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Effect of Restoration on Plant Greenness and Water Use in Relation to Drought in the Riparian Corridor of the Colorado River Delta

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Research Impact Statement: The unrestored delta riparian corridor continues to decline in EVI2 and ET but restoration has positively impacted habitats and contributed to the understanding of the continuing efforts of Minute 323.

ABSTRACT: Revitalization of the Colorado River delta riparian corridor and increasing riparian plant greenness and water use may be accomplished by added water and restoration efforts to offset declines measured since 2000 by Landsat. We use the two-band Enhanced Vegetation Index (EVI2; a proxy for greenness) and evapotranspiration (ET, mm/day) using EVI2 and potential ET(ETo) from Yuma Valley. We assess if restoration with only 7.5% landcover had an impact on the unrestored reach-level landcover by measuring these two metrics, EVI2 and ET(EVI2) by comparing restored and unrestored areas. A key finding is that over 21-years EVI2 in the unrestored corridor decreased by 23.6% and ET(EVI2) decreased by 32% (0.87 mm/day). Since 2011, the unrestored reaches lost EVI2 (11%) and −0.73 mm/day ET(EVI2) (28%), but restored sites increased in EVI2 (36%) and 0.58 mm/day ET(EVI2) (20%). Water delivered to restored sites increased EVI2 by 33.6% and 1.29 mm/day ET(EVI2) (58%). EVI2 and ET(EVI2) as a function of the Standardized Precipitation Evapotranspiration Index for drought periods highlight that restored and unrestored sites respond differently. Unrestored reaches are in decline; restored sites show increases in EVI2 and ET(EVI2). Restored sites do not have a significant impact on unrestored adjacent area, but smaller surface flows, a greater reliance on directed agricultural return flows, and deliveries of water to active restoration sites have revitalized habitat and increased ecosystem services in the delta.

(KEYWORDS: Colorado River delta; riparian plant health; evapotranspiration; restoration; drought; SPI; SPEI; vegetation greenness; Minute 319; Minute 323.)

BACKGROUND

The Colorado River provides water to nearly 40 million people for municipal use and supplies water to irrigate nearly 5.5 million acres of land (U.S. Bureau of Reclamation 2012). The $1.4 trillion regional economy supports 16 million jobs (James et al. 2014). The Colorado River has undergone rapid change over the past 100 years, primarily due to the

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building of dams and diversions to bring water for people in many cities. Along the route from its headwaters in Colorado through four states in the Upper Basin and through three states in the Lower Basin, the river expands into a delta in Mexico. The portion of the river considered to be its delta starts at the Northerly International Boundary (NIB) at Morelos Dam near Yuma, Arizona, and continues south from Morelos Dam at the NIB through to the Southerly International Boundary near San Luis, Sonora, and further into Mexico another 130 km (Figure 1). The river rarely flows into the Northern Gulf of California (Sea of Cortez) but reached the Sea of Cortez last in 2014 during an experimental Pulse Flow in the Spring (March 23 to May 18) on the Lower Colorado River (LCR) (Glenn et al. 2017). The United States (U.S.) is required to provide Mexico with 1.5 million acre-feet (maf) of Colorado River water annually as described in the 1944 Water Treaty between the U.S. and Mexico (IBWC, https://www.ibwc.gov/Treaties_Minutes/Minutes.html, last accessed May 17, 2021).

This research contribution was conducted as part of binational agreements which allocate water for the environment under two minutes to the Treaty, Minute 319 and Minute 323 (IBWC 2012, 2017). As part of Minute 319, the delta was separated into seven reaches and these were used for research and monitoring activities following the 2014 Pulse Flow, in which 130 million cubic meters (MCM) or 105,000 acre-feet of water was released in the river channel from Morelos Dam into the delta in Mexico. The estimated flow totaled 144.3 MCM, which included the volume of the pulse (130 MCM), 12.3 MCM of base flow, and 2 MCM of operational surplus (IBWC 2018). An additional 65 MCM in base flows were directed to restoration sites that were planned and implemented since 2011 (IBWC 2017). Minute 323 prescribed science and monitoring of restoration activities that have flourished with water deliveries from 2018, in the amount of 259 MCM, directed to restoration sites (IBWC 2018). Many restoration sites have been actively planted and maintained over the last decade with the initial planting date being 2010. There are now over a dozen restoration sites in the delta with the majority of them within Reach 4. These restoration sites are managed by various nongovernmental organizations in Mexico.

Riparian restoration is on the rise as these riparian areas experience deterioration and declining health. Like many places in the American Southwest which have undergone environmental changes, the riparian woodlands along the LCR and in the delta have required help to optimize their use as habitat; sites have been selected for active restoration using myriad restoration techniques. Government agencies on both sides of the border with partners and stakeholders have joined efforts in this dryland ecosystem to make headway in the restoration of riparian woodlands within Reach 2 and Reach 4. Accurate consumptive water use estimates, including transpiration rates for riparian species and evapotranspiration (ET) for wide areas such as the riparian river reach, are needed to begin these active restoration projects. Restoration resources include water negotiations; knowing specific species water requirements is a need to plan, design, and manage restoration sites. Restoration efforts require planning of infrastructure, site topography, and water delivery points, as well as land clearing, planting techniques, and other structural and compositional considerations that need to be determined during planning and implementation stages.

Recent studies have shown that riparian reaches in the delta of the Colorado River have undergone reductions in green vegetation from human-induced activities that have caused water stress to plants (Nagler et al. 2020). Their remote sensing studies utilize vegetation index (VI) values, such as the Enhanced Vegetation Index (EVI); however, in this study, we use a two-band EVI (EVI2) as a proxy for greenness. Previous studies in the delta riparian corridor have found the reduction in green vegetation cover declines in the unrestored reaches comes from a loss in healthy, green, riparian plant-cover, not a change in plant water use efficiency nor inefficiently managed water resources (Jarchow, Nagler, and Glenn 2017; Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. 2017; Gomez-Sapiens et al. 2020). The reduction in green vegetation in the delta is primarily due to the diversion of surface water at the NIB, groundwater losses, land clearing, and fire. Alterations to streamflow by water diversions and groundwater pumping for agricultural and human use can lower base flows and water tables, reducing available water for riparian plant species and affecting the extent and type of riparian vegetation and its usefulness as wildlife habitat. Additional research on the U.S. LCR riparian corridor also shows reductions in green vegetation and its ET that are comparable with the percent losses measured in the delta (Nagler, Barreto-Muñoz, Borujeni, et al. 2021).

FIGURE 1. Map of the study region showing the Colorado River delta riparian corridor along the United States–Mexico border between Yuma, AZ and San Luis, Sonora, known as the Limitrophe Zone consisting of Reach 1 and Reach 2, and the additional Reaches 3 through 7, with 13 restoration sites being shown in Reach 2 and Reach 4 in Mexico. Note that Morelos Dam, the Northerly International Border, the Southerly International Border, and the water delivery sites under Minute 323 of the Water Treaty are shown.

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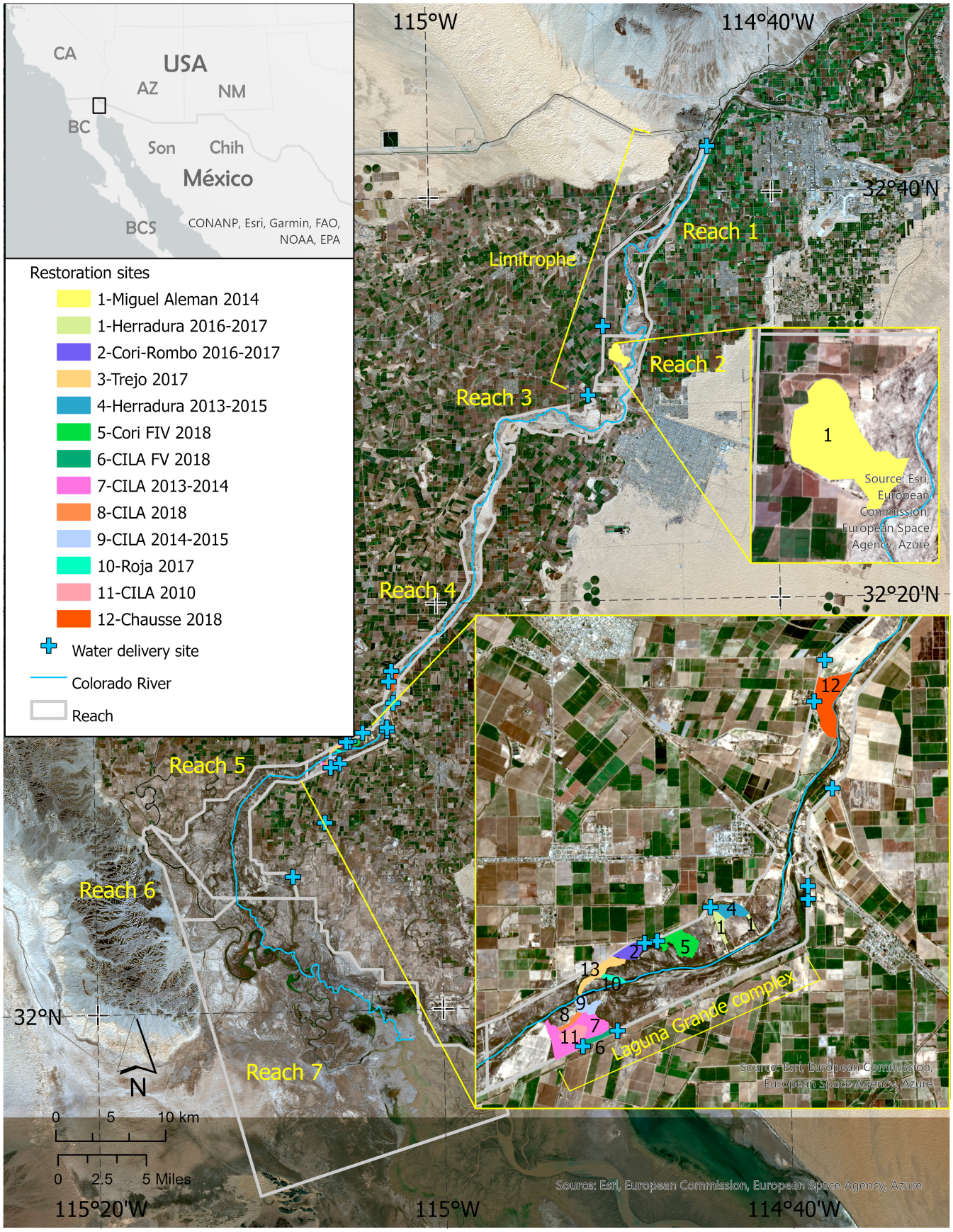

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Riparian vegetation grows primarily along waterways and serves to provide myriad ecosystem services to the environment (Clary and Booth 1993). These riparian landscape features constitute narrow wildlife corridors for upwards of 95% of wildlife in the southwestern U.S. Riparian zones (DeBano and Schmidt 2004). They provide crucial habitat to many wildlife species, serve as avian flyways, and act as important breeding grounds, these unique ecosystems occupy as little as 2% of the land surface in this arid region (Ffolliott et al. 2004; Glenn et al. 2010). Western North American birds have numerous wintering habitats in the riparian corridors within Sonora, Mexico (Mesta et al. 2006; Scott et al. 2009). Domestic livestock utilizes the available water adjacent to the riparian zone (Pinchak et al. 1991) and 70% of threatened and endangered vertebrates in Arizona depend on riparian habitat (Johnson 1989). Within this region, in the Sonoran and Mojave deserts, approximately 70%–90% of rainfall is transpired (Huxman et al. 2004; Wilcox et al. 2017; Sun et al. 2019). How much water is lost in ET from the ecosystem is directly related to the amount of vegetation in the riparian woodland corridors. In the Colorado's delta, Nagler et al. (2020) showed declines in ET on the order of 38% between 2000 and 2020; however, restoration sites, although small in size ranging from 5 to 100 ha, are demonstrating increases in ET compared to years past. The main contribution of this study is a quantification of just how successful active restoration has been in the delta after the environmental pulse flow over Morelos Dam in 2014 using remotely sensed metrics of greenness and ET for the 13 restoration plots. This study demonstrates the effectiveness of smaller surface flows, directed agricultural return flows, and directed water to the prepared restoration sites. We show for the first time that the trends in greenness and ET that have been in decline in the unrestored reaches have become positive in the restored areas. This work demonstrates the success of restoration despite environmental and anthropogenic pressures to the riparian corridor. Long-term actual ET values can be a good indicator of the resilience and resistance of vegetation under drought conditions. The knowledge of how much ET is lost in the riparian corridor helps managers partition and budget water for natural habitats and humans. Monitoring these narrow riparian ecosystems for vegetation greenness and quantifying riparian ET allows for the comparison of (1) threats from extended heat and drought, (2) extractive water demands from land-use activities, and (3) invasive species colonization.

Analysis of historical climate data for the Colorado Lower Basin indicates a decline in precipitation that started in the mid-90s with a 10-year moving average below the long-term average for the period of 1896–2019 with increases in temperature for the last 30 years (Tillman et al. 2020). In light of the declining precipitation pattern, human-induced and natural droughts with excessive heat in the Lower Basin, including its delta region, it is the expectation that water deliveries to the restoration sites in the delta are allowing these small areas of riparian woodlands to thrive. Types of drought can be defined based on the system they affect as meteorological, hydrological, and agricultural among others (Nouri et al. 2020). These types of drought can have an impact on riparian health. In this paper, we focus on meteorological drought, including an analysis using drought indices. Meteorological drought indicators may not be the best reflectors to demonstrate the impact of drought on riparian plants but it demonstrates how changes in meteorological variables impact the riparian environment through effects on the acquifer recharge and streamflow availability.

DROUGHT INDICES IN RELATIONSHIP TO VEGETATION HEALTH AND WATER USE

Drought indices have been used to forecast the future in different geographical settings and from small regions to global scales (Meza et al. 2020). A range of relationships between drought indices and meteo-hydro-agri variables have been tested to determine how well drought indices explain or reflect the ecosystem response to drought (Büntgen et al. 2021; Pokhrel et al. 2021). Multi-scalar drought indices have been used to infer past conditions of habitat for arid and semi-arid amphibian species in small water bodies (Hossack et al. 2013), to explain hydrological variability in shallow water (Sall et al. 2021), vegetation productivity responses (Khatri-Chhetri et al. 2021), and tree growth and forest dieback (Jump et al. 2017). Two multi-scalar drought indices, the Standardized Precipitation Index — SPI and the Standardized Precipitation Evapotranspiration Index-SPEI (Tirivarombo et al. 2018; Rembold et al. 2019; Spinoni et al. 2019, 2020) are utilized in this study. A range of relationships between drought indices and surface water responses, and for different durations of the same drought index from 1 to 24 months (e.g., SPI01 vs. SPI12) have been found and used to determine how well the drought indices explain water extent changes and flooding dynamics (Sall et al. 2021).

Riparian health can be affected by prolonged precipitation reductions and the effects often magnify with relative temperature rise (compared to normal) in the southwestern U.S. In this study, we assess

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how well meteorological drought indicators (using meteorological variables of precipitation and temperature) explain greenness and water use dynamics within the riparian woodlands of the delta riparian corridor. We used SPI and SPEI multiscalar drought indices to evaluate the relationship between SPI and SPEI with the greenness (EVI2) and water demand of riparian vegetation (ET derived from EVI2).

OBJECTIVES

Our objectives for this study of the Colorado River delta's riparian corridor focus on Reaches 1–4, including both the unrestored reaches and the restoration sites within Reach 2 and Reach 4. We employ monthly remote sensing data to demonstrate changes over the past 21 years (since 2000) with USGS-NASA Landsat vegetation index (VI) data and ET at the spatial resolution of 30 m (98 ft). With 21 years of data, trends in riparian vegetation greenness and water use can be observed pre- and post- the 2014 Pulse Flow, and pre- and post-restoration which began as early as 2010. Furthermore, trends between unrestored and restored areas can be measured and quantified. Lastly, the relationships between riparian plant greenness and water use and agricultural and meteorological drought can be determined. Agricultural drought is used in this study as the term referring to riparian plants, not cultivated agricultural species, that are undergoing drought.

One goal is to quantify the change in riparian plant greenness and water use of 13 restored sites planted between 2010 and 2018 which have become more widespread and successful in the recent two years, 2019–2020, due to more available water. Three sources of water have been provided to the region: (1) in 2014 as the Pulse Flow under Minute 319, (2) in 2017 as directed flows to the restoration sites under Minute 323, and (3) in 2019 as excess flows from the MODE canal. The excess agricultural return flows are delivered through Morelos Dam (Reach 1) and directed to prepared restoration sites planted in different years since 2010. The purpose of this study is to utilize our metrics to measure change in both restored and unrestored riparian Reaches 1–4 with the goal of determining the effectiveness of added water on prepared active restoration sites, which have been planted over this last decade. We acknowledge that the reach-level remotely sensed data were recently published, but did not report on restoration, nor did it focus on Reaches 1–4, and we used different metrics. In this study, we compare the plant greenness and water use values between the restored and unrestored areas during three periods: (1) the full 21 years (2000–2020), (2) the recent decade (2011–2020), and (3) after the Pulse Flow (2014–2020).

The second goal is to apply drought indices to our measurements of greenness and water use to determine predictive relationships. We combined restored sites and unrestored reaches and show that EVI2 and ET(EVI2) as a function of the SPEI have different relationships for the given drought periods of 3, 9, 12, and 24 months. Our hypothesis is that the restored and unrestored areas respond differently to drought conditions. The primary science questions are (1) whether the smaller geographical scale of restoration can prove successful at restoring the larger reach, for example, does the adjacent unrestored reach benefit from restoration activity? and whether (2) riparian plant greenness and water use trends are related to changes in drought conditions using multi-scalar drought indices and their different time scales? What multi-scalar drought index time scale best explains that relationship?

Our hypothesis is that small, active restoration plots over the last decade have increased riparian vegetation health, but at the wider, reach-level, declines which started two decades ago in 2000 persist along the riparian corridor. Our second hypothesis is that drought has an effect on both vegetation health and water use.

METHODS

Study Areas

This study focuses on four areas of interest (AOI) in the riparian corridor of the LCR delta: (1) 13 restoration sites with various initial planting dates with the earliest started a decade ago in 2010, one site in Reach 2 (Miguel Aleman), and 12 sites in Reach 4 within the Laguna Grande restoration complex and Chausse restoration site, (2) unrestored/uncultivated or natural riparian corridor existing adjacent to the restoration sties in Reach 2 and Reach 4 (exclusive of the restoration sites), (3) all the land area within Reach 2 and Reach 4 (inclusive of the restoration sites), and (4) the weighted average of the riparian corridor ("All" reaches from Reach 1 to Reach 4) (Figure 1, note that Laguna Grande complex is not shown).

