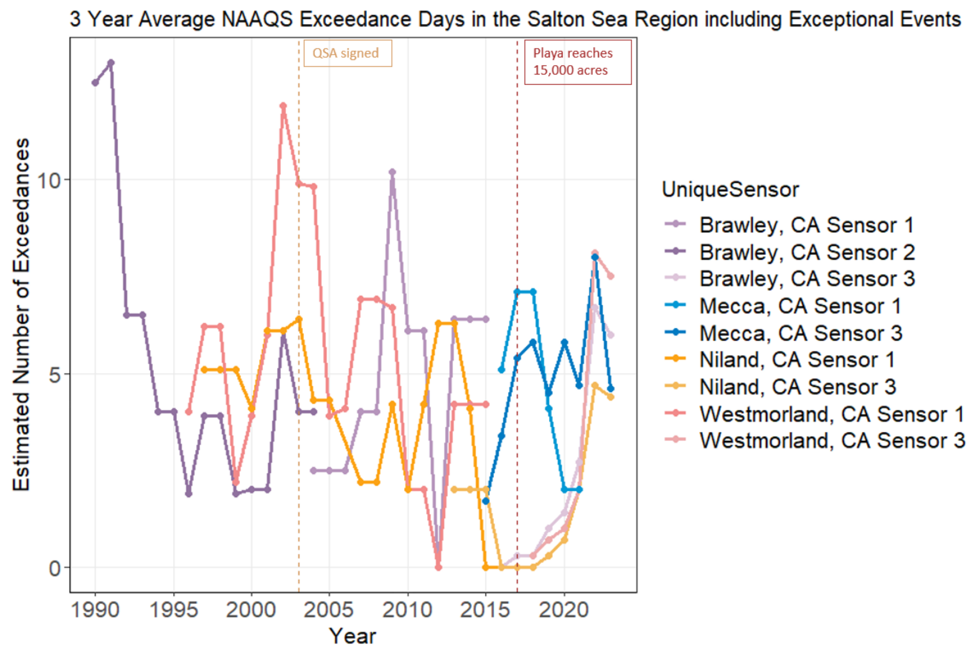

Figure 13: Three-year average number of exceedances per year at sites around the Salton Sea.

In order to better characterize the air quality closer to the sea, IID installed six air quality monitoring stations at sites on the shores of the Salton Sea (Figure 12). These sensors were designed to better characterize the conditions closer to the sea and to determine the effect of playa on $PM_{10.}$ These stations are not official regulatory sensors, however they are of the same quality as the official sensors and a comparable analysis using the criteria supplied by the Clean Air Act is possible (Figure 14).

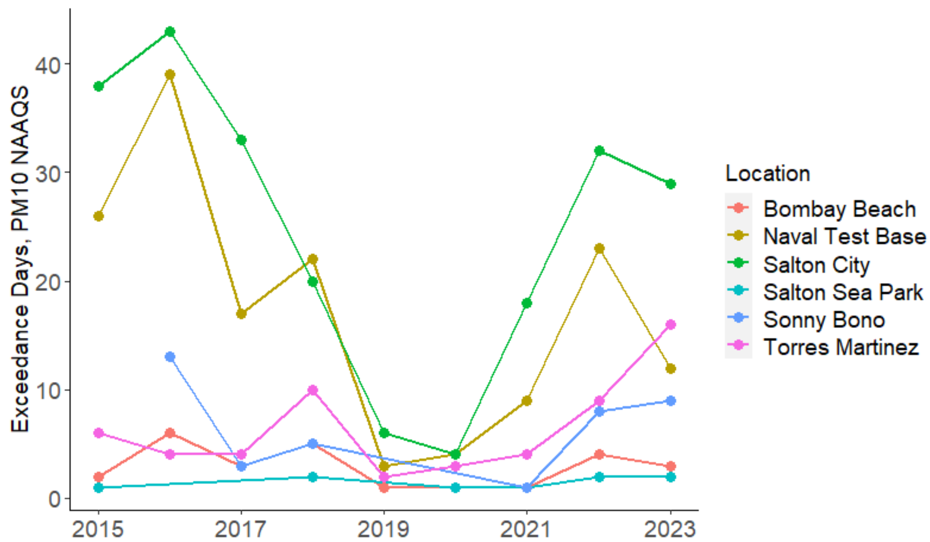

Figure 14: Estimated Exceedance days at sites on the shore of the Salton Sea as computed by the author using EPA rules.

