Sonoran Desert Drought Map
Initial Report

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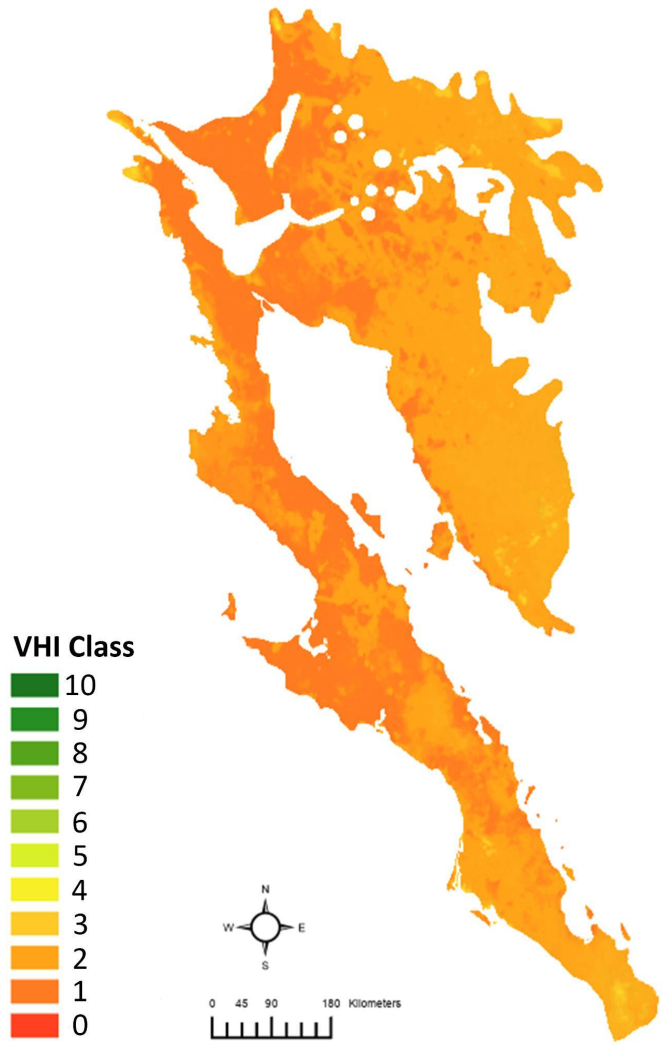

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Executive Summary

The aridification of the Sonoran Desert and greater southwest United States and northern Mexico is underway. In addition to the ongoing more than two-decade drought, anomalous heat and drought events such as experienced in 2020 through 2021 are altering the climatic underpinnings of the region. What is the impact of these recent extreme drought events on the vegetation across the region?

This report details a landscape level assessment of vegetation health, an initial step in an effort to document the consequences of drought on the vegetation of the greater Southwest. The holistic approach looks across different scales from the landscape level, to field studies at the local level, to the physiological responses of individual plants. The Sonoran Desert Drought Map uses the vegetation health index (VHI) derived from satellite imagery as a proxy to classify the vegetation state in near time.

The VHI analysis confirms what the meteorological record and on the ground observations have indicated, cumulative and acute stress from a prolonged period of below average precipitation since 2000 and the combined effect of minimal rains and above average temperatures in 2020–2022. Specifically, the drought map identifies the vegetation of the majority of Baja California as experiencing severe drought. In addition, our analyses show that in the depths of such drought, reprieve from the normally reliable summer monsoons are scattered and unreliable. This renders much of the region's vegetation especially vulnerable to extreme stress.

The drought map provides the first available presentation and analysis of drought impacts on Sonoran Desert vegetation. This robust data set of over 21,410 monthly data points supports the causative mechanism of the extreme heat and low precipitation events in driving mass stress and in some cases mortality of a diverse cross section of Sonoran Desert plants, which we can expect to become more acute.

Introduction

In recent years, the Sonoran Desert, like many other places across the globe, has experienced anomalous heat and drought events (Cook et al. 2022; Williams et al. 2022). This is in addition to the backdrop of a more than two-decade drought that has engulfed the greater Southwest United States and Northwest Mexico since the beginning of the twenty-first century (Woodhouse et al. 2010; Williams et al. 2020).

In particular, the period from 2020 through 2021 was exceptional in the widespread lack of precipitation and extreme high temperatures recorded across the region (Seager et al. 2022). Specifically, in the greater Southwest United States the precipitation totals over 20 months between January 2020 and August 2021 are the lowest on record since at least 1895 (Mankin et al. 2021). Similarly, in Baja California Sur, the period from April 2020 to March 2021 was the driest year in the meteorological record (Arnold et al. 2023). In the Loreto area the joint probability of two years in succession being as dry as 2020 and 2021 was estimated to have a recurrence interval of two thousand years, extraordinary on a scale of millennia.