High-resolution imagery of each of the first four reaches was obtained from drone flights in 2018 and 2019. In conjunction with ground observations and surveys from recent studies (Shafroth et al. 2017; Gomez-Sapiens et al. 2020), a land cover classification

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from 2013 (Milliken and Bangle 2013) and imagery available on Google Earth were used to describe land cover in the first four reaches by plant type and estimated fractional cover. In addition to bare soil, barren land, and open water, the riparian vegetation in both the unrestored and restored reaches is comprised of cottonwood (*Populus fremontii*) and willow (*Salix gooddingii*) trees, saltcedar (*Tamarix* spp.) and mesquite (*Prosopis* spp.) shrubs, arrowweed (*Pluchea sericea*), seep willow (*Baccharis salicifolia*), and other lower-height species such as desert scrub, grasses, and other ground covers. The reaches are described as follows:

Reach 1 is mainly comprised of saltcedar and arrowweed with less than 5% of cover of cottonwood and willow. The first 15–18 km of this river reach are perennial due seepage water from Morelos Dam, depth to groundwater table ranges from 0 to 8 m (Kennedy et al. 2017; Minute 319 Final report, 2018). The high groundwater table has maintained patches of native trees that in some areas can reach more than 15 meters in height, some portions of the channel have dense mats of giant reed (*Arundo donax*) and common reed (*Phragmites australis*), baccharis shrubs and herbaceous species (Shafroth et al. 2017). The upper portion of Reach 1 has been affected by fires and likely declines in the groundwater table that have reduced the cover of native trees in recent years.

Reach 2 and Reach 3 are ephemeral and depth to groundwater ranges from 7 to 15 m (Minute 319 Final report, 2018). Cottonwoods and willows become scarce in these river sections, with 50% bare ground or higher in some areas, tamarisk and arrowweed constitute the dominant plant types with the presence of native shrubs, mesquite, grasses, and herbaceous. Miguel Aleman restoration site has a total of 101 ha actively restored, mainly composed of mesquite and upland vegetation with 15% of cottonwood-willow vegetation type (Minute 319 Final report, 2018). In Reach 3 extensive areas of the floodplain have been cleared to expand farmlands in the last 10 years, increasing the barren ground cover type for short-term periods and permanently in some areas.

Reach 4, presents high groundwater Table (0–5 m) as a result of irrigation return flows, the stream is perennial in most of the reach (Ramirez-Hernandez et al. 2015; Kennedy et al. 2017). In Reach 4 the plant community is comprised by tamarisk and arrowweed as dominant species and small patches of native trees (*P. fremontii* and *S. gooddingii*), herbaceous and emergent vegetation in the stream banks, baccharis shrubs, saltbush, and mesquite species in the higher terraces. Reach 4 comprises the Laguna Grande (207 ha) and Chausse (63 ha) restoration sites. Laguna Grande includes 58% of cottonwood-willow cover type, 35% of mesquite and upland and 7% open water/marsh, Chausse presents 41% of cottonwood-willow, 43% of mesquite and upland, and 16% of open water/marsh actively restored (Minute 319 Final report, 2018 https://www.ibwc.gov/Files/Minute_319_Monitoring_Report_112818_FINAL.pdf).

This remote sensing study of the vegetation in the delta riparian corridor through Reach 4 includes the year 2020 in assessing the long-term riparian plant greenness and water use trends from 2000 to 2020. It differs from Nagler et al. (2020) which documented the reach-level findings for years 2000 to 2019 for the riparian woodlands in that we now compare (1) the vegetation health and water use in 13 restoration sites to their respective reaches (one in Reach 2 and 12 in Reach 4) (including and excluding the areas of restoration activity), and (2) show drought index trends with each metric, EVI2 and ET(EVI2). The dozen restoration sites in Reach 4 are shown in Figure 2 so that their respective vegetation type and community composition can be observed. We note that 2014 was the year that the Minute 319 pulse flow occurred (IBWC 2012). In this study, the reach-level data are comprised of 14 years of pre-pulse flow data (2000–2013) and seven years of post-pulse flow data (2014–2020).

Data used in this study from 2000 to 2020 for the delta riparian corridor and the restoration sites were acquired from three Landsat sensors: Landsat 5, Landsat 7 (ETM+), and Landsat 8 Operational Land Imager (OLI). Processing across the three sensors, including image processing, atmospheric correction, gap filling, continuity, was performed at the University of Arizona, Vegetation Index, and Phenology Lab following methods in Nagler et al. (2020), Didan et al. (2015), Didan, Barreto-Muñoz, Tucker, et al. (2018), and Didan, Barreto-Muñoz, Miura, et al. (2018). The only satellite imagery used in these analyses is from Landsat with 30 m (98 ft) resolution. The same image acquisition and processing methods reported for the reaches were applied to the restoration sites in this study as well as to the other AOIs that include the unrestored reaches for Reach 2 and Reach 4 which exclude their respective restoration sites.

EVI and ET Determined Using EVI2

Greenness of the plants within the riparian corridor is measured by satellite vegetation index "VI" which is an index between −1 and +1 that uses the reflectance in the red and infrared wavelengths. VI captures photosynthetically active green leaves or "greenness" of the landscape within the spatial resolution (pixel size) and is used as an indicator of plant health (Jarchow, Nagler, and Glenn 2017). Landsat is used in our study and has a pixel size of 30 × 30 m (98 × 98 ft) for an area of 900 m^2 (9,688 sq ft) per

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FIGURE 2. Landscape images in the Colorado River Delta showing the dozen restoration sites in Reach 4. Note the 12 site names with their dominant vegetation type: Miguel Alemán (cottonwood-willow and mesquite) (a), Miguel Alemán (upland: native shrubs, mesquite and palo verde, and ironwood) (b), Chausse (cottonwood-willow) (c), Chausse (cottonwood-willow, uplands, and marshland) (d), Herradura (cottonwood-willow, mesquite, marshland, and open water) (e), Cori-FIV (cottonwood-willow, mesquite, upland, and open water) (f), Cori-Rombo (mesquite and cottonwood) (g), Trejo (open water, upland, mesquite, and cottonwood-willow) (h), Roja (cottonwood-willow and open water) (i), CILA (cottonwood-willow, mesquite, and arrowweed) (j), CILA (marshland, open wáter, cottonwood-willow, saltcedar, and arrowweed) (k), CILA (cottonwood-willow and arrowweed) (l).

pixel. Our study employs two remotely sensed measurements, one an indicator of vegetation greenness, the EVI2 (unitless) and ET (yearly average of monthly data) for riparian woodlands, which requires EVI2 (ET(EVI2), mm/day). Because of the use of EVI in other VI-based ET publications, we notate this as not just ET but as ET(EVI2).

EVI is available as part of the standard Landsat data acquired from Collection 1 Level-2 (Tier-1 only) and is computed following Equation (1):

$$\mathrm{EVI} = 2.5 \times (\mathrm{NIR} - \mathrm{red})/(\mathrm{NIR} + 6.0 \times \mathrm{red} - 7.5 \times \mathrm{blue} + 1.0), \quad (1)$$

where NIR, red, and blue are the corrected surface reflectance.

Atmospherically corrected surface reflectance in the red and near-infrared (NIR) (https://www.usgs.gov/centers/eros, last accessed June 29, 2021) was also acquired to derive the two-band, EVI2, time-

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series data following Jiang et al. (2008), which is computed following Equation (2):

$$\mathrm{EVI2} = 2.5 \times (\mathrm{NIR}-\mathrm{red})/(\mathrm{NIR} + 2.4 \times \mathrm{red} + 1.0), \quad (2)$$

where NIR and red are the corrected surface reflectance.

For the delta riparian corridor, EVI and EVI2 had an $r^2 = 0.99$ (Nagler et al. 2020) and thus we chose to report the EVI2 only for this study.

There are differences in the dynamic range of EVI2 derived from the three Landsat sensors (TM5, ETM+, and OLI) which complicates time-series and change analyses when going back to the year 2000. To mitigate this issue, original methods (Didan et al. 2015; Didan, Barreto-Muñoz, Miura, et al. 2018; Didan, Barreto-Muñoz, Tucker, et al. 2018) aimed at minimizing inter-scene biases and inter-sensor differences which were used and also applied in recent research (Jarchow, Nagler, and Glenn 2017; Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. 2017; Nagler et al. 2020).

The ET algorithm used in this study was first developed with data from Bowen ratio and eddy covariance moisture flux towers in riparian areas in the southwestern U.S., including the LCR (Nagler, Cleverly, et al. 2005; Nagler, Scott, et al. 2005), and was then parameterized Nagler, Morino, Murray, et al. (2009) and further calibrated in not only other riparian zones but also adjacent agricultural areas (Nagler et al. 2013). However, the ET estimates in Nagler et al. (2013) were derived from Moderate Resolution Imaging Spectrometer (MODIS) Terra satellite imagery EVI and were thus at 250-m resolution. To account for the narrow riparian corridor, ET at the 30-m resolution was produced by modifying the MODIS-based ET equation to use with Landsat EVI and ground station potential ET (Nagler et al. 2020). Therefore, the Landsat-based ET equation has been adopted and applied to finer scales, demonstrating an important improvement and beneficial tool for assessing narrow corridors of riparian vegetation (Nagler et al. 2020). The equation to predict ET using optical band satellite data for all the AOI in the delta from 2000 through 2020 used EVI2 following Equation (3):

$$\mathrm{ET}\ (\mathrm{Landsat}, 30\ \mathrm{m\ resolution}) = \mathrm{ETo} \times 1.65\left(1-e^{-2.25\mathrm{EVI2}}\right)-0.169, \quad (3)$$

where $\mathrm{ET_o}$ was acquired from the Arizona Meteorological Network (AZMET) Yuma Valley station near Yuma, Arizona (https://cals.arizona.edu/azmet/) because it was the closest operating meteorological station to the delta region. We produce a monthly time series and derived a yearly average ET (mm/day) from the 12 months for each year 2000 to 2020.

There is a lack of available meteorological stations in the delta of the Colorado River in Mexico, although we have identified three stations that are in the proximity; none of these stations has any long-term data and are not useful for the dates of our study. Due to the lack of weather station data for this region, we investigated using Daymet (1 km) but it is not available; however, PRISM is available but only at 4-km resolution. The AZMET station has given us consistent ETo and allowed us to provide actual ET for the riparian corridor in Mexico, despite the location near the U.S.–Mexico border in Yuma, AZ.

Reach-Level and Restoration-Site EVI2 and ET(EVI2) and Spatial Accuracy

The first actively restored plots in the delta began in 2010 (first plantings) and have continued through 2018. There are restoration sites with more than one plot (e.g., CILA, Herradura) with different planting dates; in this research, the plot or site name is followed by the initial planting year. The area and number of pixels in each of the four reaches and associated names for each of the restoration sites are shown in Table 1. Restoration sites were extracted to separately acquire site-level EVI2, and then were used to produce estimates of ET following Equation (3), which uses Landsat EVI2 and potential ET from the AZMET Yuma Valley weather station. Restoration sites only exist within Reach 2 and Reach 4 and are described using a number, name, and associated initial planting date. Reach 2 contains only one restoration site, 1-Miguel Aleman (2014). Reach 4 includes the following 12 restoration plots: 1-Herradura (2016–2017), 2-Cori-Rombo (2016–2017), 3-Trejo (2017), 4-Herradura (2013–2015), 5-Cori-FIV (2018), 6-CILA-FV, 7-CILA (2013–2014), 8-CILA (2018), 9-CILA (2014–2015), 10-Roja (2017), 11-CILA (2010), and 12-Chausse (2018). We also provide the same information for the unrestored or naturally occurring, uncultivated, riparian vegetation that exists in Reach 2 and Reach 4 which excludes the restoration sites. Despite the small size of the restoration sites, enough pixels were measured in each restoration site to complete the analyses (Table 1). Note that the restoration sites, while small compared to their surrounding reaches (which contain from 9,200 pixels to 32,560 pixels), contain from 52 pixels for the smallest site (10-Roja (2017) in Reach 4) to 2,635 pixels for the largest site (1-Miguel Aleman in Reach 2). The total number of pixels in Reaches 1–4 is 79,410.

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TABLE 1. The Colorado River delta study areas showing Reach 1, 2, 3, 4, plus 13 restoration sites, one in Reach 2 and 12 in Reach 4, and their corresponding Area in hectares (ha) and acres (ac), as well as the number of Landsat pixels for each area of interest. Note that each pixel is 30 × 30 m (98 × 98 ft) for an area of 900 m^2 (9,688 sq ft) per pixel.

Reach	Area (ha) (ac)	Number of pixels
1	1,647.0 (4,069.8)	18,300
2	828.0 (2,046.0)	9,200
3	2,930.4 (7,241.2)	32,560
4	1,741.5 (4,303.3)	19,350
Total of Reach 1–4	7,146.9 (17,660.5)	79,410
Restoration sites		
Reach 2		
1-Miguel Aleman (2014)	237.2 (586.0)	2,635
Reach 4		
1-Herradura (2016–2017)	9.9 (24.5)	110
2-Cori-Rombo (2016–2017)	16.0 (39.6)	178
3-Trejo (2017)	19.4 (48.0)	216
4-Herradura (2013–2015)	18.5 (45.8)	206
5-Cori-FIV (2018)	8.7 (21.6)	97
6-CILA-FV (2018)	31.7 (78.3)	352
7-CILA (2013–2014)	57.5 (142.1)	639
8-CILA (2018)	5.2 (12.9)	58
9-CILA (2014–2015)	12.9 (31.8)	143
10-Roja (2017)	4.7 (11.6)	52
11-CILA (2010)	15.5 (38.3)	172
12-Chausse (2018)	100.2 (247.5)	1,113
ALL restored areas	537.4 (1,328.0)	5,971

The Landsat sensor samples the same ground area every 16-days, but not precisely the same target because the view area may change slightly (±12 m) with each overpass. Thus, pixels may sample bare ground adjacent to restored site. Any error due to variation in target acquisition due to wobble or short-term drift will affect the pixels on the boundaries of the restoration site ROIs more than in their centers. Given the large number of pixels in each site, the average EVI2 and ET(EVI2) values for each site are not likely to be strongly affected by variation in pixel location at the site margins. EVI2 and ET(EVI2) estimates of the restoration sites are likely to be minimum estimates because of possible edge effects (see IBWC Report).

Drought Indices and Their Relationship to Riparian Plants and ET

In this study, we used two multi-scalar drought indices, the SPI and the SPEI with their respective durations (1, 3, 9, 12, and 24 months). We downloaded SPI drought indices from the National Oceanic and Atmospheric Administration for Yuma County, Arizona, climate division 5 (Vose et al. 2014; NOAA's Gridded Climate Divisional Dataset 2015). The SPEI data were downloaded from the SPEI Global Drought Monitor (https://spei.csic.es/map/maps.html, accessed May 24, 2021). SPI drought indices data have a resolution of 1° equivalent to 111 km. We evaluated drought indices with different durations to ascertain time periods that were most useful for describing greenness (EVI2) and water demand or riparian vegetation (ET using EVI2) trends within Reach 1 to Reach 4 in the delta riparian corridor.

Data Analysis

EVI2 and ET data are presented as absolute values, the difference and percent change over time. To evaluate the performance of the different drought indices and assess the drought index (SPEI vs. SPI) and time scale (1, 3, 9, 12, and 24 months) that best explain EVI2 (Table 2) and ET(EVI2) trends (Table 3), Generalized linear mixed-effects models (lme4 in RStudio v 1.4.1106) (Bates et al. 2015) were utilized. The different models (drought indices with 1, 3, 9, 12, and 24 months time scales) were fit using maximum likelihood methods (Gamma distribution (loge link)). We ranked the models according to their log-likelihood (LogLik) and differences in Akaike information criterion (ΔAIC). The results of the top-ranked drought index time scale model allowed us to draw inferences on EVI2 and ET(EVI2) trends. Last, we derived predicted riparian vegetation greenness (EVI2) and ET (EVI2) over 21 years (2000–2020) using the estimated regression between the two multi-scalar droughts and time scale and EVI2 (Table 2) and ET(EVI2) (Table 3). To investigate the effects of restoration on vegetation greenness (EVI2) and water use (ET), we created a dummy variable for restoration with a value of "1" if the reach was restored and "0" otherwise. The variable restored represent restoration as a factor in our model. The inclusion of this variable allows us to derive from our model the impact of drought on vegetation greenness and water use for restored and unrestored reaches at different time scale within our study area (Tables 2 and 3). We finally added the variable year to evaluate the trends of both EVI2 and ET(EVI2) over the time period 2000–2020.

RESULTS

Throughout the results section, we have paired plots for each figure, the first shows the Landsat EVI2 results and the second shows the plant water

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TABLE 2. Models using combined restored sites and reaches without restored sites for Landsat two-band Enhanced Vegetation Index (EVI2). Estimates (SE) of the regression between vegetation greenness (EVI2) and common drought indices and time from 2000 to 2020 derived from generalized linear mixed-effects models (Gamma distribution, loge link) and using combined restored and unrestored sites. Significance at three levels is noted as "†".

	EVI2					
Drought index	**Intercept (SE)**	**Drought (SE)**	**Restored (SE)**	**Year (SE)**	**LogLik**	**ΔAIC**
SPEI03	−2.041 (0.102)***	−0.027 (0.003)***	0.257 (0.116)*	−1.052 (0.230)***	8,094.81	0
SPEI01	−2.031 (0.102)	−0.019 (0.003)***	0.257 (0.116)*	−0.916 (0.229)***	8,079.13	31.34
SPEI09	−2.003 (0.102)***	0.019 (0.004)***	0.257 (0.116)*	−0.504 (0.234)*	8,075.19	39.24
SPEI12	−2.000 (0.102)***	0.020 (0.005)***	0.257 (0.116)*	−0.432 (0.238)†	8,074.82	39.98
SPI03	−2.024 (0.102)***	−0.012 (0.004)**	0.257 (0.116)*	−0.707 (0.229)**	8,069.90	49.81
SPI24	−2.025 (0.102)***	−0.011 (0.005)*	0.257 (0.116)*	−0.555 (0.244)*	8,067.35	54.90
SPI01	−2.022 (0.102)***	−0.008 (0.004)*	0.257 (0.116)*	−0.745 (0.228)***	8,066.62	56.38
SPI09	−2.024 (0.102)***	−0.007 (0.004)	0.257 (0.116)*	−0.658 (0.235)**	8,066.11	57.40
SPEI24	−2.017 (0.102)***	0.004 (0.005)	0.257 (0.116)*	−0.668 (0.257)**	8,064.82	59.98
SPI12	−2.023 (0.102)***	−0.002 (0.004)	0.257 (0.116)*	−0.721 (0.238)**	8,064.68	60.26

Notes: Models are ranked according to their log-likelihood (LogLik) and differences in Akaike information criterion (ΔAIC). Year was standardized when analyses were performed. Significance codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "†".
SPEI, Standardized Precipitation Evapotranspiration Index; SPI, Standardized Precipitation Index.