The first and most striking trend in these data is the dip in the number of exceedance days at Salton City and the nearby Naval Test Base in 2019 and 2020. This dip can also be seen in official regulatory sensors further from the sea. IID and their contractor (Formation Environmental) ascribe this dip to an unusually wet year during which the playa and surrounding desert remained wet longer, making substrates less emissive (Victoria Quinn, personal communication, 2024). A former Air Resource Board employee suggested that landslides in the mountains to the west of the sea caused large areas of easily entrainable sediment to be exposed in 2014, and that as this reservoir of sediments depleted or changed, the number of exceedance days decreased (Earl Withycombe, personal communication, 2024).

Overall, Naval Test Base and Salton City had many more exceedance days than the other four sites. These sites are the only sites on the west side of the sea. As the predominant wind in the region originates from the west-northwest (D'Evelyn et al., 2021; Evan, 2019), the dust causing the majority of these exceedance days must have been entrained upwind of the site in the deserts to the west of the sea. This matches the findings of IID's analysis of these data which show that the highest concentrations of PM_{10} were at the monitoring stations to the west of the Salton Sea, and occurred when the wind was blowing in from the west (Figure 15; Imperial Irrigation District & Formation Environmental LLC, 2016b).

If the Naval Test Base and Salton City are excluded entirely, we find that playa area is again a poor predictor of the number of exceedance days (RLM; df = 120, T = -0.14, p = 0.89), indicating that the increase in playa area is not having a detectable impact on the number of poor air quality days.

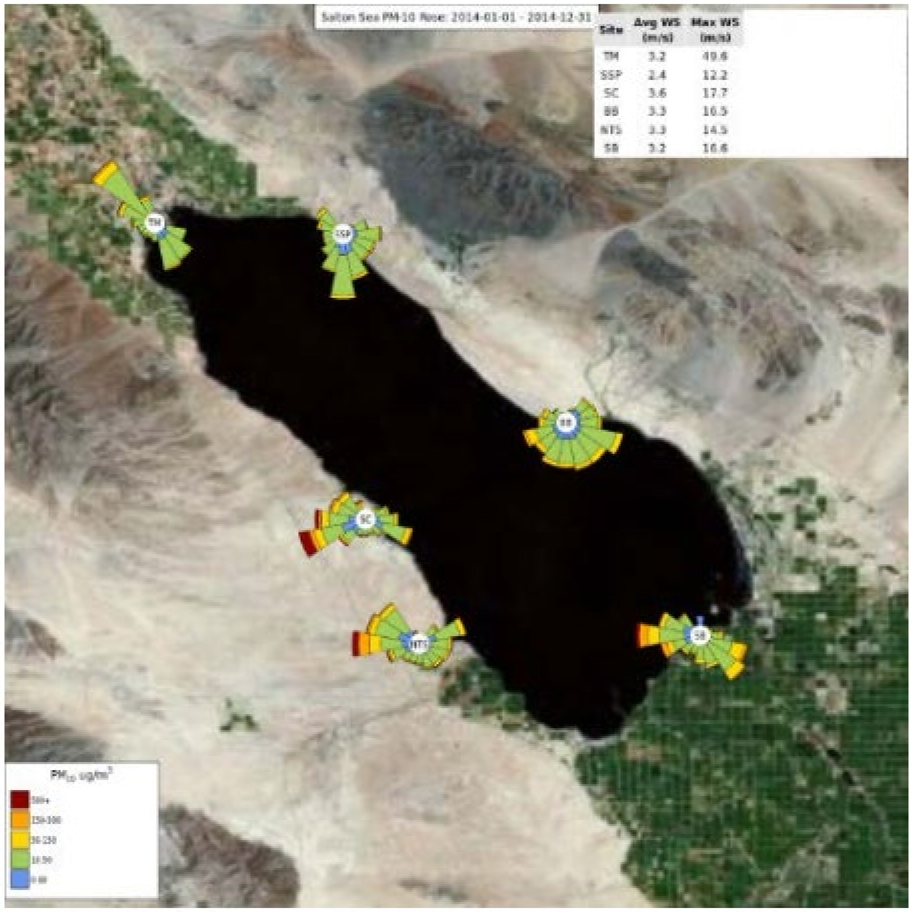

Figure 15:PM10 wind roses for monitoring sites on the shores of the Salton Sea. The size of the triangular shape emerging from each point shows the amount of wind the site receives from that direction, and the color indicates the air quality. Reprinted from Salton Sea Air Quality Mitigation Program Report 2016.