What is the impact of these recent extreme drought events on the vegetation across the region? Widespread observations of severe plant stress and mortality observed across an array of species throughout the Sonoran Desert indicate acute and severe physiological stress responses.

The occurrence of these extreme drought events has been predicted for the greater SW region due to anthropogenic climate change (Seager et al. 2007). There is a high degree of likelihood for similar future events (Overpeck & Udall 2020; Seager et al. 2023), driven especially by decreases in cool season precipitation and warming that enhances evaporative demand and dries soils (Gao et al. 2014; Seager et al. 2023)
As the climate warms, precipitation decreases, and evapotranspiration rises, many individual plants and certain species may pass physiological thresholds leading to their abrupt decline (Munson et al. 2021), especially in cacti (Hultine et al. 2023). Accordingly, there is urgency to better understand the severity of these events in space and time at the regional landscape level and within the context of species-specific responses at specific locations.

To explore a causative relationship between anomalous drought and high temperature events and vegetation stress now and in the future we have developed a Sonoran Desert Drought map based on vegetation indices derived from remote sensing technologies. This report presents the initial results of the Sonoran Desert Drought Map.

Data Source – Vegetation Health Index (VHI)

The Drought Map is based on the Vegetation Health Index (VHI), a product of NOAA's National Environmental Satellite, Data, and Information Service (NOAA-NESDIS) STAR Center for Satellite Applications and Research (NOAA 2023a). VHI is a proxy characterizing vegetation health through a combined estimation of moisture and thermal conditions. It uses global, 4 km resolution satellite images, which are condensed into 7-day composites as the input data sets.

VHI is calculated in the following way:

$$VHI = \alpha * VCI + (1 - \alpha) * TCI$$

VCI, the Vegetation Condition Index, is a proxy for moisture conditions. It evaluates the current vegetation health in comparison to the historical trends from radiance measurements from the Advanced Very High Resolution Radiometer (AVHRR) satellite in the visible (VIS) and near infrared (NIR) wavelengths. VIS and NIR values are converted to the Normalized Difference Vegetation Index (NDVI=(NIR-VIS)/(NIR+VIS)). The VCI relates current decadal NDVI to its long-term minimum and maximum, normalized by the historical range of NDVI values for the same decade (NOAA 2023b).

TCI, Temperature Condition Index, is a proxy for thermal conditions. It is based on 10.3-11.3 μm from the AVHRR satellite radiance measurements converted to brightness temperature (NOAA 2023b).

α is a coefficient determining contribution of the two indices, which is set at 0.5 for the non-modified VHI calculations (NOAA 2023b).

VHI has a range of values from 0 (extreme drought) to 10 (excellent conditions). Values below 4 indicate vegetation stress (NOAA 2023a).

An additional data source has also been considered, which is a Drought Modified VHI (D-VHI) developed by Zeng et al. (2023). This version of VHI varies the value of the α coefficient from a default 0.5 to reflect soil moisture conditions, which are well known to be key drivers of vegetation structure and health in deserts (Shreve 1951; Bento et al. 2020). The D-VHI dataset covers the time period between 1981–2021.

Methods

Data processing, presentation, and analysis

In the Geographic Information System, a map with boundaries of the larger Sonoran Desert was assembled. The boundaries include Shreve's Sonoran Desert subdivisions (Shreve 1951), plus the Cape region and the Sierra de la Giganta, in the Baja California peninsula, to incorporate the whole peninsula in the analysis (González-Abraham et al. 2010). Within this map of the Sonoran Desert, we masked-off all the large irrigation districts such as the Imperial Valley in the United States, the Mexicali Valley in the State of Baja California, Mexico, and the large plains of southern Sonora; namely, the Yaqui and the Mayo irrigation districts. Because all these regions are artificially irrigated, the surface reflectance properties of the vegetation do not reflect climate-driven drought cycles but rather water availability in deep wells and river dams, largely uncoupled from seasonal variations in precipitation.

The resulting map frame contained 21,410 pixels covering an area of ca. 85,640 km^2. Within this map frame, we downloaded the monthly VHI values between January 2020 and December 2022 for each pixel, totaling 36 monthly files with VHI data for each of the 21,410 pixels during that month. Then, in each monthly file, we calculated the mean VHI value for the whole Sonoran Desert, as well as its standard deviation, and the monthly coefficient of variation (*mean*/*st.dev.*).