TABLE 3. Models using combined restored sites and reaches without restored sites for Landsat EVI2. Estimates (SE) of the regression between ET(EVI2) and common drought indices and time from 2000 to 2020 derived from generalized linear mixed-effects models (Gamma distribution, loge link) and using reaches excluding restored sites. Significance at three levels is noted as "†".

	ET(EVI2)					
Drought index	**Intercept (SE)**	**Drought (SE)**	**Restored (SE)**	**Year (SE)**	**LogLik**	**ΔAIC**
SPEI03	0.717 (0.076)***	−0.103 (0.011)***	0.289 (0.088)**	−1.891 (0.566)***	−5,900.58	0
SPEI01	0.744 (0.076)***	−0.094 (0.010)***	0.289 (0.089)**	−1.749 (0.566)**	−5,907.2	13.23
SPEI09	0.875 (0.078)***	0.086 (0.011)***	0.289 (0.089)**	−0.627 (0.568)	−5,918.86	36.56
SPI03	0.786 (0.076)***	−0.049 (0.010)***	0.288 (0.089)**	−1.189 (0.569)*	−5,935.3	69.43
SPEI12	0.846 (0.078)***	0.050 (0.013)***	0.289 (0.089)**	−0.726 (0.588)	−5,939.92	78.67
SPEI24	0.860 (0.079)***	0.052 (0.015)***	0.290 (0.089)**	−0.376 (0.636)	−5,941.77	82.37
SPI09	0.788 (0.076)***	−0.022 (0.010)*	0.289 (0.089)**	−1.023 (0.590)	−5,945.21	89.26
SPI01	0.793 (0.076)***	−0.024 (0.011)*	0.289 (0.089)**	−1.335 (0.569)*	−5,945.29	89.41
SPI12	0.789 (0.076)***	−0.016 (0.011)	0.289 (0.089)***	−1.083 (0.599)	−5,946.44	91.71
SPI24	0.788 (0.076)***	−0.016 (0.013)	0.289 (0.089)**	−1.102 (0.612)	−5,946.92	92.67

Models are ranked according to their LogLik and differences in ΔAIC. Year was standardized when analyses were performed. Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "†".
ET, evapotranspiration.

use or "ET(EVI2)". Figure 3 shows the months in a year with all of the Reach 4 restoration sites (n = 12) averaged over the most recent five-year period in bold for both EVI2 (top) and ET(EVI2) (bottom). These estimates for the restored areas are contrasted with the average of the Reach 4 unrestored areas and shown as individual years. Note the large gap between restored and unrestored sites and the falling vegetation greenness in the unrestored part of Reach 4 in each consecutive year. Because greenness as measured through EVI2 is not linearly correlated with water use, the ET(EVI2) annual phenology curve has a different shape than EVI2. The ET(EVI2) plot lines for unrestored areas do not decrease year-by-year in the same order by month as EVI2. ET peaks in July for the restored sites, but EVI2 peaks in August and stays high through October, in contrast, ET(EVI2) observations start to fall after July. ET(EVI2) is a function of ETo and thus cloud cover and other meteorological variables drive actual ET by the atmospheric demand. These results indicate that restoration activities have exceeded the estimates of greenness and water use compared to the unrestored reach area, year after year, as the effects of drought and added water are impacting the declining unrestored riparian corridor plant greenness as well as its corresponding ET.

Figures 4–7 each show the reach-level results in vegetation greenness and water use for the full reach (including restoration sites) and the unrestored

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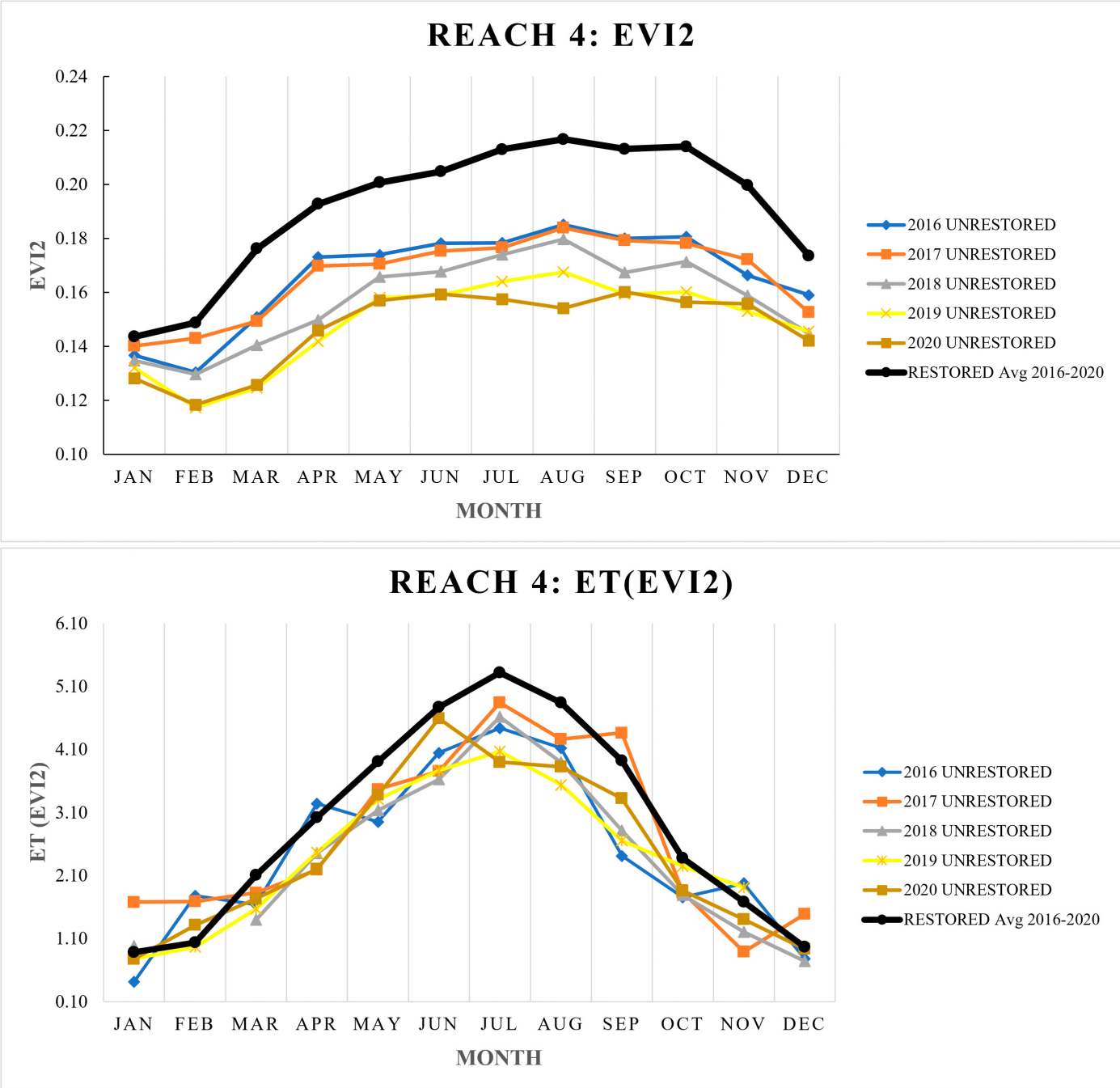

FIGURE 3. Landsat EVI2 (top) and ET(EVI2) (bottom) showing annual phenology cycles at a monthly time-step for the last five years (2016–2020) for Reach 4. Note the 12 restoration sites (black) are showing their average over this period while the unrestored area of the riparian corridor in Reach 4 is plotted year by year (blue for 2016, orange for 2017, gray for 2018, yellow for 2019, brown for 2020).

vegetation (excluding restoration) in comparison to the restored sites (averaged across all 13 sites) for the most recent decade (2010–2020) to highlight the period since restoration sites were planted (Figure 4). We found very little difference in all years between the reach-level data that includes the restoration sites (black line) and the reach-level that excludes the restoration sites (yellow line with "x") simply due to the weighted average using the small number of pixels in the restoration sites compared with the reach-level (Reaches 1–4). The results also show that Reach 2 with only one restoration site is nearly the same as Reach 2 excluding the restoration site, again because the restoration site is small compared with its corresponding reach-level. Similarly, the results for Reach 4, including the dozen restoration plots,

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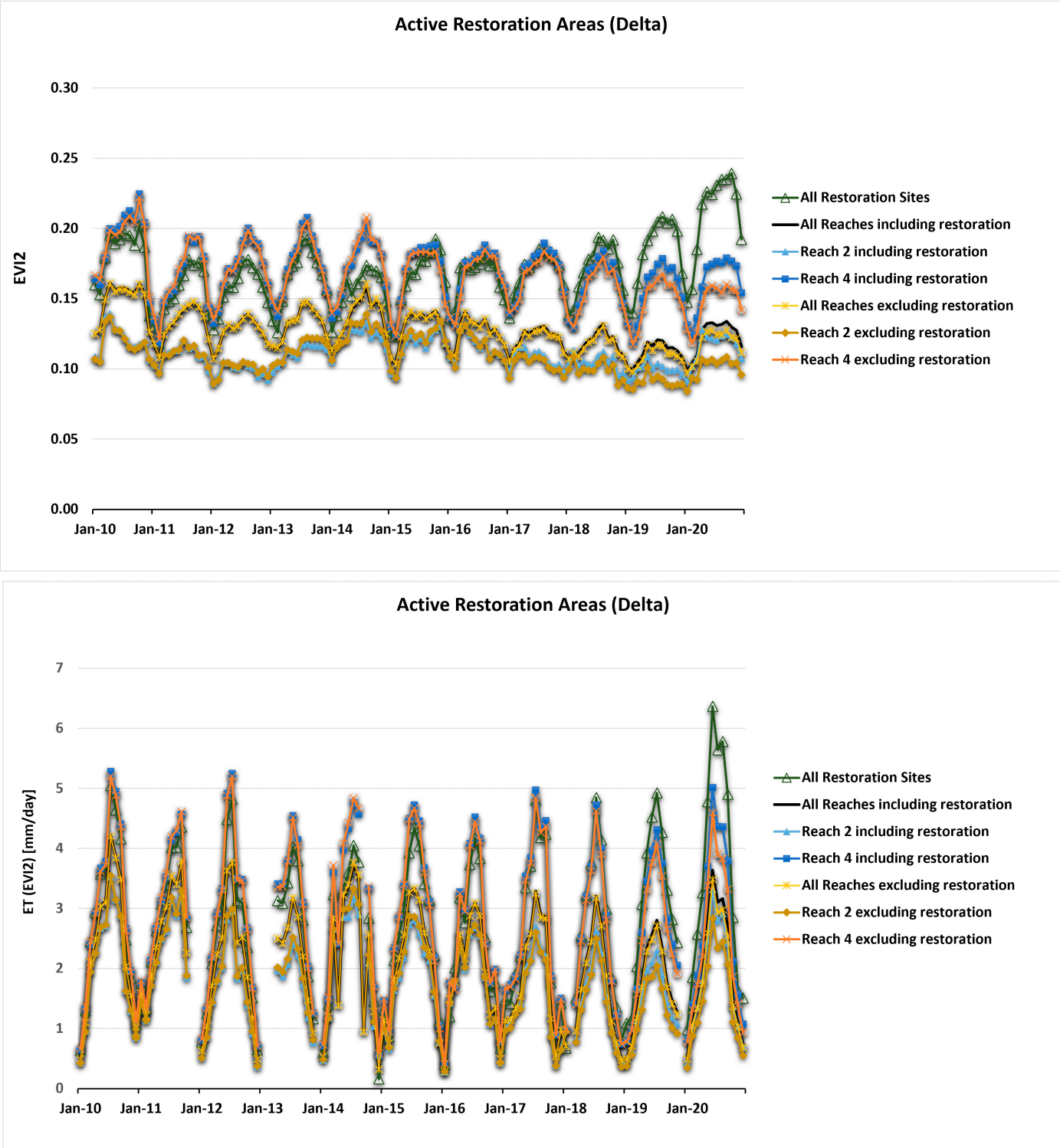

FIGURE 4. Landsat EVI2 (top) and ET(EVI2) (bottom) from 2010 to 2020 for the reaches and restoration sites of interest along the riparian corridor of the Colorado River delta. Note that the weighted average of All Restoration Sites (green line with triangles) is contrasted with the reach-level data that include the averaged restoration sites (All Reaches [weighted average of Reaches 1–4, black line], Reach 2 and Reach 4 including the averaged restoration sites), and is further contrasted with the reach-level data that exclude the averaged restoration sites (All Reaches [Reaches 1–4, yellow line with x and nearly the same as black line], Reach 2 and Reach 4 excluding the averaged restoration sites).

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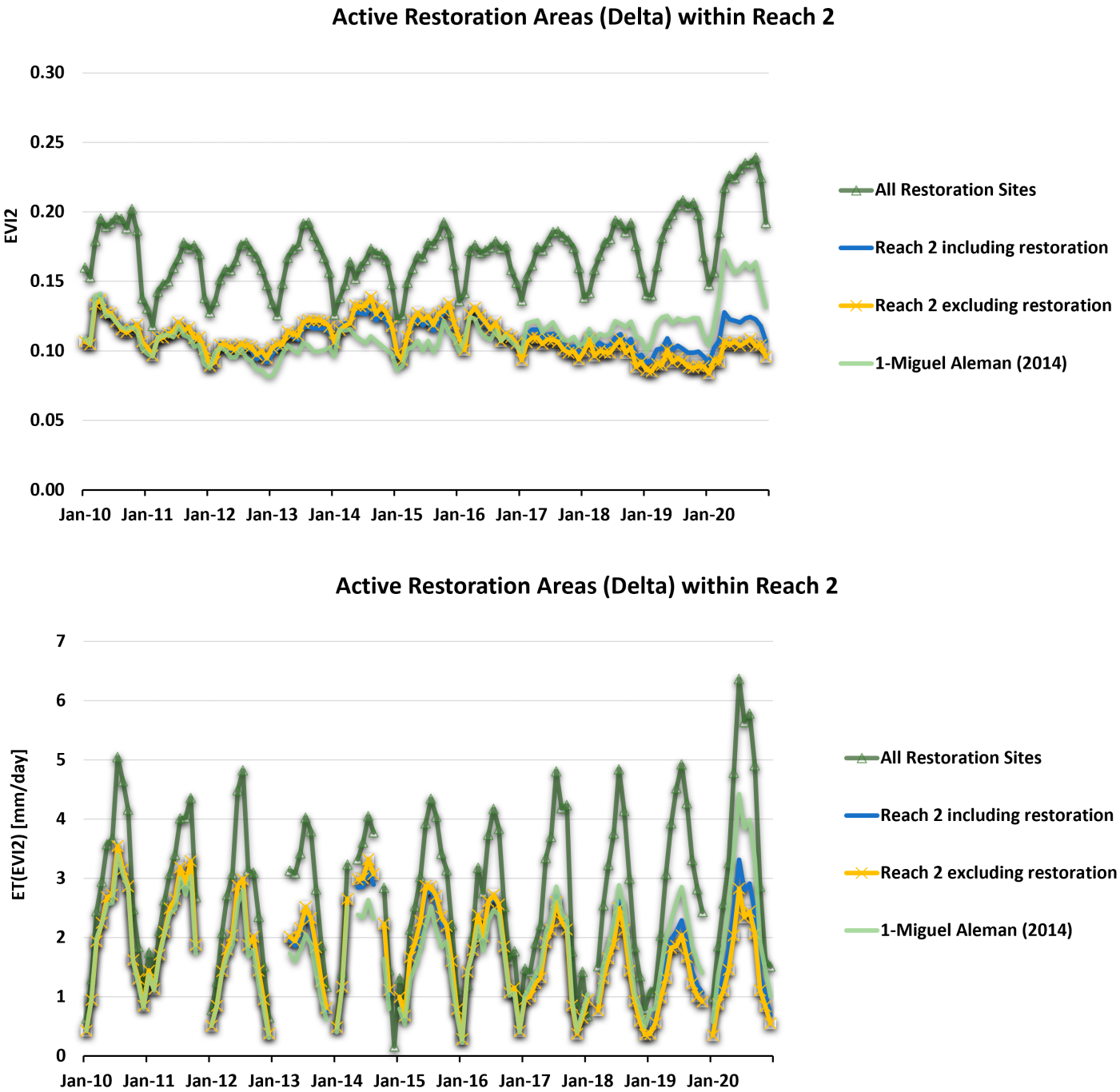

FIGURE 5. Landsat EVI2 (top) and ET(EVI2) (bottom) from 2010 to 2020 for the reaches and restoration sites of interest along the riparian corridor of the Colorado River delta. Note that the lines show EVI2 for Reach 2 (including restoration), Reach 2 (excluding restoration), the 1-Miguel Aleman (2014) restoration site (the only one in Reach 2), contrasted with the weighted average of All restoration sites (13 total, a dozen in Reach 4).

were indistinguishable from Reach 4 excluding the restoration plots, but starting in 2018 through 2020, the growth of vegetation in these plots resulted in a distinguishable difference in EVI2 and ET(EVI2). In the same period over the last 2–3 years, All Restoration Sites, as a weighted average of the 13 plots, increased by more than 0.05 EVI2 units and more than 1 mm/day in ET(EVI2) (Figure 4). Figure 4 indicates that the following four categories remain low (All Reaches (Reaches 1–4); Reach 2 including the one restoration site; Reach 2 excluding the resoration site; and Reach 4 excluding the restoration site); these are low in greenness and ET relative to Reach 4 with and without restoration sites and much lower than All Restoration Sites since