Magnitude of Exceedances

From the previous analysis, it appears that the number of PM_{10} exceedance days has not increased in response to increased playa area. It could be, however, that as the overall number of exceedance days are largely driven by wind events, an increase in playa area would not lead to an increase in the number of exceedance days, but only to an increase in their magnitude. That is, the number of events would not increase, but the amount of pollution per event would increase. The EPA records the maximum hourly average value PM_{10} on each exceedance day. Figure 16 compares those data to playa area. In an analysis including all data through 2022, there is a significant relationship between magnitude of the exceedance days and the playa area in hectares (robust linear model (RLM); df=549, t=3.94, $p < 0.0001$) with an effect size of 0.003 ppm PM_{10} per hectare of playa exposed (Figure 16). This effect size amounts to an increase in the severity of exceedance days of 3 ppm per thousand hectares exposed or 40 ppm between the completely full lake and current playa levels. This shows that playa is increasingly contributing to dust in the region and currently contributes about 20% of regional PM_{10}.

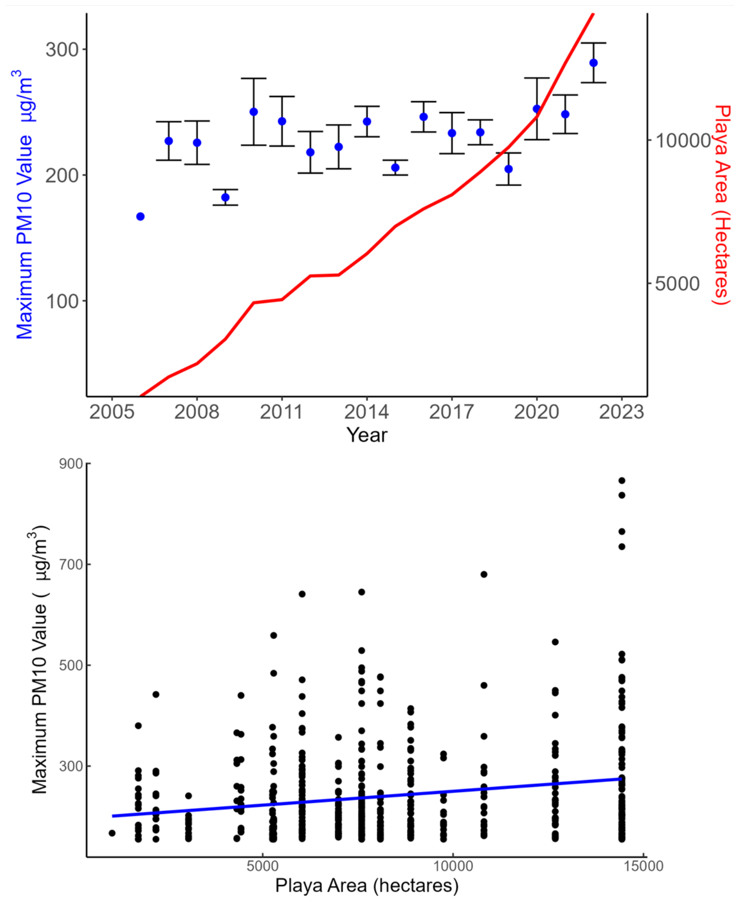

Figure 16: Analysis of maximum one-hour average PM10 reading on exceedance days 2005-2022.

The California Department of Public Health asthma data show that in 2015 emergency department visits in Imperial County for children 5-17 were already double the state average at 150 incidents per 10,000 residents. For the playa to have a causal link with asthma-related emergency department visits, the playa would need to affect exceedance magnitude prior to 2015. An analysis of the years up to and including 2015 shows no relationship between playa area and exceedance magnitude (Figure 17; RLM; df=225, t=-0.19, p=0.85). Figure 17's upper graph shows the mean maximum exceedance value per year and the increase in playa area. Figure 17's lower graph shows the linear relationship between maximum 1-hour average PM_{10} exceedance value on exceedance days and the area of the expanding playa.