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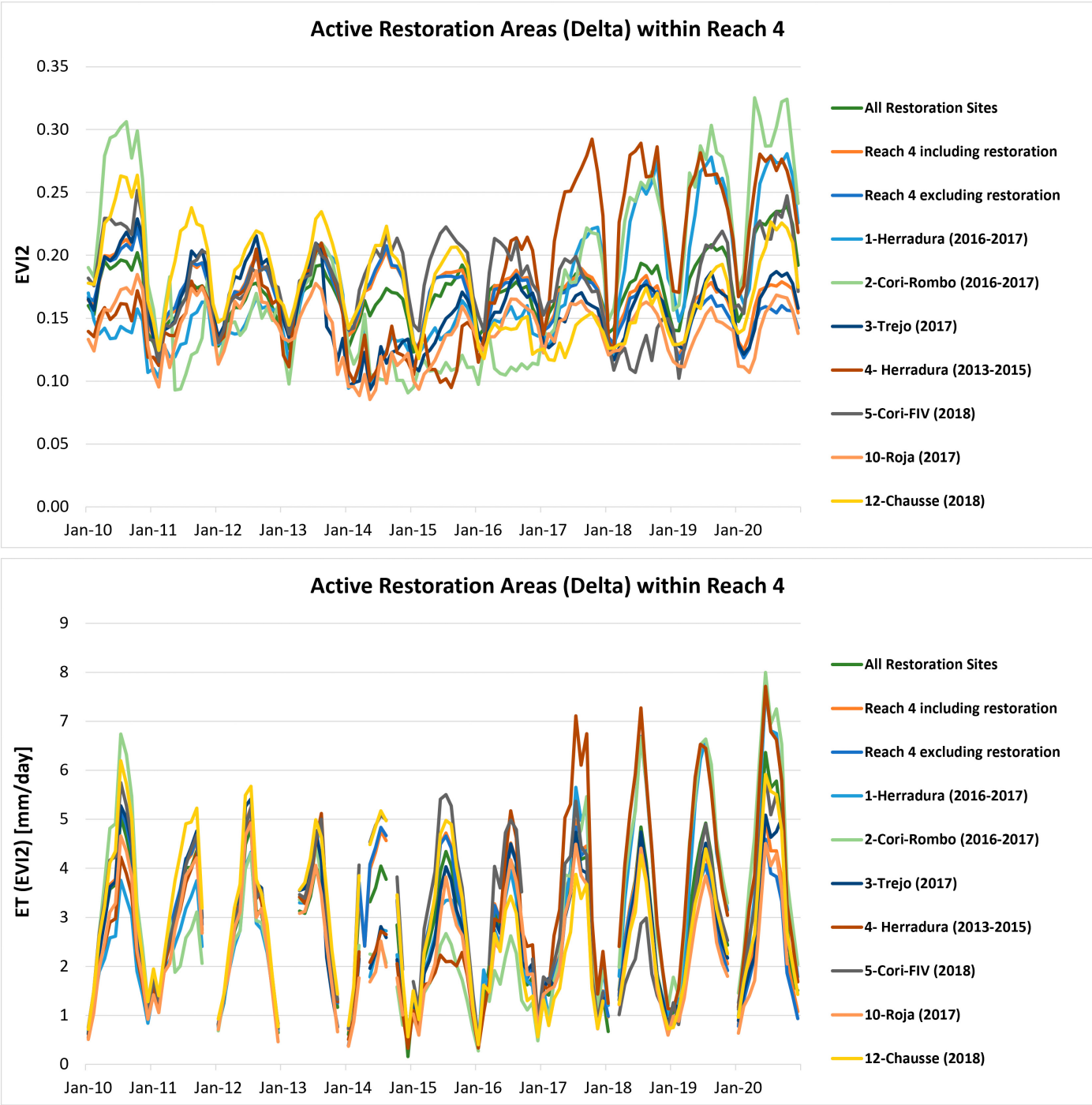

FIGURE 6. Landsat EVI2 (top) and ET(EVI2) (bottom) from 2010 to 2020 for the individual restoration sites in Reach 4 that are non-CILA sites along the riparian corridor of the Colorado River delta. Note that the lines show ET(EVI2) for Reach 4 (including restoration), Reach 4 (excluding restoration), the seven non-CILA restoration sites [1-Herradura (2016–2017), 2-Cori-Rombo (2016–2017), 3-Trejo (2017), 4-Herradura (2013–2015), 5-Cori-FIV (2018), 10-Roja (2017), and 12-Chausse (2018)], contrasted with the weighted average of All restoration sites (13 total, a dozen in Reach 4).

2018 when the combined impact from active restoration, particularly in Reach 4, has increased dramatically. In sum, restoration plots have had a marked increase on the two metrics measured since 2018, and even have increased overall greening and water use in Reach 4, but they have not caused reach-level increases in either metric for All Reaches consisting of Reaches 1–4.

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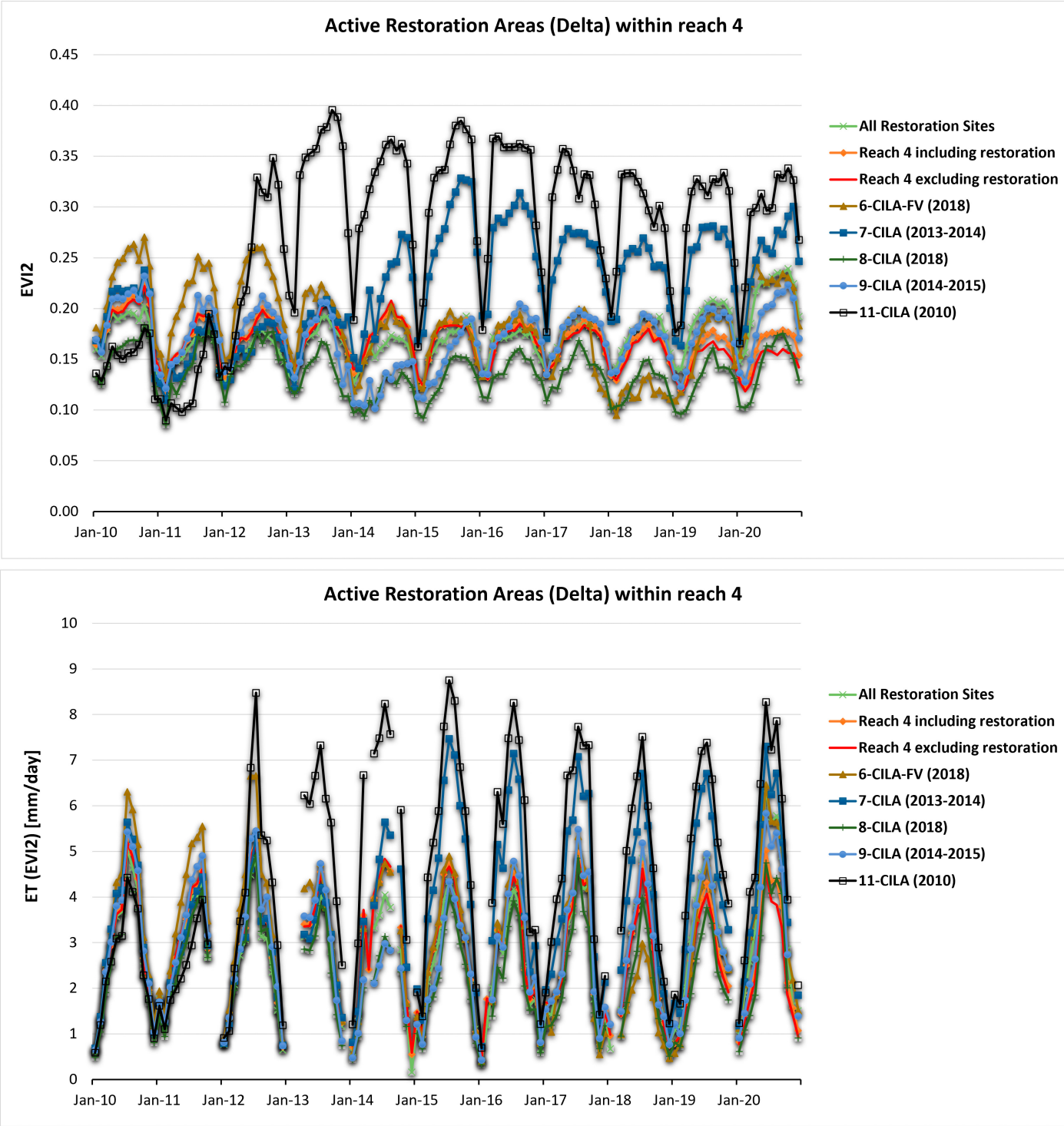

FIGURE 7. Landsat EVI2 (top) and ET(EVI2) (bottom) from 2010 to 2020 for the individual restoration sites in Reach 4 that are CILA sites along the riparian corridor of the Colorado River delta. Note that the lines show ET(EVI2) for Reach 4 (including restoration), Reach 4 (excluding restoration), the five CILA restoration sites [6-CILA (2018), 7-CILA (2013–2014), 8-CILA (2018), 9-CILA (2014–2015), and 11-CILA (2010)], contrasted with the weighted average of All restoration sites (13 total, a dozen in Reach 4).

The one restoration site, 1-Miguel Aleman (initially planting in 2014) was sufficiently large and successful enough to have an impact at the reach-level within Reach 2; starting in 2019 about five years' post-planting, the site became distinguishable from the unrestored part of the reach with growth measured by both EVI2 and ET(EVI2) (Reach 2 excluding restoration) (Figure 5). This site contributed

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significantly to recent increases in greenness and ET in the last year, doubling values of EVI2 from 2019 and more than 1.4 mm/day in ET(EVI2).

Figure 6 (top) shows EVI2 for Reach 4 (including restoration), Reach 4 (excluding restoration), contrasted with the weighted average of All Restoration Sites (13 total, a dozen in Reach 4). Figure 6 (bottom) shows ET(EVI2) for the same AOIs. Over the past decade (2010–2020) all the restoration sites shown were planted, so until the initial year of planting (shown with the site name), the data are showing the unrestored natural condition of the site area. For example, 12-Chausse (2018) consisted of high EVI2 and ET 2010 through 2016, but then some of the vegetation was cleared in an effort to restore native species, and the metrics we used to measure the vegetation in 2020 are now much the same as they were a decade ago. Both plots in the Herradura site, 1-Herradura, and 4-Herradura, as well as 2-Cori-Rombo, have markedly increased over the past four years. Other sites such as 3-Trejo (2017) and 10-Roja (2017) are coming along in terms of growth but additional monitoring is needed to determine when their increases will be larger than the reach-level averages in Reach 4 (including and excluding restoration).

As expected, the plots that were started longer ago (7-CILA (2013–2014) and 11-CILA (2010) are thriving now (Figure 7). From this time-series data, we learn that these plots started to show increases in greenness and water use at the plot-level as soon as two years' post-planting. As in Figure 6, vegetation data from sites that had not yet been planted were acquired for the future restoration site areas; for example, 6-CILA (2018) shows healthy vegetation on the ground between 2010 and 2017 before being cleared for native species in 2018. Following 2018, the actively restored vegetation in 6-CILA (2018) increased by 0.1 EVI2 and from 3 to 6.5 mm/day in ET. Because of the varying initial planting dates among the restoration sites and plots, a future manuscript will be devoted to tracking the native, restored riparian plant growth and ET.

Figure 8 shows the change per year in both EVI2 and ET(EVI2) from 2000 through 2020 and contrasts All Reaches including restoration to All Restoration post-pulse flow. Over the 21-year period from 2000 to 2020, greenness of the riparian zone, as measured by the EVI2, decreased by 22%, an annual decline of 1.1%. For All Reaches (Reaches 1–4) including restoration sites, before the 2014 Pulse Flow, between 2000 and 2013, greenness decreased annually by 1.1%. Between 2014 (the year of the pulse flow) and 2020, greenness decreased annually by 1.5%. The average yearly EVI2 value in 2020 was 10% higher than in 2019 likely due to excess water from the MODE flows (see IBWC Report, 2021). The 2020 EVI2 values were lower than those from the post-pulse year of 2014 and lower than in 2000. The All Restoration Sites had been decreasing in EVI2 between 2000 and 2013; we measured a loss in EVI2 of 12.0% during the pre-pulse flow years. However, since 2014, the year of the Minute 319 Pulse Flow, the EVI2 in the restoration sites increased by 34%, or 4.9% per year and increased by 14.1% between 2019 and 2020.

ET(EVI2) in Figure 8 also showed a similar temporal and spatial pattern for All Reaches including restoration and All Restoration post-pulse flow. We

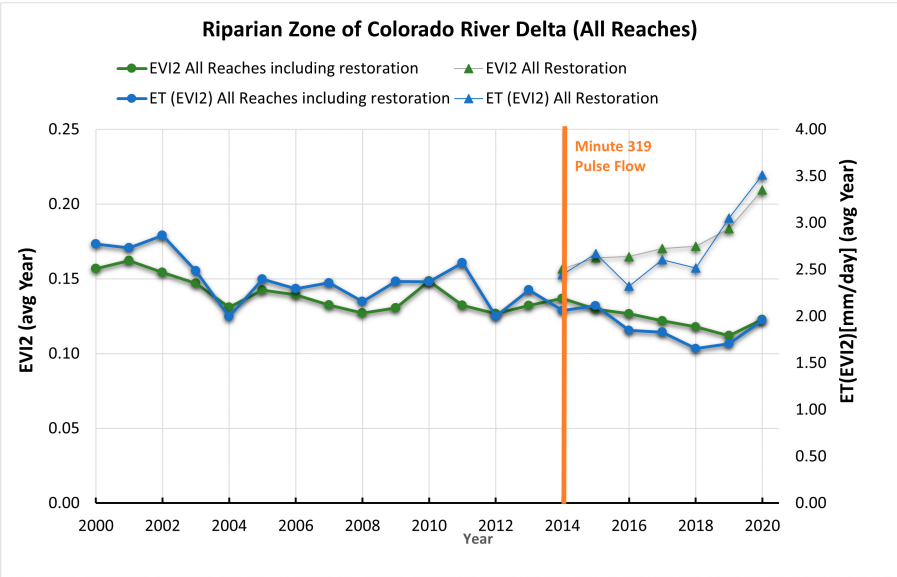

FIGURE 8. The Colorado River delta riparian corridor greenness and water use change per year as measured by Landsat EVI2 and ET (EVI2) using the weighted average from the All Reaches (Reach 1–4) including restoration sites and All Restoration Sites from 2000 through 2020.

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show the riparian EVI2 (green trend) and ET(EVI2) (blue trend) as a function of time before and after the Minute 319 pulse flow. The restoration trends increased (triangles) while the unrestored reaches decreased (circles) (Figure 8). Over the 21-year period from 2000 to 2020, ET(EVI2) in riparian Reaches 1–4 decreased by 30%, an annual decline of 1.4%. Before the 2014 Pulse Flow, between 2000 and 2013, ET (EVI2) had an annual decline of 1.3%. Between 2014 (the year of the pulse flow) and 2020, ET(EVI2) decreased annually at 0.75%. The average yearly ET (EVI2) value in 2020 was 15% higher than in 2019 likely due to excess water from the MODE flows (see IBWC Report, 2021). The 2020 ET(EVI2) values were lower than those from the post-pulse year of 2014 and lower than in 2000. The All Restoration Sites had been decreasing in ET(EVI2) between 2000 and 2013; we measured a loss in ET of 12.6% during the pre-pulse flow years. However, since 2014, the year of the Minute 319 Pulse Flow, the ET(EVI2) in the All Restoration Sites increased by 58%, or 8.3% per year which is an additional 0.18 mm/day in ET(EVI2), plus ET(EVI2) increased by 15.1% between 2019 and 2020 yielding an additional 0.46 mm/day.

Figure 9 shows Landsat 8 EVI2 and ET(EVI2) data from 2014 to 2020 with each year depicted as a bar for shown categories. These bars show the average yearly values for comparison to All Restoration Sites. There is increasing greenness from the Minute 319 Pulse Flow in 2014 through 2020 for All Restoration Sites (Figure 9, top) but this trend has more oscillations in ET(EVI2) over the same years and yet started to show increases from 2018 to 2020, ending with ET in 2020 of 3.5 mm/day, a 1.0 mm/day increase since the pulse flow (Figure 9, bottom). For All Reaches that includes Reaches 1–4, and for Reach 2 and Reach 4 individually, there is very little difference due to relative ground cover between the restored areas and the unrestored reaches in both greenness and water use between the data including and excluding the restoration sites. Both metrics at the reach-level generally show decreases from 2014 through 2019, with 2020 showing increases, except for Reach 4 excluding the restoration sites which were nearly the same as in 2019, but not an increase. Only All Restoration Sites reversed the declining trend and showed increases in both metrics.

Ten restoration sites showed increases in greenness using EVI2 over the last five years and there are only three restoration sites that have less greenness in 2020 than in 2016: 7-CILA (2017), 10-Roja (2017), and 11-CILA (2010) (Figure 10, top). For all 13 restoration sites, ET(EVI2) was higher in 2020 than in 2016, thus showing total success of the restoration sites (Figure 10, bottom). When averaged together (last dataset), the improvement in ET(EVI2) over the last five years is clear, showing an increase from 2.3 to 3.5 mm/day (Figure 10, bottom).

Figure 11 shows the percent change between groups of years for EVI2 and ET(EVI2). Greenness in the last one to two years (2018- and 2019- to 2020) increased in all categories except for Reach 4 (excluding restoration). In the past 5, 7, and 21 years, only the All Restoration Sites category showed increases in greenness as measured by EVI2, and those increases were all more than 10% positive changes, with the post-pulse flow (2014–2020) change as much as 34% (Figure 11, top). The same changes held for the water use estimates as for the greenness estimates. ET(EVI2) in the last one to two years (2018- and 2019- to 2020) increased in all categories except for Reach 4 (excluding restoration) (Figure 11, bottom). In the past 5, 7, and 21 years, only the All Restoration Sites category showed increases in water use as measured by ET(EVI2). The All Restoration Sites demonstrated a post-pulse flow (2014–2020) change as much as 58%, and was more than 10% across the other compared years of change for restoration. A key finding is that since the pulse flow, restoration sites have increased in both greenness and water use, but these increases did not help the reach-level riparian vegetation. Importantly, since 2018, the unrestored areas of riparian vegetation in All Reaches, Reaches 1–4, are improving as documented by estimates in both metrics. In the last year, Reach 2 (including 1-Miguel Aleman) had a higher (positive) percent change in EVI2 and ET(EVI2) than the combined average restoration sites. This increase may be due to excess water from the MODE flow.

Change maps using the differences over the last five years (using 2020–2016) are shown in Figure 12a (EVI2) and Figure 12b (ET(EVI2)) and highlight change within each of the restoration sites in Reach 2 and Reach 4. On each map, there are also enlarged regions for selected sections to better show the restoration sites. The brown color indicates a loss in the metric while the green color represents a gain. A histogram at the top of each map shows the frequency distribution for pixels with differences below zero (loss in greenness and ET) or above zero (gain in greenness and ET). The maps show areas within the unrestored reaches that are greening without the contributions of active restoration. Similarly, the maps show areas where losses persist and are not simply cleared areas for future restoration sites.