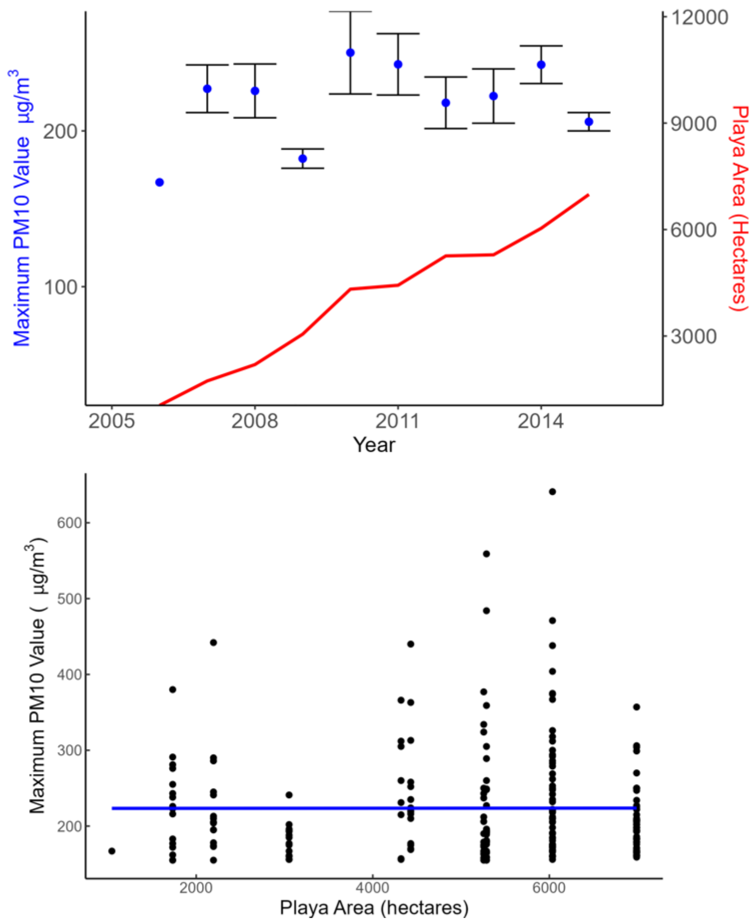

Figure 17: Analysis of maximum one-hour average PM10 reading on exceedance days 2005-2015.

The drivers of dust emission in the Salton Sea are complex, and this coarse analysis does not capture this complexity, but it does suggest that other causes of the asthma problem deserve more thorough investigation.

Is Playa Dust Toxic?

The playa is not the biggest contributor to PM_{10} in the region by mass basis, but it has been widely reported that the playa dust is toxic (e.g. Griswold et al., 2024; Sandusky, 2023; Singh, 2021). If this is the case, then a relatively small contribution to total PM_{10} could lead to outsized effects on human health. A thorough investigation of this possibility is warranted.

Very few studies have directly analyzed the dust. One study (Frie et al., 2017) looked at the occurrence of heavy metals in collected dust and found that there was no evidence that heavy metals were present in the playa dust. They did, however, find elevated levels of selenium. No studies have addressed the presence of current or agricultural chemicals in the playa dust. Experiments to determine this are difficult and costly (Amato Evan, personal communication, 2024).

What is clear is that the water and sediments flowing into the Salton Sea are highly contaminated with agricultural chemicals. Contemporary pesticides, either currently or recently in use, such as dacthal, chlorpyrifos, pendimethalin, and trifluralin were the most commonly pesticides found in suspended sediment in the New and Alamo Rivers in 2003 (Leblanc et al., 2004). Chlorpyrifos, permethrin, tetraconazole, and trifluralin were detected in over 75% of suspended sediment samples in a 2006-2007 study (Orlando et al., 2008). These pesticides are often present in concentrations exceeding federal standards. For example, in the same

2006-2007 study, carbofuran, chlorpyrifos, diazinon, and malathion were all present at levels exceeding standards for the health of aquatic life.

Although banned in 1972, organochlorine pesticides such as DDT are present in sediments throughout the inflowing rivers. In 2003, the DDT metabolite p,p'DDE was found in all sites on the Alamo River and two sites on the New River (the Whitewater River was not sampled; Leblanc et al., 2004). In 2001 and 2002, p,p'DDE was found in all three inflowing rivers at similar concentrations (Leblanc et al., 2003). In a 2006-2007 study, DDE was found in suspended sediment samples in all eight study sites on the New and Alamo Rivers (Orlando et al., 2008). Concentrations of p,p'-DDE in mosquitofish were 0.58 $\mu g\ g^{-1}$ wet weight, almost three times greater than averages recorded in national monitoring programs from past years (Leblanc et al., 2004).

While there is ample evidence that the sediment and water flowing into the sea are contaminated with numerous pesticides, the spatial distribution of pesticide contamination on the lakebed has fewer studies. A 1996-1997 study documented water samples from locations within 5 km of the mouth of the Alamo River and found concentrations of organophosphate pesticides at all sites, including the furthest site (Crepeau et al., 2002). A 2012 study is the most comprehensive and looked at sites around the outlets of the New and Alamo Rivers. They found that the majority of legacy pesticide contamination was from DDT, with a maximum concentration of 109 $\mu g\ kg^{-1}$ (W. Wang et al., 2012), more than thirty times the threshold effect concentration, and more than three times the probable effect concentration. DDT was found in all soil layers, but concentrations increased with soil depth due to limited deposition since the chemicals were banned. Deposition has been continuously occurring from eroding sediments in the New and Alamo Rivers, supplying the top layer with some presence of DDT derivatives. Based on their sampling, the authors were able to estimate a map of the DDT distribution around the mouths of the New and Alamo Rivers. Samples that exceeded the threshold effect concentration were taken close to the mouth of the river. The concentrations decrease with distance from the mouth of the river. Within 3 km from the river mouth, the concentrations drop below 1 $\mu g\ kg^{-1}$. Surface sediments at the river mouths are highly contaminated, but surface sediments 3 km from the river mouth did not have DDT derivatives at detectable levels. In lower soil layers, DDT was found further out, but the exact extent is not known.

Two studies have looked at the effect of aerosolized playa dust on the respiratory health of mice. Dust collected at the eastern shore of the Salton Sea aerosolized and exposed to mice for 7 days caused elevated recruitment of eosinophils and Th-2, which is consistent with inflammation, but not with an asthma-specific inflammation (Biddle et al., 2023; Biddle, personal communication 2024). The inflammation caused by this dust is of a type that would not continue if the person were no longer exposed to the irritant. Interestingly, in the same study, aerosolized playa dusts did not cause the same inflammation. This may be due to methodological issues (large salt crystals may dominate in the aerosolization process, diluting the effects of other contaminants) or there may be a concentration effect of hydrophobic pollutants as the dust is aerosolized (Biddle, personal communication 2024). The causes of this inflammatory effect, which is more than typical dust but not an asthma specific inflammation, remain unknown. The same group examined the effects of aerosolized Salton Sea water, with the idea that any irritants present in the water will be deposited in the soil, and came to similar findings (Biddle et al., 2021).

Another group looked at the inflammatory effects of different size fractions (eg. coarse (PM_{10}-2.5, > 2.5 μm, but < 10 μm), fine (PM2.5-0.1), and ultrafine (< 0.1 μm)) of collected Imperial Valley PM on macrophage cell lines (D'Evelyn et al., 2021). They found that PM_{10} triggered the highest inflammatory response of the particulate matter size classes and suggest that this is due to the presence of endotoxins (the byproducts of toxic gram-negative bacteria) present in the dust. This biological cause is consistent with the findings of Biddle et al. (2023), but the exact pathway or source of this biological component is not known. Cyanotoxins secreted from large blooms of cyanobacteria are common in the Salton Sea's water (Carmichael & Li, 2006) and could be causing this inflammation if the cyanotoxins can survive precipitation and desiccation, but this needs to be explored.

Despite playa dust constituting a small portion of total PM_{10} emissions, the elevated presence of endotoxins and pesticides in playa dust could lead to significant health impacts.

Other Possible Sources of Pulmonary-related Pollution

Although playa is likely a contributor to PM_{10}, the evidence that the asthma crisis predates the detectable contribution of playa to PM_{10} should inspire research into other explanations for the high level of disease in the region. The region has many sources of pollution (Farzan et al., 2019; Johnston et al., 2019) In this regard, Cheney et al. (2022) found that farmworkers in the Mecca, CA area were regularly exposed to high levels of agricultural chemicals and brought them home on clothing. Forty-three percent of these farmworkers reporting never receiving chemical handling safety training. To look at another example, a meta-analysis of the health of children living in agricultural communities found that about three-fourths of all studies reported negative effects of pesticides on childhood respiratory health, and 90% of papers reported negative respiratory health effects from agricultural burning (Van Horne et al., 2022). Although regulations on both exist in Imperial County, these practices still occur at harmful levels (Harnly et al., 2012).