EVI2 and ET(EVI2) percent change is shown as box and whisker plots for seven AOIs of riparian vegetation (Figure 13). Mean percent change in greenness was negative for All categories, with the exception of Reach 4 (both including and excluding restoration) that shows nearly zero mean change and for the All Restoration Sites category which has

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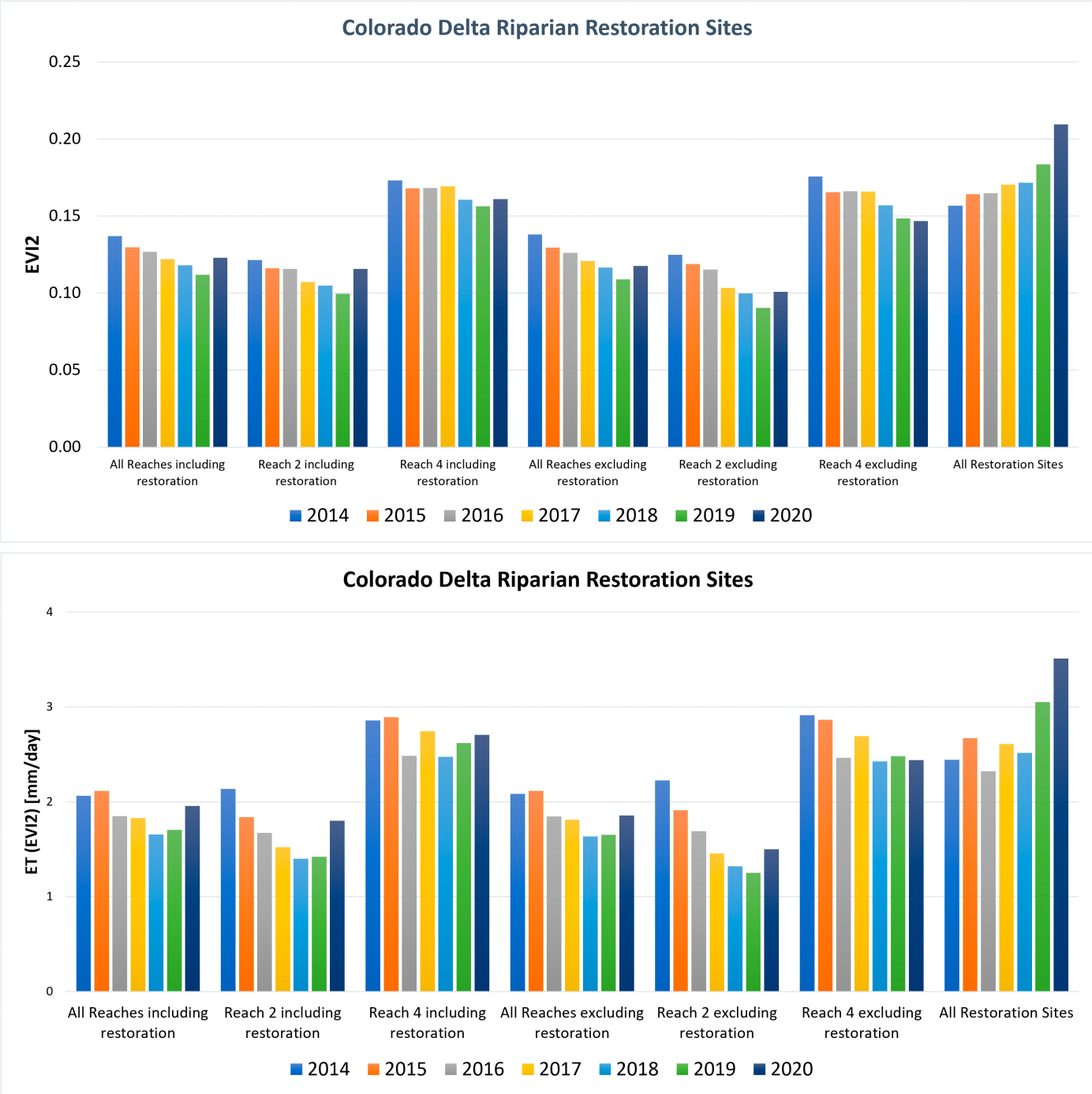

FIGURE 9. The Colorado River delta riparian corridor water use change per year using Landsat 8 (OLI) EVI2 (top) and ET(EVI2) (bottom) for years 2014–2020 (various color bars) for seven areas of interest (AOI) in this study, (1) weighted average for All Reaches (Reach 1–4) including the restoration sites, (2) Reach 2 including the one restoration site, (3) Reach 4 including the 12 restoration sites, (4) weighted average for All Reaches (Reach 1–4) excluding the restoration sites, (5) Reach 2 excluding the one restoration site, (6) Reach 4 excluding the 12 restoration sites, and (7) the weighted average of All Restoration Sites.

positive mean change, but the also the largest variance (Figure 13, top). The categories measured show that mean percent change in water use is also mostly negative, except for Reach 4 including restoration which is positive mean percent change, as well as the All Restoration Sites category. Reach 2 shows the largest variance in ET percent change (+27% to −31%) (Figure 13, bottom).

The EVI2 percent change and the ET(EVI2) percent change year-to-year from 2000 to 2020 are

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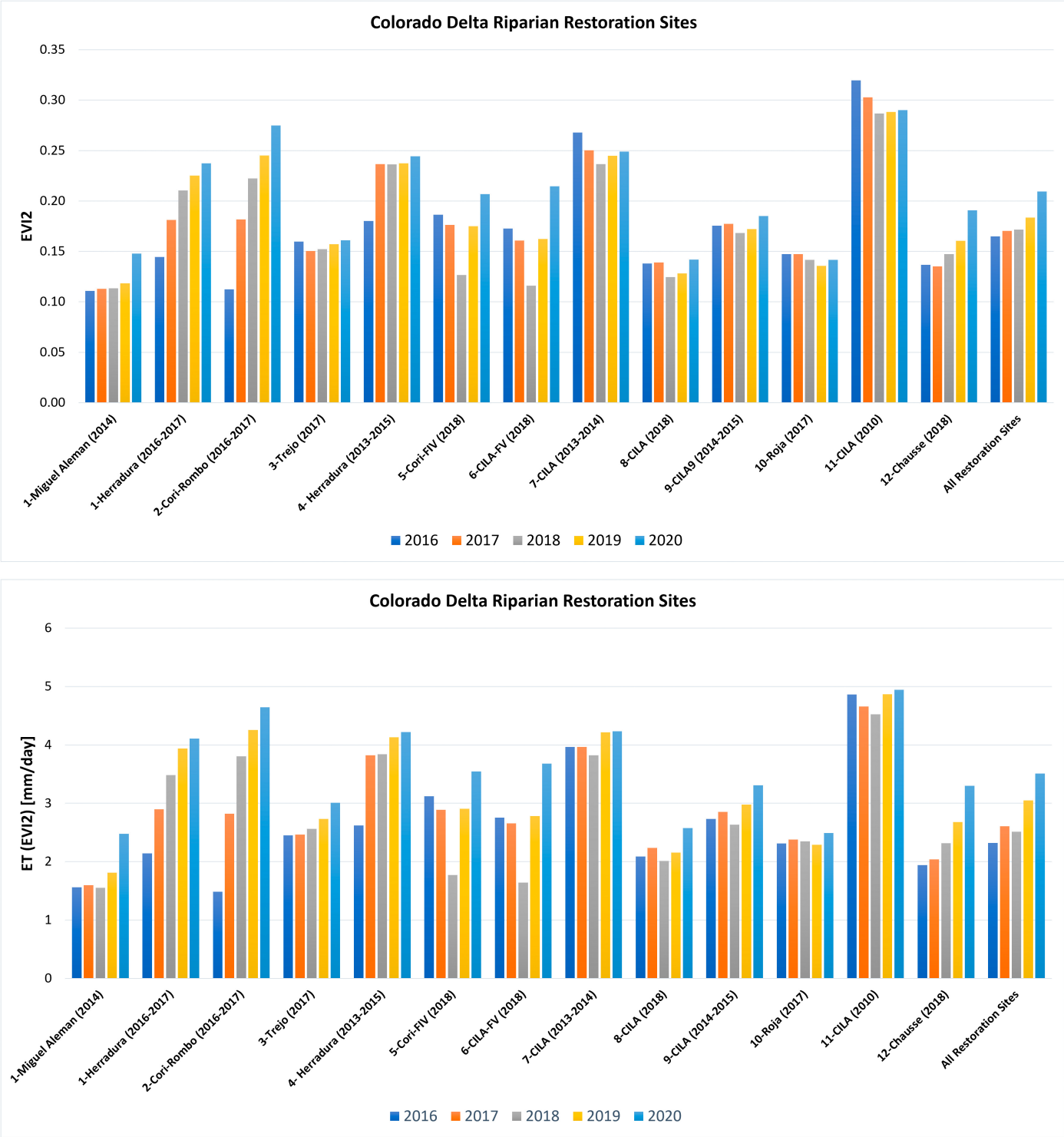

FIGURE 10. The Colorado River delta water use change per year in the riparian restoration sites using Landsat 8 (OLI) EVI2 (top) and ET (EVI2) (bottom) for years 2016–2020 (various color bars) for each of 13 restoration sites within Reach 2 [1-Miguel Aleman (2014)] and Reach 4 [1-Herradura (2016–2017), 2-Cori-Rombo (2016–2017), 3-Trejo (2017), 4-Herradura (2013–2015), 5-Cori-FIV (2018), 6-CILA (2018), 7- CILA (2013–2014), 8-CILA (2018), 9-CILA (2014–2015), 10-Roja (2017), 11-CILA (2010), and 12-Chausse (2018)] and the weighted average of All Restoration Sites.

demonstrated in Figure 14. The change between 2010 and 2011 was the most negative in both metrics for all categories. The recent positive change from 2019 to 2020 was similar to the observed increases in EVI2 and ET(EVI2) between 2004–2005, 2009–2010, and 2011–2012; the increase seen in the ET plot between

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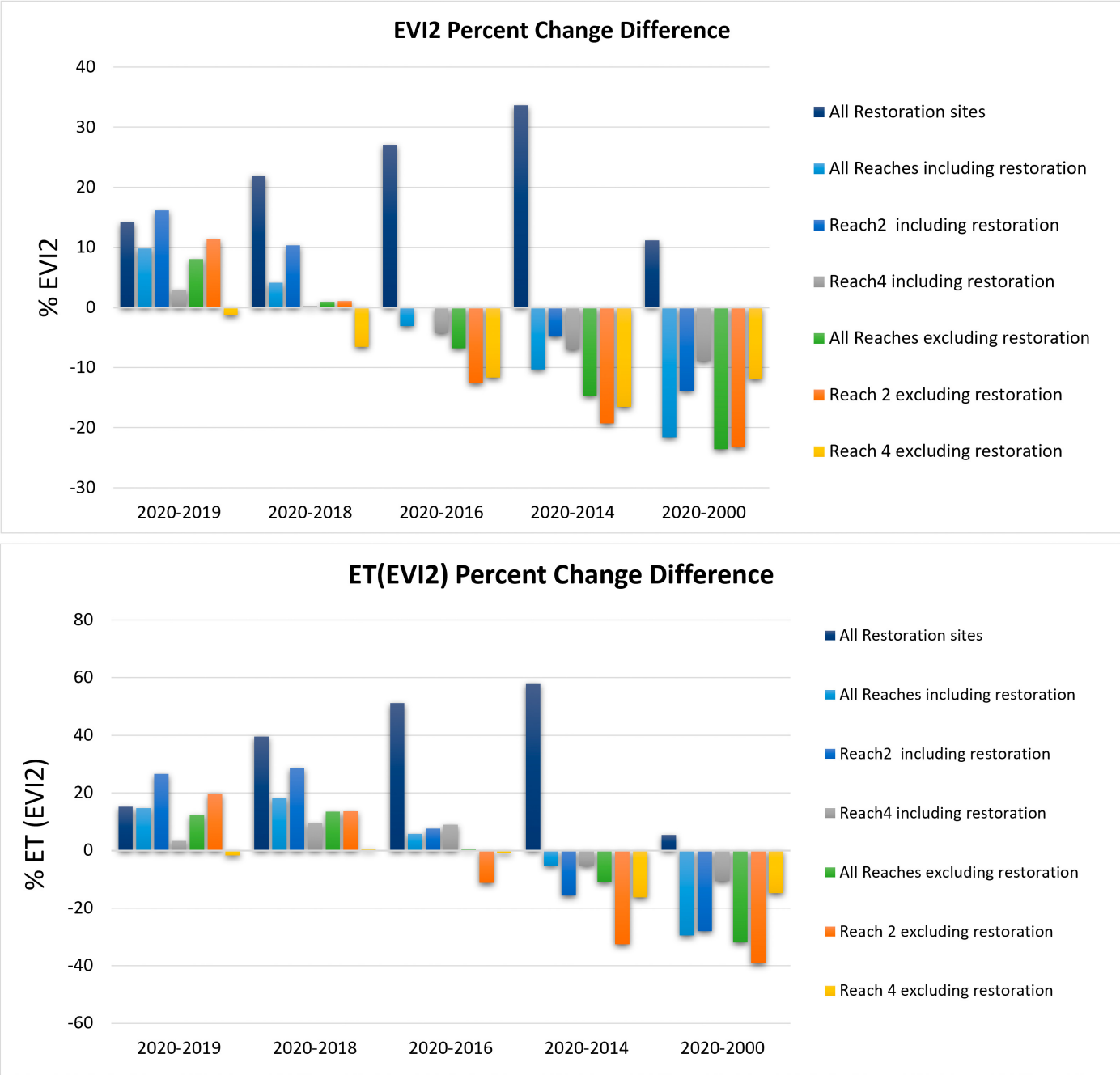

FIGURE 11. The Colorado River delta percent change in water use per year in the riparian corridor using Landsat 8 (OLI) EVI2 (top) and ET(EVI2) (bottom) for change between five sets of years that include 2020–2019, 2020–2018, 2020–2016, 2020–2014, 2020–2000, respectively one-year change, two-year change, five-year change, seven-year change since the 2014 Pulse Flow, and 21-year change (various color bars) for each area of interest, the weighted average of All Restoration Sites, All Reaches including restoration, Reach 2 including restoration, Reach 4 including restoration, All Reaches excluding restoration, Reach 2 excluding restoration, and Reach 4 excluding restoration.

2014 and 2015 for All Restoration Sites was also as large as it was in 2012–2013.

We combined drought indices and EVI2 data using restoration sites and reaches that excluded restoration sites to produce relationships between them over 21 years (2000–2020). Models are ranked according to their LogLik and ΔAIC. Year was standardized when analyses were performed. Table 2 shows the estimates (SE) of the regression between vegetation greenness (EVI2) and common drought indices, restoration status, and time (2000–2020) derived from generalized linear mixed-effects models (Gamma distribution, loge link), using combined restored and non-restored sites. Table 3 shows the regression

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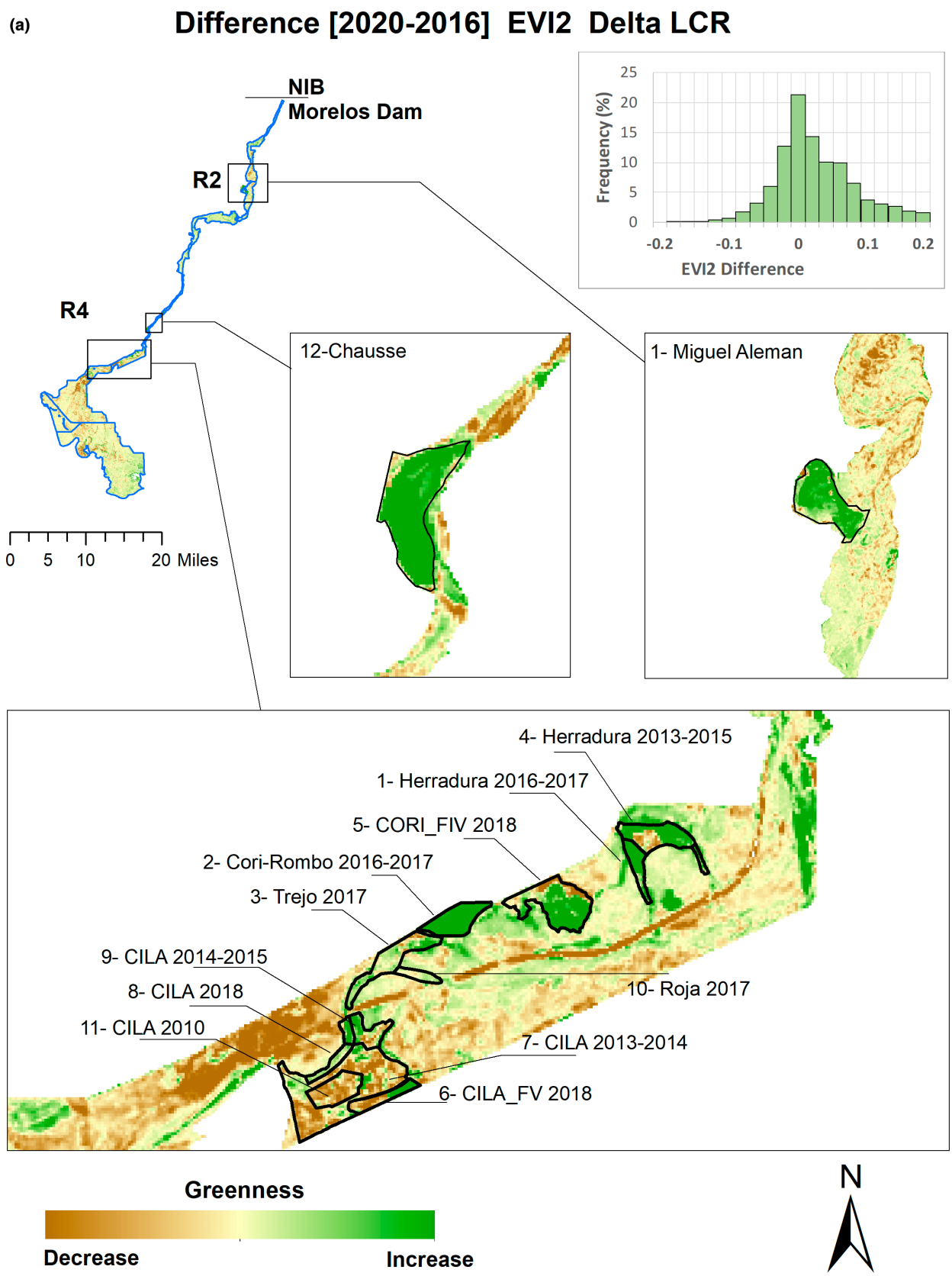