Conclusions

The marginalized communities of the Salton Sea face myriad environmental challenges. Deciding what to do about the sea has been the subject of debate for nearly half a century, with little substantive action (M. Cohen, 2014). Despite this, we still lack basic information needed to better understand the problems facing the ecosystems and human populations of the region. This research supports four main conclusions:

1. The asthma crisis at the Salton Sea is poorly understood.

CDPH datasets indicate extremely high levels of emergency department visits and hospitalizations among children at the Salton Sea, and qualitative data (Cheney et al., 2023), media accounts (Griswold et al., 2024; Sandusky, 2023; Singh, 2021), and the testimony of community groups indicate that there are respiratory health problem in the area, but the quantitative data are complicated by socioeconomic factors, such as insufficient access to PCPs, and other sources lack specificity. A comprehensive approach to this problem requires epidemiological data to understand the risk factors and causes of the problem and pathology data to insure the best treatment. Furthermore, current approaches to the solution to the problem have not prioritized information about the health problem, but rather the reduction of emissions from the playa.

2. The Salton Sea playa is a source of PM_{10}, but in most places in the Salton Sea region, it is not the main contributor.

The studies by IID and others show that the majority of particulate matter emissions in the Salton Sea region comes from the desert to the west of the Salton Sea. This is sensible as the dominant wind direction is from the west, the desert has a much larger surface area, and desert washes have been shown to be one of the most emissive landcover types in the region. The historical air quality data show that there has not been an increase in the number of poor air quality days (as defined by the NAAQS) since records began or since the playa area has increased. However, the magnitude of the PM_{10} measurements on those poor air quality days has increased with playa area since 2017.

3. Playa dust may be toxic to people, but we do not know if it is or by what mechanism.

The soils at the mouths of the rivers contain toxic legacy pesticides that are likely being aerosolized in those areas. We do not know if they are being aerosolized or in what concentrations. Nor do we know if these pesticides are present in other areas of the playa. There is evidence that the playa dust may cause an inflammatory response due to the presence of endotoxins (Biddle et al., 2021, 2023; D'Evelyn et al., 2021), but we do not have information on the origin or type of these endotoxins. There is evidence that playa dust does not contain heavy metals (Frie et al., 2017).

4. The region's current asthma crisis is likely due to factors that pre-date the shrinking of the Salton Sea.

Given contribution of playa dust to PM_{10}, the distance between the playa and the major population centers in the county, the available asthma data, and the dominant wind direction, it seems unlikely that the Salton Sea playa dust exposure could be the primary cause of the current asthma crisis. Of the data presented here, only the increase in the concentration of pollutant in PM_{10} exceedance days track with expansion of the playa, but this trend emerged after the asthma problem had already become severe.

Recommendations

An ideal remediation and restoration plan for the sea would implement solutions that support and improve the health of the people in the region. Taking action on confirmed problems while using the best available science to target the sources of pollution that are making people ill is an essential first step. Several recommendations in three broad categories emerge from this research:

1. Mitigate the potential impacts to communities

As there are many unknowns regarding the impacts of expanding exposed playa on public health, the precautionary principle should be applied. To this end:

The shrinking of the sea should be slowed or arrested by **reinstating the mitigation flows**. This can be done by implementing a subsidized fallowing program in Imperial Valley, as occurred between 2003 and 2017. Stabilizing the sea at a higher level or decreasing the rate of its decline will buy time for research to provide better data and implement plans to make the area more habitable for people and wildlife.

The playa remediation efforts should not have a main goal of reducing total PM_{10} from the playa, as the playa PM_{10} is still a fraction of the total for the area. Instead, these efforts should focus on **reducing PM emissions from areas where legacy pesticides are found** in significant quantities in the soil. Playa remediation will not have a meaningful effect on the total volume of PM_{10} pollution in the area due to high emissions in the western deserts at current playa exposure levels, but could help suppress the emissions of toxic hydrophobic pollutants. Playa dust remediation should use techniques that do not disturb the soil in areas with known high levels of DDT contamination as the DDT contamination is worse in lower soil profiles, even 15 cm below the surface (W. Wang et al., 2012).

The state of California should allocate funds to establish **a free respiratory health clinic** to treat and document the reportedly high numbers of asthma cases in children. This effort should include incentives to attract more physicians to the region. This clinic should be designed in a way that would reduce barriers to care that people experience and should undertake outreach to residents through community groups.