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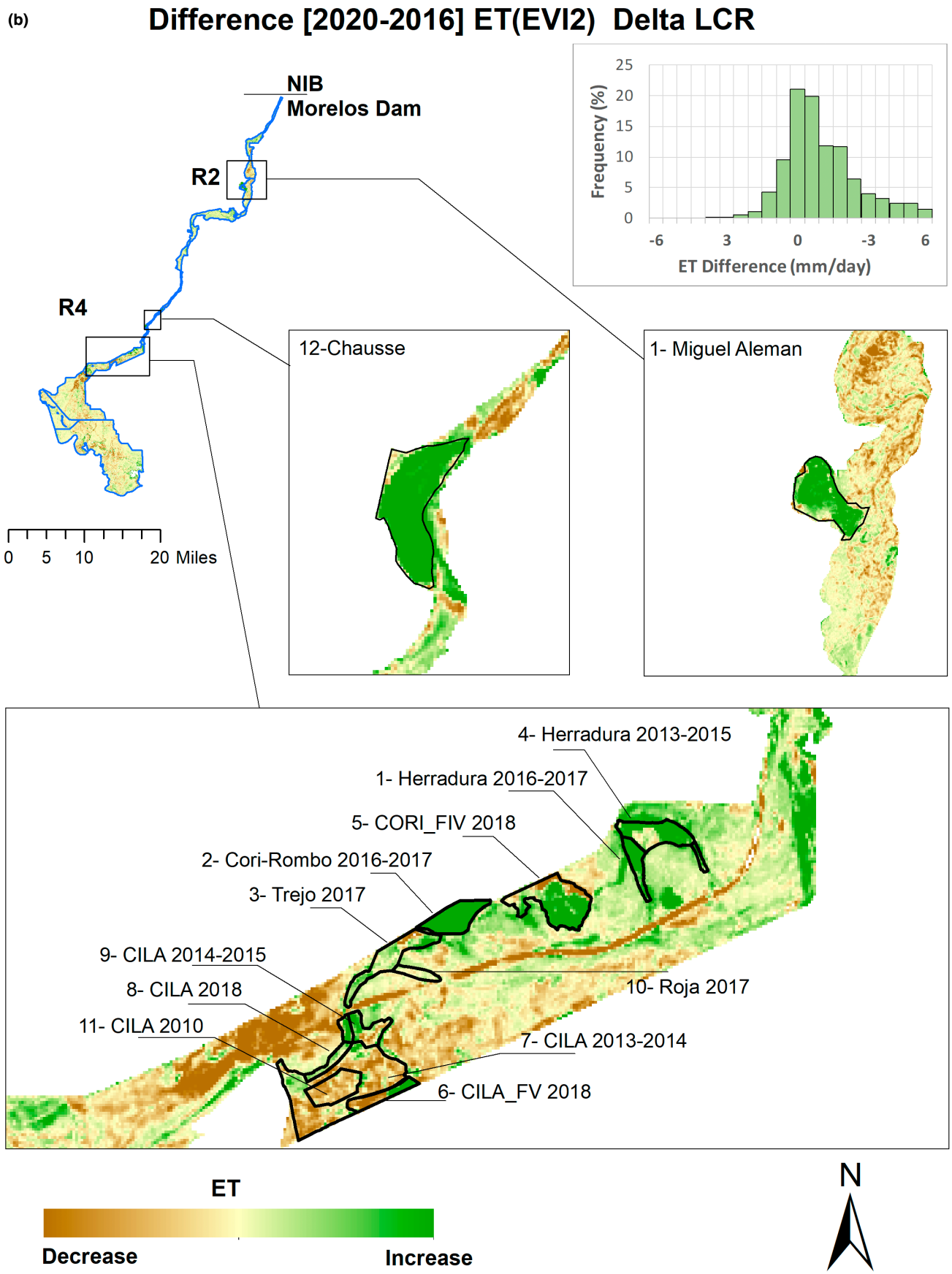

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FIGURE 12. (a) Change maps using Landsat EVI2 to depict the differences over the last five years (2020–2016) to highlight greenness change within not only the river reach, but also each of the restoration sites in Reach 2 and Reach 4. Note that brown indicates a loss in greenness and green represents a gain in greenness. On each map, there are also enlarged regions for selected sections to better show the restoration sites. A histogram at the top of each map shows the frequency distribution for pixels with differences below zero (loss in greenness) or above zero (gain in greenness). (b) Change map using Landsat ET(EVI2) to depict the differences over the last five years (2020–2016) to highlight water use change within not only the river reach, but also each of the restoration sites in Reach 2 and Reach 4. Note that brown indicates a loss in ET and green represents a gain in ET. On each map, there are also enlarged regions for selected sections to better show the restoration sites. A histogram at the top of each map shows the frequency distribution for pixels with differences below zero (loss in ET) or above zero (gain in ET). LCR, Lower Colorado River.

estimates between ET(EVI2) and common drought indices, restoration status, and time from 2000 to 2020 derived from generalized linear mixed-effects models (Gamma distribution, loge link) and using reaches excluding restored sites.

Using our model with drought indices at different time scales, our results show a negative relationship between drought and EVI2 or ET(EVI2) for SPI at all duration levels and for SPEI of one to three months duration (Tables 2 and 3). However, SPEI with a duration of nine months and more (e.g., 9-, 12-, and 24-month trends) show a positive relationship with vegetation greenness and water use. The longer periods of drought indicate that the drier the period, the less greenness and water use from the riparian corridor and the wetter the period (or the less drought), the higher the EVI2 and ET(EVI2) (Figure 15). EVI2 (Figure 15, top) and ET(EVI2) (Figure 15, bottom) for combined sites within Reaches 1–4 as a function of the SPEI and shown for four periods of drought. The relationships in the top plots are EVI2 relative to SPEI for four time-intervals of drought for 3 (A), 9 (B), 12 (C), and 24 (D) months (shaded to show the 95% confidence interval shown in brown). The relationships in the bottom plots are for ET(EVI2) relative to SPEI for four time-intervals of drought for 3 (A), 9 (B), 12 (C), and 24 (D) months (shaded to show the 95% confidence interval shown in brown). Over 21 years in our study, both Landsat EVI2 and ET (EVI2) metrics as a function of the shorter drought period, SPEI03, show declines, while the longer the drought for both metrics with SPEI09, SPEI12, and SPEI24 show increases.

All models indicated a decrease in EVI2 and ET (EVI2) over time (Tables 2 and 3; Figure 16). Our model based on seasonal drought SPEI03 (−0.027) and the long term drought SPEI09 (+0.019) and SPEI12 (+0.020) have the highest effects based on their coefficient estimates' magnitudes and their statistical significance (Tables 2 and 3). The estimated decrease in average vegetation greenness (EVI2) for SPEI03 was ca. 5.05% (Figure 16, top) and average decrease in plant water use (ET(EVI2)) was ca. 12.16% (Figure 16, bottom) between 2000 and 2020. The estimated decrease in average vegetation greenness (EVI2) for SPEI09 was ca. 2.45% (Figure 16, top) and average decrease in plant water use (ET (EVI2)) was ca. 5.68% (Figure 16, bottom) between 2000 and 2020. The estimated decrease in average vegetation greenness (EVI2) for SPEI12 was ca. 2.10% (Figure 16, top) and average decrease in plant water use (ET(EVI2)) was ca. 6.09% (Figure 16, bottom) between 2000 and 2020. The estimated decrease in average vegetation greenness (EVI2) for SPEI12 was ca. 3.24% (Figure 16, top) and average decrease in plant water use (ET(EVI2)) was ca. 4.04% (Figure 16, bottom) between 2000 and 2020.

Figure 17 shows the predicted EVI2 (top) and ET (EVI2) (bottom) for restored (blue) and unrestored (red) sites in Reaches 1–4 as a function of four time periods of drought (SPEI) with relationships depicting the 95% confidence level boundary. In all models, the dummy created for restoration shows a positive relationship with both EVI2 and ET(EVI2) (Tables 2 and 3). This can be translated as positive impact of restoration on vegetation greeness and water use.

DISCUSSION

Measurements of the Delta's Riparian Corridor

Our study found that effects from restoration efforts measured over the past decade (2010–2020 since the first plantings began) were limited to the restored sites. Restoration sites have a small footprint (ca. 7% of the river reach) and thus have a minimal impact on the reach-level vegetation greenness and water use. On the other hand, using EVI2 and ET metrics we were able to determine the trend in restoration sites' greenness and water use and detect when both metrics surpassed the unrestored reaches values. The influence of spatial resolution and accuracy in remotely sensed and ground-based ET estimation is important in water availability and land productivity research (Blatchford et al. 2019; Blatchford, Mannaerts, Njuki, et al. 2020; Blatchford, Mannaerts, Zeng, et al. 2020); however, little has been done to quantify the influence of spatial scale on productivity and ET in arid riparian ecosystems. These

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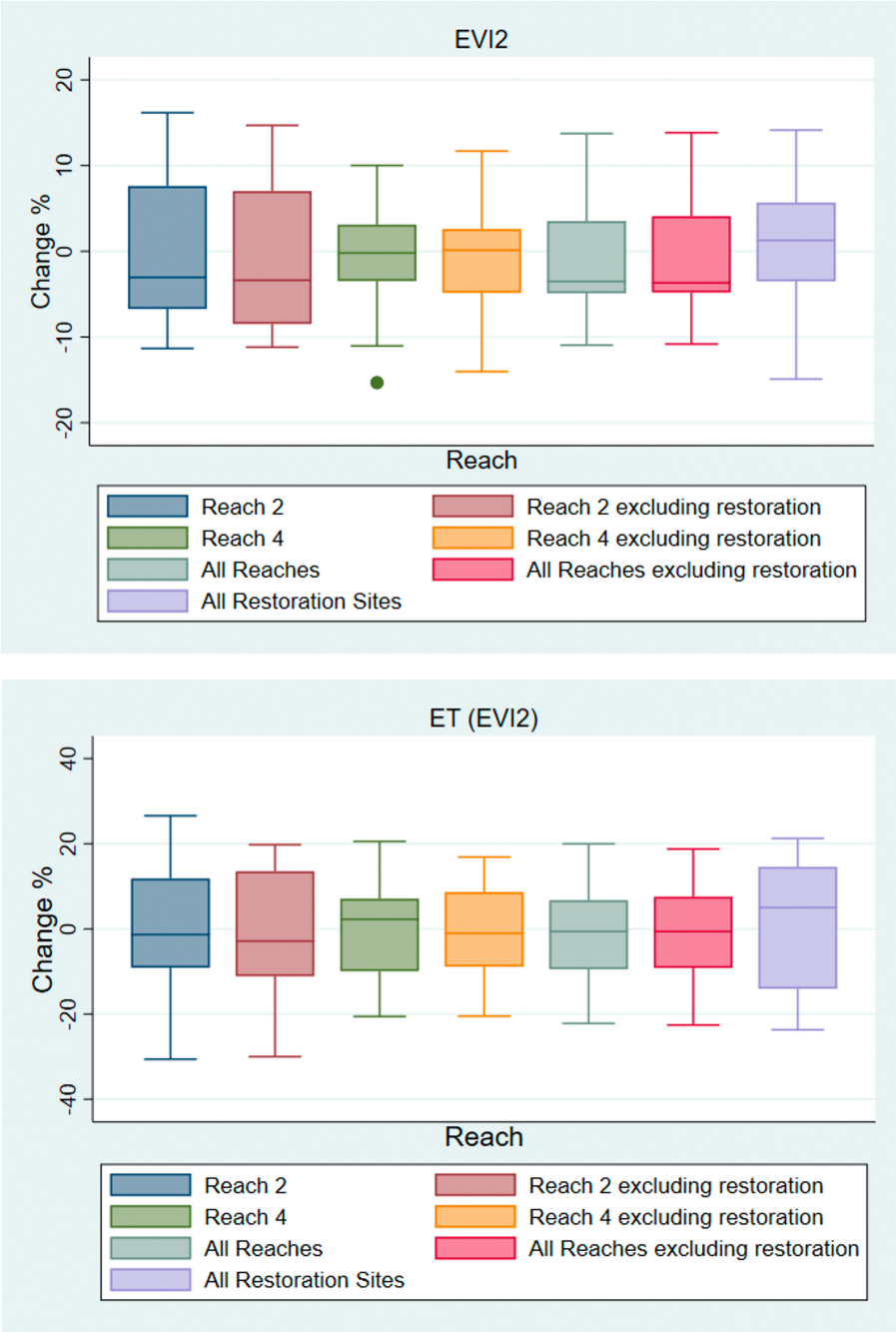

FIGURE 13. The EVI2 (top) and ET(EVI2) (bottom) percent change as box and whisker plots for seven AOIs of riparian vegetation (e.g., Reach 2 including the restoration site, 1-Miguel Aleman (2014), Reach 2 excluding the restoration site, 1-Miguel Aleman (2014), Reach 4 including a dozen restoration sites (1–12, see Table 1), Reach 4 excluding a dozen restoration sites (1–12), All Reaches including restoration plots (Reaches 1–4 as a weighted average), All Reaches excluding restoration sites (Reaches 1–4 as a weighted average), and finally, All Restoration Sites as a weighted average). Note the plot contains horizontal line, box, and whisker ends that indicate the median, 25th and 75th percentiles, and the 10th and 90th percentiles, respectively, and the data points outside this range are shown by dots.

data, tools, methods, and results can be utilized by decision makers in their quest to mitigate and understand how declines of riparian ecosystems can be slowed or possibly reversed. This information is important for our readers who are interested in long-term planning of actively managed sites comprised of a diversity of vegetation species, community composition, complexity, and water use. Baseline data on restoration sites in terms of our metrics, vegetation greenness, and ET, are useful for differentiating

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FIGURE 14. The rate of change using EVI2 (top) and ET(EVI2) (bottom) percent change year-to-year from 2000 to 2020 for All restoration sites and All reaches (Reaches 1–4) including restoration, Reach 2 including restoration, Reach 4 restoration, All reaches excluding restoration, Reach 2 excluding restoration, and Reach 4 excluding restoration.

anomalies in their growth and water usetrends which may be identified as a departure from the natural variability of the site. These data may help to inform scientific and policy decisions regarding whether adaptive management is needed.

Zaimes (2007) notes in his book chapter that it is important to note that riparian areas are very dynamic and disturbance-driven (Cartron et al. 2000); these factors lead to rapid changes in riparian vegetation composition and condition depending on the weather conditions and disturbances of a particular year (Larsen et al. 1997). All riparian ecosystems are dependent on disturbances, primarily flooding, to regenerate some of their vegetation communities (e.g., cottonwood) (Shafroth et al. 2000; Baker 2002; Shafroth et al. 2002; Glenn and Nagler 2005). Jones et al. (2010) showed multi-decadal changes in riparian habitat across the U.S. from 1972 to 2003. For many years, reports in the literature have indicated that large percentages of

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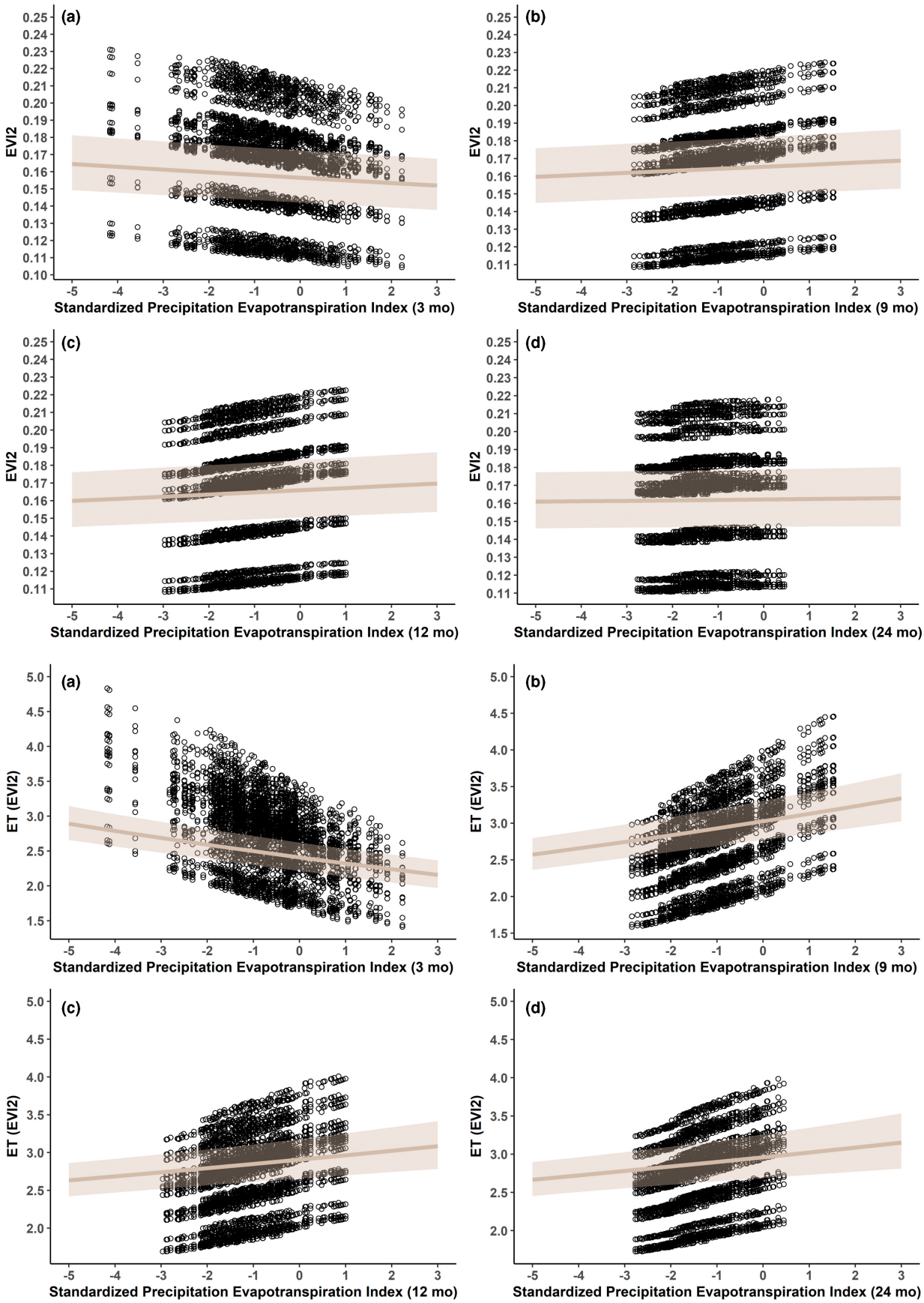

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FIGURE 15. Estimated EVI2 (top) and ET(EVI2) (bottom) (for all sites including the restoration sites and the reaches excluding the restoration sites, and thus is the estimated average vegetation greenness for combined areas) as a function of the SPEI and shown for 3 (a), 9 (b), 12 (c), and 24 (d) months. The trend data are shaded to show the 95% confidence range for EVI2 (top) and ET(EVI2) (bottom) relative to SPEI.

riparian areas are considered in degraded and nonfunctional conditions and in need of restoration (NRC 2002; Ffolliott et al. 2004; Allen et al. 2015; Jump et al. 2017; Albano et al. 2020). All along the LCR and in the delta, declining riparian vegetation greenness and ET has recently been measured (Nagler et al. 2020; Nagler, Barreto-Muñoz, Borujeni, et al. 2021; Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. 2021).