2. Improve understanding of the problem through targeted research

The many unknowns of this problem impair our ability to accurately target the sources of pollution and mitigate them. Therefore, key knowledge gaps should be identified, and research should be funded to get answers. Among these should be:

The **toxicity of playa dust and the spatial distribution of those toxins** could help shape more effective mitigation strategies and guide policy. A comprehensive understanding of the spatial distribution of pesticides in sediments, and how readily they are aerosolized would drive the selection of areas of high priority for dust suppression. The current mitigation plan targets areas of playa based on the emissivity of the substrate only. Knowing that legacy pesticides are found at higher concentrations 15cm underneath the surface of the playa could lead to selecting mitigation techniques that do not disturb the soil (like the plowing of furrows, which is a common practice (Imperial Irrigation District & Formation Environmental LLC, 2016a)). An understanding of what biological agents might be driving increased inflammatory reactions in mice (Biddle et al., 2021, 2023) could potentially help prevent their further production.

Other sources of particulate matter exposure should be thoroughly investigated. The region has many sources of PM_{10} and myriad sources of other pollutants that could have negative impacts on respiratory health. As the asthma problem appears to predate the expansion of the playa, sources of pollution extant before the expansion of the playa should be thoroughly investigated.

The nature of the asthma epidemic needs elaboration both in pathology and epidemiology. Clinical studies of asthma are needed to understand the extent and specific nature of the epidemic that include airway measurements and life histories of local residents to understand what pollution sources they are exposed to. These studies could have the two-fold impact of helping to better understand the problem and helping doctors better treat their patients.

Based on these data, **developing a model of future playa emissions** can help us understand the impact on communities of various scenarios.

These studies should be conducted to better understand the problem so that the next round of decision making can occur with better data that targets the sources of pollution that have negative effects on the health of people in the region.

3. Develop an integrated plan for the region

A new plan should have explicit targets for emissions based on empirical models (a feature lacking in current plans), a program to decrease asthma rates, and plans for the sequestration or remediation of areas with legacy pesticides. A targeted, science-based approach to remediation will reduce the overall cost of remediation by allocating resources to the investments that have the highest public health impact. Plans for the sea need to have a pragmatic focus on providing the most benefit to the human and non-human ecological communities of the sea by targeting the actual sources of pollution affecting them.

Appendix A: Imperial County Asthma Data from the California Department of Public Health "California Breathing" Database

TABLE A1: California Department of Public Health Asthma Prevalence Data for Imperial County

		2015-16				2017-18				2019-20			
		Imperial City	CA Average	CA Rank	Number of Countiies with Data	Imperial City	CA Average	CA Rank	Number of Countiies with Data	Imperial City	CA Average	CA Rank	Number of Countiies with Data
Lifetime Asthma Prevalence		percent	percent			percent	percent			percent	percent		
Total Population	All Ages	12.1	8.7	8	58	14.7	15.4	45	58	15.9	15.1	34	58
Children vs. Adults	0-17	19.1	10.1	3	14	NA	13.7	NA	12	10.4	11.9	33	46
	18+	8.9	8.3	36	58	17.7	15.9	34	58	18.1	16.2	29	58
Age Group	0-4	NA	4.5	NA	NA	NA	4.8	NA	1	NA	4.6	NA	4
	5-17	20.5	12.3	6	14	NA	17.1	NA	10	12.1	14.5	34	45
	18-64	8.7	8.1	38	58	16.6	16.3	38	57	18.3	16.6	31	58
	65+	NA	9.2	NA	55	22.1	14.1	3	51	17.3	14.6	20	58
Current Asthma Prevalence													
Total Population	All Ages	12.1	8.7	8	57	11.4	8.8	28	56	10.6	8.7	21	58
Children vs. Adults	0-17	19.1	10.1	2	9	NA	8	NA	6	7.5	7.4	21	32
	18+	8.9	8.3	36	58	12.9	9.1	26	56	11.9	9.1	12	58
Age Group	0-4	NA	4.5	NA	NA	NA	4.1	NA	1	NA	3.3	NA	5
	5-17	20.5	12.3	2	7	NA	9.5	NA	5	NA	8.9	NA	27
	18-64	8.7	8.1	39	56	11.1	9	32	55	11.5	9	18	58
	65+	NA	9.2	NA	43	20.9	9.4	3	34	13.5	9.2	8	58

Column Key

Imp Cty	Percentage prevalence
CA Avg	Average percentage prevalence in counties with available data
CA Rank	Rank in CA counties
# Counties	Number of counties for which data was available and rank was calculated

TABLE A2: California Department of Public Health Asthma Emergency Medical Care Data for Imperial County

		2015				2016				2017			
		Imperial City	CA Average	CA Rank	Number of Countiies with Data	Imperial City	CA Average	CA Rank	Number of Countiies with Data	Imperial City	CA Average	CA Rank	Number of Countiies with Data
Asthma ED Visit Rates		Ct/10k	Ct/10k			Ct/10k	Ct/10k			Ct/10k	Ct/10k		
Total Population	All Ages	71.2	50.4	**5**	51	66.3	45.8	7	56	65.7	46.9	12	57
Children vs. Adults	0-17	140.1	80.6	**3**	41	133	75.3	**3**	56	126.8	74.5	**3**	56
	18+	47.2	40	22	50	43.1	35.5	19	56	44.5	37.4	25	57
Age Group	0-4	100.9	98.7	17	37	105.6	94.8	11	49	87.8	91.5	18	50
	5-17	154.5	74	**1**	36	143	68.1	**1**	54	141.1	68.2	**1**	55
	18-64	46.3	40.7	24	49	44.1	68.1	23	56	46.2	40.2	26	57
	65+	51.7	36.4	**5**	43	38.3	21.4	**1**	51	36.5	23.4	**5**	48
Asthma Hospitalization Rates													
Total Population	All Ages	8.7	7	7	51	6.4	4.8	**3**	47	5.4	4.7	9	47
Children vs. Adults	0-17	21.3	10.1	**1**	41	17	9.4	**3**	43	14.7	9.2	**3**	45
	18+	4.3	5.9	33	50	2.7	3.1	22	44	2.2	3.1	33	45
Age Group	0-4	28	18.3	**3**	37	22.4	16.9	6	42	17.6	16.6	16	40
	5-17	18.8	7.1	**1**	36	15.1	6.7	**1**	36	13.6	6.5	**1**	37
	18-64	3.1	4.3	29	48	2	2.8	29	43	1.8	2.8	32	43
	65+	10.4	14.2	25	43	6.4	4.6	**4**	34	NA	4.8	NA	34

Column Key	
Imp Cty	Number of incidents per 10,000 residents
CA Avg	Average number of incidents per 10,000 residents in california counties for which there is data in that year
CA Rank	Rank in CA counties
# Counties	Number of counties for which data was available and rank was calculated

TABLE A3: California Department of Public Health Asthma Emergency Medical Care Data for Imperial County 2018-2019

		2018				2019			
		Imperial City	CA Average	CA Rank	Number of Countiies with Data	Imperial City	CA Average	CA Rank	Number of Countiies with Data
Asthma ED Visit Rates		Ct/10k	Ct/10k			Ct/10k	Ct/10k		
Total Population	All Ages	58.1	42.4	11	57	60.2	42.6	6	56
Children vs. Adults	0-17	108.5	64.7	**4**	57	111.7	63.4	**2**	56
	18+	40.6	34.6	27	56	42.3	35.4	18	56
Age Group	0-4	73.9	77.9	21	46	75.6	77	24	50
	5-17	121.2	59.9	**2**	55	125	58.4	**1**	53
	18-64	43.1	37.3	27	56	45.4	38.1	19	56
	65+	28.6	21.6	9	50	27.2	22.1	11	49
Asthma Hospitalization Rates									
Total Population	All Ages	5.8	4.4	**4**	45	6	4.5	**3**	50
Children vs. Adults	0-17	12.3	8.4	3	40	15.7	8.3	**2**	42
	18+	3.6	3	10	43	2.6	3.1	23	46
Age Group	0-4	11.7	14.9	23	35	16.2	14.8	10	41
	5-17	12.5	6	**1**	36	15.5	6	**1**	37
	18-64	3.9	2.7	6	42	2.5	2.8	22	43
	65+	NA	4.5	NA	36	NA	4.7	NA	32

Column Key	
Imp Cty	Number of incidents per 10,000 residents
CA Avg	Average number of incidents per 10,000 residents in california counties for which there is data in that year
CA Rank	Rank in CA counties
# Counties	Number of counties for which data was available and rank was calculated

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