Riparian woodlands also change in structure and composition of biomass, including the individual shrubs and trees, their leaves, branches, and stems as well as their roots (Baker 2002; Tague et al. 2019). We provide a few examples of the restoration sites to demonstrate how satellite measured vegetation health is related to ground-based structure and composition of species. For example, the oldest restoration sites, such as those in CILA which contain mainly native trees with cottonwood and willow (C-W) habitat (11-CILA and 7-CILA), show their peak EVI2 values during the growing season of three years after planting. These two sites had similar ranges of greenness (0.25–0.35) and ET(EVI2) values (6–8 mm/day). For the last three years, three sites (1-Herradura, 4-Herradura, and 2-Cori-Rombo) contain a more heterogeneous plant community with C-W and mesquite (M) in the 1- and 4-Herradura sites; the 2-Cori-Rombo site is primarily M habitat. This indicates that restored sites with different plant communities or planting designs can be comparable in terms of greenness and water use. In contrast, 1-Miguel Aleman EVI2 and ET(EVI2) peaks were observed much later after six years' post-planting. This result is probably from a large proportion of the site being planted with upland species after 2014. In 1-Miguel Aleman the planting design includes more open areas that are likely contributing to lower EVI2 (<0.20) and ET(EVI2) (about 4 mm/day) during the peak year (2020) compared to Reach 4 sites.

Generally for the restoration sites, the earlier the planting year (e.g., 11-CILA (2010) and 7-CILA (2013–2014), the higher the EVI2 and ET. This seems like an obvious response to vegetation growth over time, but this is not always straightforward as demonstrated in the figures by noting that 9-CILA (2014–2015) is only an additional year of growth from planting date than 7-CILA (2013–2014); the 9-CILA site lacks the vigor seen in either 7-CILA or 6-CILA (2018) planted four years later. Given the canopy cover/extent, density, and other species information per restoration site, the response could vary by planting date. Furthermore, the response may vary as a result of local factors which include planting design, soil variability, irrigation method, and so forth.

Our remote sensing methods and monitoring tools capture some of the riparian changes on the ground using satellite measurement of the vegetative cover through VIs to estimate landcover greenness, and we have used these VI measurements as an indicator of plant health for more than 20 years (Nagler et al. 2001). However, all remote sensing methods need to be validated using ground measurements (Glenn et al. 2007, 2008, 2010, 2011). Riparian cohorts and stands of overstory trees and their understory biomass, grasses, and bare soils, have been quantified in this region using fractional cover measurements (Glenn and Nagler 2005; Nagler, Glenn, et al. 2005; Nagler, Hinojosa-Huerta, et al. 2005; Nagler et al. 2007; Nagler, Glenn, Didan, et al. 2008; Nagler, Morino, Murray, et al. 2009). For the riparian species in the delta region, we have used extensive measurements of leaf area, plant area, above-ground biomass, structure, and water use, through field and sap flux measurements (Nagler, Glenn, Hinojosa-Huerta, et al. 2008; Nagler, Glenn, et al. 2009; Nagler, Morino, Didan, et al. 2009). These landcover measurements have been compared with corresponding landscape-level measurements using flux towers and satellite data which were used to derive an empirical algorithm for scaling riparian water use to the wide-area or reach-level (Murray et al. 2009; Nagler, Morino, Murray, et al. 2009; Nagler et al. 2013). In the delta, both ground surveys and drones have been used to aid in vegetation measurements in the delta (Gómez-Sapiens et al. 2020, 2021).

For vegetative landcover types that are generally easy to measure (i.e., agriculture, grasslands), the Penman-Monteith equation is often used for estimating actual ET and the inputs to the drivers of water need and water use are quantified; however, simpler empirical models approximate ET using easily measured variables such as potential ET, air temperature, and satellite-based vegetation indices (Glenn et al. 2011). These vegetation-index-based ET measurements have been applied to riparian corridors along the LCR and delta and have successfully informed natural resource land and water managers (Murray et al. 2009; Nagler, Morino, Murray, et al. 2009; Jarchow, Nagler, and Glenn 2017; Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. 2017). Nagler et al. (2013) created the ET

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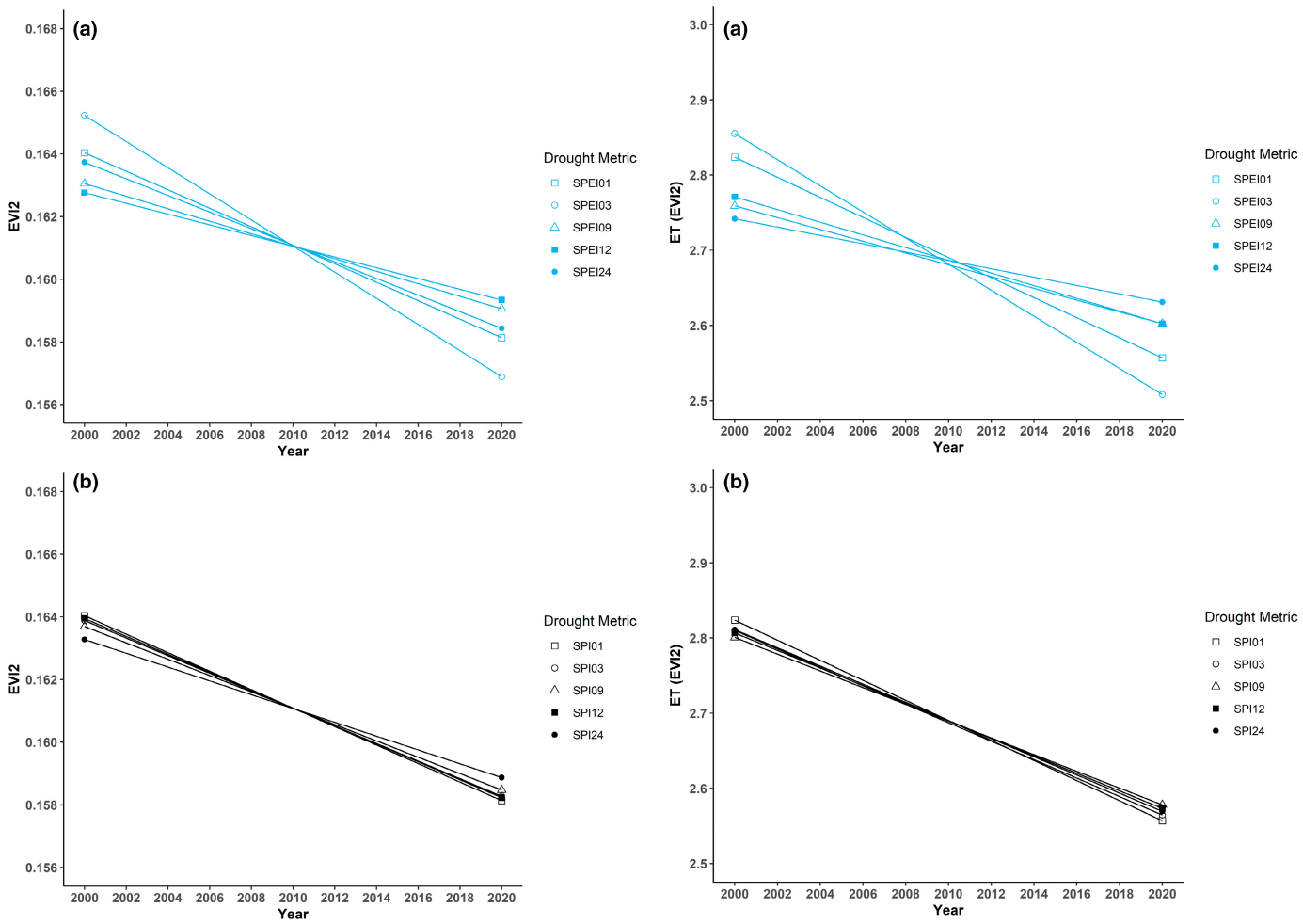

FIGURE 16. Predicted EVI2 (top) and ET(EVI2) (bottom) over the past 21 years (2000–2020) using the estimated relationship between EVI2 and the SPI and the SPEI with their respective durations (1, 3, 9, 12, and 24 months) based on the dataset of combined restored sites and reaches without restored sites (Reaches 1–4) (see Tables 2 and 3) in the delta riparian corridor.

formulation with the MODIS EVI that is used in this research with Landsat EVI2 since the algorithm has been adjusted for use at finer scales (Landsat at 30 m) (Jarchow et al. 2018). On the Lower Colorado riparian corridor, both peak average growing season ET and annual ET have been mapped with remote sensing (Khand et al. 2017; Nagler, Barreto-Muñoz, Borujeni, et al. 2021; Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. 2021).

As a result of the Minute 319 Pulse Flow in 2014, riparian vegetation in the Colorado River delta was revitalized throughout the delta reaches for the immediate one to two years that followed, but declines continued because the pulse flow impact was short lived (Jarchow, Nagler, and Glenn 2017). A decline throughout the seven riparian reaches in the delta as measured by the remote sensing metrics of greenness and water use was documented before and after the Minute 319 Pulse Flow in 2014, with a few post-pulse flow years contributing to a small increase in greenness across the reaches as a result of the added surface water (Jarchow, Nagler, and Glenn 2017). The increase in riparian health only occurred in 2014–2015 and declined in the following years (Nagler et al. 2020). Shannafield et al. (2017) measured EVI and ET responses to the 2014 Pulse Flow in three restoration sites (1-Miguel Aleman, 12-Chausse, and 7-CILA); they found a direct response

FIGURE 17. Predicted EVI2 (top four plots) and ET(EVI2) (bottom four plots) for restored (blue) and unrestored (red) sites in Reaches 1–4 as a function of the SPEI over four time periods and shown for 3 (a), 9 (b), 12 (c), and 24 (d) months. The relationships are shaded to show the 95% confidence level range.

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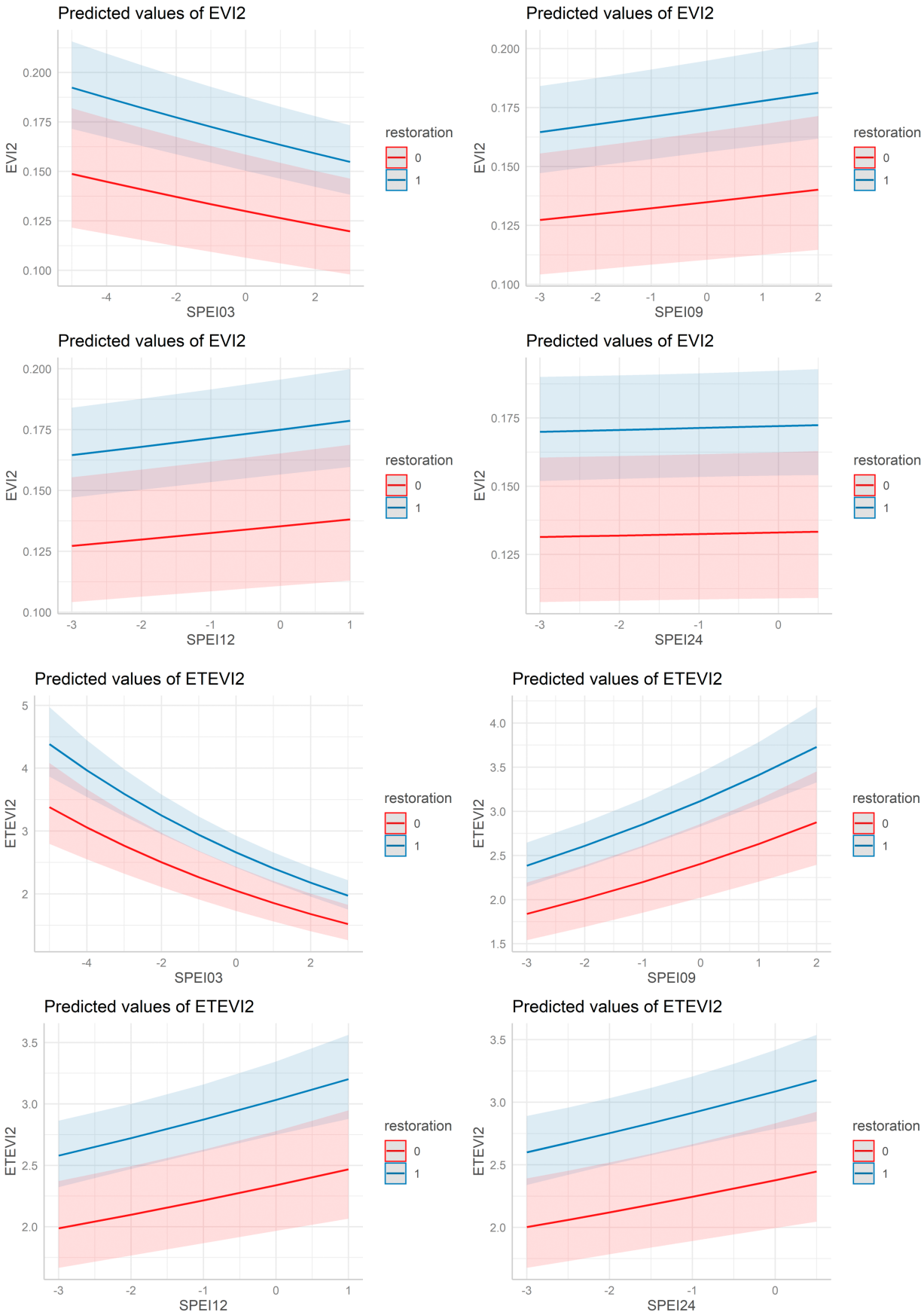

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to the Pulse Flow was not detectable in the following year, likely due to the site management activities occurring during the study period as clearings and also due to vegetation which likely relied on groundwater. Similarly, in our study, we found that the response in EVI2 and ET(EVI2) at the restoration sites after the Pulse Flow was not strong. The local factors including site maturity and groundwater dynamics are more relevant to producing the changes in productivity and water use at these sites.

Vegetation Greenness and ET in Relation to Drought

Nagler et al. (2020), Nagler, Barreto-Muñoz, Borujeni, et al. (2021), and Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. (2021) measured how average peak growing season ET for the LCR riparian corridor has changed over the last 20 years, but they did not specifically correlate how these ET measurements changed in response to drought. Other researchers used the classic Budyko curve (Li et al. 2013) but this model is not particularly used for riparian vegetation and does not take into account changes in vegetation composition, structure, and biomass (Tague et al. 2019), particularly critical for the narrow riparian corridors. Albano et al. (2020) selected riparian areas in 45 ecoregions in Nevada and found a correlation between Landsat Normalized Difference Vegetation Index (NDVI) and the SPEI drought index. Their novel approach resulted in a drought-adjusted NDVI which improved the statistical significance of riparian vegetation response (or health) trend estimates, thereby improving the ability to detect changes occurring in response to drought vs. other pressures. Our study also employs the SPEI at varying time-scales and we found correlations as well, between Landsat EVI2 and SPEI. Furthermore, we derived the relationship between Landsat ET(EVI2) and SPEI at five time intervals as is normal with using the drought index, SPEI.

We measured riparian plant greenness and water use for the purpose of comparing these data with drought indices so these relationships between our measured metrics and the SPEI over different time-periods ranging from 1 to 24 months could be determined for the first time in the riparian reaches of the Colorado River delta. Our results suggest that drought indices based on ET best describe relationships between vegetation health (greenness), riparian water use, and drought conditions in our study region, of which the ET(EVI2):SPEI03 relationship showed declines, but other periods (SPEI09, SPEI12, SPEI24) were positive.

On the x-axis of Figure 15, the range of values is SPEI from −5 to +3; the more negative the longer the period of dryness (drought) and the more positive represents a greater period of wetness. This is a transformation of the probability of observing a given amount of precipitation lasting between 3 (A), 9 (B), 12 (C), and 24 (D) months. A "0" (zero) index value reflects the median of the distribution of precipitation, a − 3 indicates a very extreme dry spell, a range between −1 to +1 indicates near normal, and a + 3 indicates a very extreme wet spell (McKee et al. 1993). The more the index value departs from zero, the drier or wetter an event lasting 3 (A), 9 (B), 12 (C), and 24 (D) months is when compared to the long-term climatology of the location. Our results demonstrate that with longer periods of drought, the compounded effect reduced riparian greenness, and specifically, with a drought lasting two years, green riparian vegetation is completely reduced or lost as indicated by the flatter lines depicted in EVI2 as a function of SPEI24 (Figure 15, top) and somewhat flat lines depicted in ET(EVI2) vs. SPEI24 (Figure 15, bottom).

This study also produced estimates of EVI2 and ET(EVI2) as a function of another drought index, the SPI; out estimates of greenness and water use vs. SPEI (Figure 16, top) and SPI (Figure 16, bottom), are shown for five time periods (1, 3, 9, 12, and 24 months) for the years 2000–2020. All correlations between EVI2, ET(EVI2), and SPEI and SPI show linear declines that depict how these metrics are greatly affected by long-term drought (Figure 16).

To further understand the effect of restoration on riparian health in arid and semi-arid regions, it will be essential to investigate drought effects on restoration sites and unrestored riparian areas separately. The positive sign of the dummy variable used to account for restoration suggests possible different drought responses between restored riparian units and non-restored sites and indicates that restoration has a positive impact on both vegetation greenness and water use (Tables 2 and 3). Even though drought has an impact on restored and unrestored reaches, the reduction of vegetation health and water use is more pronounced in unrestored reaches with an increase in drought severity (negative signs) as shown by the predictive estimates in Figure 17. Also, the performance of our models with the highest effects (in terms of coefficient estimates' magnitudes) (Tables 2 and 3) was based on seasonal drought (three months) and long-term drought (9- and 12-months). However, given the negative signs of the estimates for SPI and one- and three-month SPEI (Tables 2 and 3), our results indicate that SPEI drought indices with a time scale of 9 and 12 months are better suited in explaining the effect of drought on riparian vegetation health and water use. For this study with riparian reaches that contain both restored and unrestored areas, we found it to be

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important to test the robustness of our methods by analyzing the relationships between SPEI, EVI2, and ET(EVI2) during the most relevant season for riparian woodlands (e.g., peak growing season, summer, winter).

Recent studies in 2020 have shown increases in ET for the same region, the Colorado Basin; however, as discussed in great length by Tague et al. (2019) estimates of ET increasing or decreasing depend on geographic spatio-temporal scale among many factors. Milly and Dunne (2020) discuss their findings that the Colorado River flow has been drastically reduced because warming has driven the loss of snow; the lack of bright and reflective snow has caused a reduction in albedo and an increase in solar radiation absorption from dark surfaces, and has energized evaporation and increased ET across the Colorado River Basin which has led to shortages in surface water (Milly and Dunne 2020). They note that the drying trend is greater than the projected precipitation in this vulnerable region where increases in severe water shortages are expected with climate warming. Vose et al. (2014) have produced improved historical temperature and precipitation time series for U.S. climate divisions. Ecological forecasts have been produced for natural resource managers to cope with rapid changes in both environmental conditions and ecosystems (Bradford et al. 2020). As climate change impacts regional forests and causes plant stress and mortality, we expect that vulnerable riparian ecosystems in arid and semi-arid regions will be largely affected and water storage and availability will continue to change riparian ecosystem structure and function (McDowell 2013; Maupin et al. 2018; Smith et al. 2019; Miller et al. 2021; Park Williams et al. 2021). The climate changes and drought will likely affect not only restoration techniques and management, but also the human element (Stella et al. 2013; Rood et al. 2016; Palmer and Ruhi 2019; Sher et al. 2020; Palmquist et al. 2021). In addition to climate change and an extended drought from rising local temperatures, the Colorado River flow is threatened by increasing anthropogenic demands from a growing population (Hobbins and Barsugli 2020).

In many riparian areas of Mediterranean-type forests, surface and subsurface water is redistributed, and therefore ET in narrow streamside corridors is high at the landscape-level in comparison with low ET at the local-level due to reduced forest cover or areas experiencing drought. In these riparian environments, Tague et al. (2019) noted a lack of research in which both plot- and landscape-scale changes in ET are measured concurrently at multiple locations following a canopy density reduction event. However, there are a few recent studies that have documented changes in ET before and after natural canopy thinning events at the river-reach level. The tamarisk beetle (*Diorhabda* spp.) has defoliated large swaths of riparian corridors in the southwestern U.S. (Nagler et al. 2012, 2014; Nagler, Nguyen, et al. 2018; González, Shafroth, Lee, Ostoja, et al. 2020; González, Shafroth, Lee, Reed, et al. 2020) mimicking canopy density reduction events described by Tague et al. (2019). Nagler, Jarchow, et al. (2018) and Nagler, Nguyen, et al. (2018) used remote sensing to measure before and after landscape-level ET in riparian areas that experienced defoliation by the tamarisk beetle (a canopy density reduction event). Nagler et al. (2020) also employed Landsat data to evaluate changes in ET in small-area restoration sites that had been comprised of natural riparian corridor vegetation, then cleared for restoration (a canopy density reduction event), then became dominated by a young riparian canopy.

Garcia and Gracia and Tague (2015) studied the Colorado Basin and found cascading effects of warmer air temperatures leading to earlier snowmelt, earlier-in-the-season runoff, reduced spring recharge, and reductions in forest ET. Water limitations in a critical part of the year reduced total annual ET (Garcia and Gracia and Tague 2015). Phenological shifts coinciding with early snowmelt may mitigate reductions in ET that would exist with increases in warming or extended high temperatures. In the LCR and delta areas, warming is perhaps lengthening the growing season as described in Westerling et al. (2006); however, observations of ET under the recent warming trends and/or extended number of days with high temperatures in the LCR and delta region, have led to plant water stress and measured decreases in riparian vegetation greenness and reductions in ET over consecutive years of these drought conditions (Jarchow, Nagler, and Glenn 2017; Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. 2017; Nagler, Jarchow, et al. 2018; Nagler et al. 2020; Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. 2021).

Declines in the Unrestored Riparian Corridor vs. the Increases Due to Restoration

In this section, we quantify the percent change in the greenness and water use results between the unrestored and restored sites. The riparian zone data for the unrestored (All Reaches (1–4) excluding restoration) show a 24% decrease in greenness or a 1.1% yearly decrease. In the pre-pulse flow years between 2000 and 2013, greenness decreased 14% at an annual rate of decline of 1.0%. Between 2014 (the year of the pulse flow) and 2020, greenness decreased 15%, an annual rate of decline of 2.1%. Although

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minor, the rate of change in greenness was larger since the 2014 Pulse Flow for Reaches 1–4 excluding restoration sites. However, the average yearly EVI2 value in 2020 was 8% higher than in 2019 likely due to excess water from the MODE flows (see IBWC Report (2021)). The 2020 EVI2 values were lower than those from the post-pulse year of 2014 and lower than in 2000. The category for restoration, All Restoration Sites, shows decreases in EVI2 between 2000 and 2013 for the reason that during this period the majority of the ground-area measured was unrestored riparian vegetation not active restoration sites; for these areas we measured a loss in EVI2 of 12.0% during the pre-pulse flow years. However, between 2014 and 2020, greenness in All Restoration Sites increased by 34%, or 4.9% annually, and was ca. three times higher in the last year, showing increases in EVI2 of 14.1% between 2019 and 2020.

Our new findings using Landsat EVI2 and ET (EVI2) for the 21-year period from 2000 to 2020 show a decline in both metrics for the unrestored area in the first four reaches (excluding restoration sites) after the 2014 pulse flow, but both metrics show an incline in restored areas, demonstrating the success of the water deliveries to the restoration sites (see Appendix S1, Tables A1 and A2). The differences from one year to the next, and for groups of years, show oscillations in these remotely sensed metrics, but only restored sites (last columns) have overwhelmingly positive changes (see Appendix S1, Tables A3 and A4). The impact of the pulse flow was higher on restoration sites due to the active management that happened before the event. Sites were cleared from non-native and undesirable shrubs species as (*Pluchea sericea*) in order to create bare ground for recruitment of native species (see Shafroth et al. 2017). Also, land grading was used in order to maximize inundation. At the reach level, the pulse flow did not have a long-lasting measured response of greenup after two years (2014–2016) (Nagler et al. 2020). We believe the targeted water deliveries to the restoration sites have a greater influence than the pulse flow. Minute 319 results published by Jarchow, Nagler, and Glenn (2017) and Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. (2017) led to the use of smaller surface flows to the delta and a greater reliance on directed agricultural return flows and deliveries of water to active restoration sites. Those findings have continued to be used to assist managers with decision-making for ecological restoration success.

Annual percent change in greenness and water use is calculated to demonstrate year-to-year change as well as between select groups of years and show a similar temporal and spatial pattern with changes being mostly, largely negative for unrestored reaches and positive for restoration sites, except between 2000 and 2013, prior to the majority of the restoration activities (see Appendix S1, Tables A5 and A6). Over the 21-year period from 2000 to 2020, ET(EVI2) in the riparian zone decreased by 32%, a 1.5% yearly decrease. Between 2000 and 2013, ET(EVI2) decreased by 16.4%, an annual decline of 1.2%. Between 2014 (the year of the pulse flow) and 2020, ET(EVI2) decreased by 11%, an annual decline of 1.6%. The rate of change in water use was slightly higher since the 2014 Pulse Flow than before it (2000–2013) for Reaches 1–4 excluding restoration sites. However, the average yearly ET(EVI2) value in 2020 was 12% higher than in 2019 probably due to the additional MODE canal flows (Nagler et al. 2020). The 2020 ET(EVI2) values were lower than those from the post-pulse year of 2014 and lower than in 2000. The category for restoration, All Restoration Sites, shows decreases in ET(EVI2) between 2000 and 2013 because the majority of the restoration sites had not yet been planted; we measured a loss in ET (EVI2) of 12.6% during the pre-pulse flow years. However, since 2014, in the restoration sites ET (EVI2) increased by 58%, or 8.3% annually, and was ca. two times higher in the last year, showing increases in ET(EVI2) of 15.1% between 2019 and 2020.

To summarize, over the 21-year study period from 2000 through 2020, we focused on the first four reaches of the delta because restoration activities, with 13 sites with initial planting dates between 2010 and 2018, have taken place in two of the reaches, Reach 2 and Reach 4. We assessed if restoration sites had an impact on reach-level riparian health and water use by calculating data from the adjacent unrestored areas in Reaches 1–4 including and excluding the restored sites. A key finding is that over 21 years in the unrestored riparian corridor of the Colorado River delta (Reaches 1–4, excluding restoration) greenness decreased by 23.6% and ET decreased by 32.0% (0.87 mm/day), whereas in "All Restoration Sites" greenness increased by 11.2% and ET increased by 5.4% (0.18 mm/day). However, for most of these 21 years, very little restored vegetation existed so we focus on restoration activities "All Restoration Sites" over the last decade (2011–2020). During these 10 years, the unrestored riparian corridor of the Colorado River delta, that excluded restoration sites, decreased in vegetation greenness (11.3%) and showed reductions in ET of 28.2% (−0.73 mm/day); however, restored areas increased in both metrics. Over the period from 2011 to 2020, restored vegetation greenness increased by 35.8% and ET increased by 19.6% (0.58 mm/day). The increases in All Restoration Sites were for small areas only, and All Reaches including restoration

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continued to decline losing both EVI2 (17.3%) and ET (28.2%) during the last decade. We measured the adjacent unrestored riparian vegetation in the corresponding reaches (All Reaches 1–4, Reach 2, and Reach 4, with each category excluding restoration) and found that the data in the unrestored part of the reaches for the same decade (2010–2020) showed a decrease of 20.6%, 15.3%, and 23.3% EVI2 and a decrease of 30.2%, 39.6%, and 14.9% ET, respectively. Since the Minute 319 pulse flow in 2014, All Restoration Sites greenness increased by 33.6% and ET increased by as much as 1.29 mm/day (58%). The corresponding unrestored reaches showed losses of 14.7% greenness and a loss of −0.23 mm/day in ET (11%).

We found that greenness (EVI2) and ET(EVI2) trends are in opposite directions between the category, All Restoration Sites (increasing) and All Reaches, excluding restoration (namely the unrestored reaches) (decreasing). Although very subtle, the yearly percent change decline of 2.1% EVI2 and decline of 1.6% ET(EVI2) for the reach-level are both slightly greater declines rates after the 2014 Pulse Flow than before, and the rate of greening in the restoration sites is increasing by 4.8% EVI2 and by 8.3% ET(EVI2), much greater than the decreasing rates in the unrestored reach-level.

Further increases in available water in the years 2019–2020 helped the post-pulse average greenness and ET considerably though, and this somewhat mitigated the long-term declines over the last 21 years by providing a small boost to the two measurement metrics. In Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. (2021), they used EVI (not EVI2) and found similar results to using EVI2; they noted that the decline in greenness was slowest in Reach 4 (high water table). Reaches 2 had slower declines than the reaches south of Reach 4 (Nagler, Barreto-Muñoz, Didan, Gómez Sapiens, et al. 2021).

Added water for restoration was outlined in Minute 323 (IBWC 2017) and has been a benefit to the riparian corridor. The restoration sites in Reach 2 and Reach 4 have greened-up in the 2014–2020 post-pulse flow period as a result of this directed water and show corresponding increases in ET. Separating these periods into shorter periods, and the last year (2019–2020), the 2 most recent years (2018–2020), the past five years (2016–2020) and the post-pulse flow period (2014–2020) demonstrates the spatiotemporal dynamics of the restored and unrestored areas and shows that a remarkable and significant increase in greening and ET occurred during the last years in both restored and adjacent riparian areas. The increased greenness (22%) and ET (40%) between 2018 and 2020 in All Restoration Sites are because of directed flows to the restoration sites and the excess MODE flows helped All Reaches (1–4) in the last year 2019 to 2020. These data confirm that these restoration sites are patches of success in a declining riparian woodland landscape, but that the riparian corridor has had access to available water during the past year or two, since 2018 as measured by positive changes in both metrics for all categories except Reach 4 excluding the restoration sites. This may be due to further land clearing for future restoration sites in Reach 4 and not due to the adjacent reach land cover comprised of declining riparian vegetation. Importantly, active restoration of native plants and timing of water deliveries since 2014 have been significant, not only for the successful restoration but for the unrestored riparian vegetation in the corresponding reaches, Reach 2 and Reach 4 as well as the category for All Reaches (1–4).

CONCLUSION

Although the unrestored delta riparian corridor continues to decline in vegetation greenness and water use, restoration efforts have positively impacted the delta's habitats and native plant health. This study contributes to a greater understanding of the continuing efforts of Minute 323 and helps to inform decision-making to restore and maintain native vegetation through (1) the use of smaller surface flows, (2) a greater reliance on directed agricultural return flows, and (3) deliveries of water to active restoration sites. It provides information regarding how different the relationship between restored and unrestored areas is for EVI2 and ET (EVI2) as a function of drought indices over 21 years.

One purpose of directed surface flows in the delta is to provide water for the environment and facilitate ecosystem restoration. Long-term survival of established vegetation depends in part on access to a long-term water supply, which in this area is groundwater. Despite the effects of drought in the delta region, negotiated small surface flows and agricultural return flows directed to restoration sites, which are delivered frequently, will sustain restored riparian woodlands. Riparian vegetation greenness and ET, in restored river reaches, responds to human actions to provide available water for plants and mitigate meteorological drought, as shown by trends over time and/or abrupt changes, and can be contrasted with unrestored vegetation along the river corridor. This knowledge can inform decisions about future water requirements for restoring natural environments and dryland riparian ecosystems. One hope is that the methods and results provide information for decision makers tasked with improving water deliveries for site-specific irrigation to prepared restoration sites.

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We acknowledge that there are limitations of this study, but addressing these topics in greater depth, such as further exploring drought indices as predictors of our greenness and water use measurements in restoration sites, is outside the scope of this manuscript, but is a research topic being explored. In future papers, we will assess the effect of changes in not only meteorological variables but also hydrological (e.g., stream flow) and plant-based, known as agricultural (e.g., soil water stress) variables on riparian vegetation's greenness and water demand. This is a work in progress under Minute 323 efforts; as such, we did not test this hypothesis and can only expect these improvements in timing and volumes were effective. We will be able to test this hypothesis compiling information on the restoration treatments and water application details for the restoration sites. Note that in the past several years, operational improvements have been made to improve the timing and volumes of water delivered to the restoration site as direct site irrigation. In particular, 2020, and more recently, the water orders have been filled more closely to what was requested. In some years, the irrigation to the restoration sites has left some restoration sites with inadequate irrigation during the growing season, and this has improved over 2020–2021. It is a big factor in the effectiveness of the restoration program.

After Minute 319 allowed for the 2014 pulse of surface water to be released into the delta's reaches of the Colorado River, Minute 323 followed and allowed for directed water to restoration sites. Additional flows from the MODE canal in 2019, provided more water for the delta's riparian zones. Restoration sites in Reach 2 and Reach 4 are showing positive trends in greenness as measured by Landsat EVI2 and in riparian water use as measured by Landsat ET (EVI2). The restoration sites, individually and averaged together, show increases in vegetation health, in both greenness and ET metrics as measured using remote sensing alone. The restoration site scale, being comprised of small plot-sizes and fewer pixels than the corresponding reaches or Reach 1–4 in our study area, can be successfully measured using Landsat resolution of 30 m (98 ft). Restoration sites and reach-level results have opposite trends in vegetation cover, health, greenness, and water use, with the restoration sites having a positive effect on overall vegetation growth, and the unrestored reaches having negative trends in greenness and water use. The impact of the restored sites does not affect the wider-area unrestored riparian vegetation in the corresponding reaches, Reach 2 and Reach 4, and does not affect the riparian health in the full area, Reaches 1–4; the reach-level data were measured separately for this study so that comparisons could be made between the restoration sites and the surrounding riparian corridor. However, 2020 showed the highest increase in greenness as estimated by EVI2, at the reach level (and across Reaches 1–4) since 2014, the year of the pulse flow. Greenness was highest in those reaches (including Reach 4) with a shallow water table. Greenness increases were observed for all reaches, but naturally, there was a boost in Reach 2 and Reach 4 due to restoration activities that flourished on the directed water.

Added in-stream water from Minute 319 in 2014 helped both native and non-native riparian species at the reach-level in terms of vegetation extent and greenness, but only for the very short-term (one to two years) and then declines resumed as measured in this study for Reaches 1 through 4, until 2019. Dramatic greening and increased ET occurred in 2020 compared with 2019 following the MODE canal diversion of flow into the river. At the restoration plot-level, greening has shown a tremendous increase especially in 2020 with irrigation effectiveness improving over the year 2019 and with daily water use levels are in the normal range for native species. The impact of restoration on the reach-level declines in riparian vegetation health and water use is not yet clear, but in the last one to two years, reach-level greenness and daily ET for all AOIs showed positive percent changes, except in the unrestored part of Reach 4 (excluding restoration sites) and this may be due to land clearing for additional restoration sites in the future. It will be important to test the robustness of our methods by analyzing the relationships between drought indices, greenness, and riparian water use during relevant seasons to riparian vegetation (peak growing season, summer, winter, etc.) in our study area and other regions.

The restoration areas are markedly greener than the surrounding reach area unrestored vegetation for all differences and percent changes measured between years with the exception of 2018–2020 and 2019–2020, which shows greening and increased ET outside the restoration zones in the natural reach areas. The change maps demonstrate the success of the restoration activities. Without additional environmental flows and more active restoration areas, long-term reduction of vegetation and increase in bare soils at the reach-level is expected to continue at a rate of 1%–2% yearly decreases as measured remotely and as predicted by the drought indices demonstrate over the 21-year dataset. We believe the targeted water deliveries to the restoration sites (see Figure 1) have a greater influence than the pulse flow. Minute 319 results published by Jarchow, Nagler, and Glenn (2017) and Jarchow, Nagler, Glenn, Ramírez-Hernández, et al. (2017) led to the use of smaller surface flows to the delta and a greater reliance on

directed agricultural return flows and deliveries of water to active restoration sites. Those findings have continued to be used to assist managers with decision-making for ecological restoration success. These data, tools, methods, and results can be utilized by decision makers in their quest to mitigate and understand how declines of riparian ecosystems can be slowed or possibly reversed.

DATA AVAILABILITY STATEMENT

Data generated during this study are available from the USGS ScienceBase-Catalog (Nagler, Barreto-Muñoz, and Didan 2021).

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Data detailed in six tables provide values for interested audiences to see (1) average annual EVI2 and ET(EVI2) for each year 2000 through 2020, (2) the difference in EVI2 and ET(EVI2) annually for each year of change between 2000 and 2020, and between selected groups of years to demonstrate changes, and (3) the percent change in EVI2 and ET (EVI2) annually for each year of change between 2000 and 2020, and between groups of years to demonstrate percent change over these selected periods.

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AUTHOR CONTRIBUTIONS

Pamela Nagler: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing – original draft; writing – review and editing. Ibrahima Sall: Formal analysis; investigation; methodology; software; validation; visualization; writing – review and editing. Armando Barreto-Muñoz: Data curation; formal analysis; methodology; resources; software; validation; visualization. Martha Gómez-Sapiens: Data curation; visualization; writing – review and editing. Hamideh Nouri: Investigation; methodology; visualization; writing – review and editing. Sattar Chavoshi Borujeni: Formal analysis; methodology; visualization. Kamel Didan: Data curation; project administration; resources; supervision.

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