Similarly, we then downloaded all the monthly D-VHI values (drought-modified Vegetation Health Indices) available between August 1981 and December 2021, totaling 477 monthly files with information for 21,410 pixels in each file. As in the previous analysis, we calculated for each monthly file the mean D-VHI value for the whole Sonoran Desert, as well as its standard deviation. Because this second data series encompasses 40+ years, we also calculated the long-term trend in vegetation health. Using simple time series analysis for linear trend evaluation, we calculated whether the long-term slope of the D-VHI index had tended to decrease, increase, or remain constant over time over the last four decades.

The whole dataset was composed of 513 files with monthly data x 21,410 pixels in each monthly file x 6 data items per pixel (pixel ID, latitude, longitude, VIH value, source metadata, and O-ID). That is, the analysis dealt with 65,899,980 data records distributed in 513 different files. Because of its large size, we programmed a data-handling code in the statistical language R, to read each file one at a time and process their pooled contents as big data.

Results

2020–2022

Using the base VHI index, we assessed the values of the extent of the drought throughout the Sonoran Desert from 2020 through 2022 visually in map form (Figures 1 and 2) and quantitatively (Figures 3–5).

The majority of the Sonoran Desert suffered severe (VHI<4) to extreme (VHI<2) vegetation response in these three years, especially in 2021 (Figures 1 and 2). The central portion of the Baja California peninsula, including the Gulf of California and Pacific coasts, were similarly impacted with extreme VHI values. The areas that seem to show elevated VHI and ameliorated drought stress are the northern portions of the Sierra Madre in mainland Mexico, the Cape Region of Baja California Sur, the and mid-peninsula mountains in Baja California.

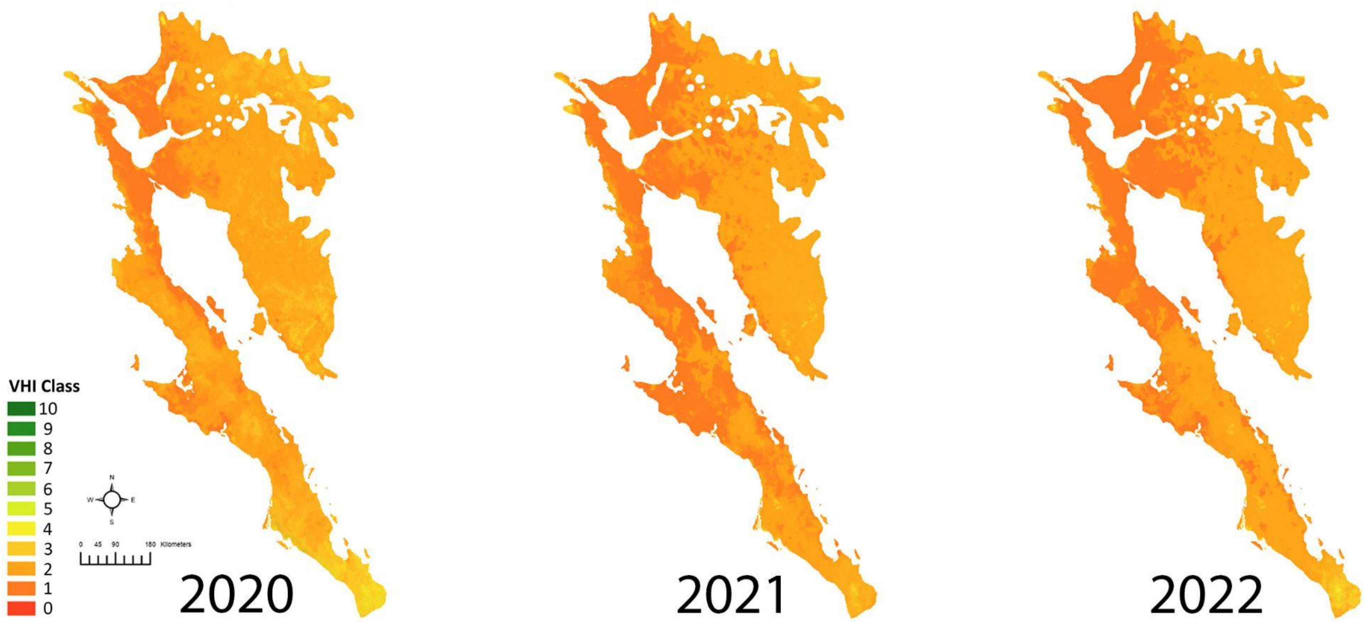

Figure 1. Summary Drought maps for 2020, 2021, and 2022 in the Sonoran Desert.

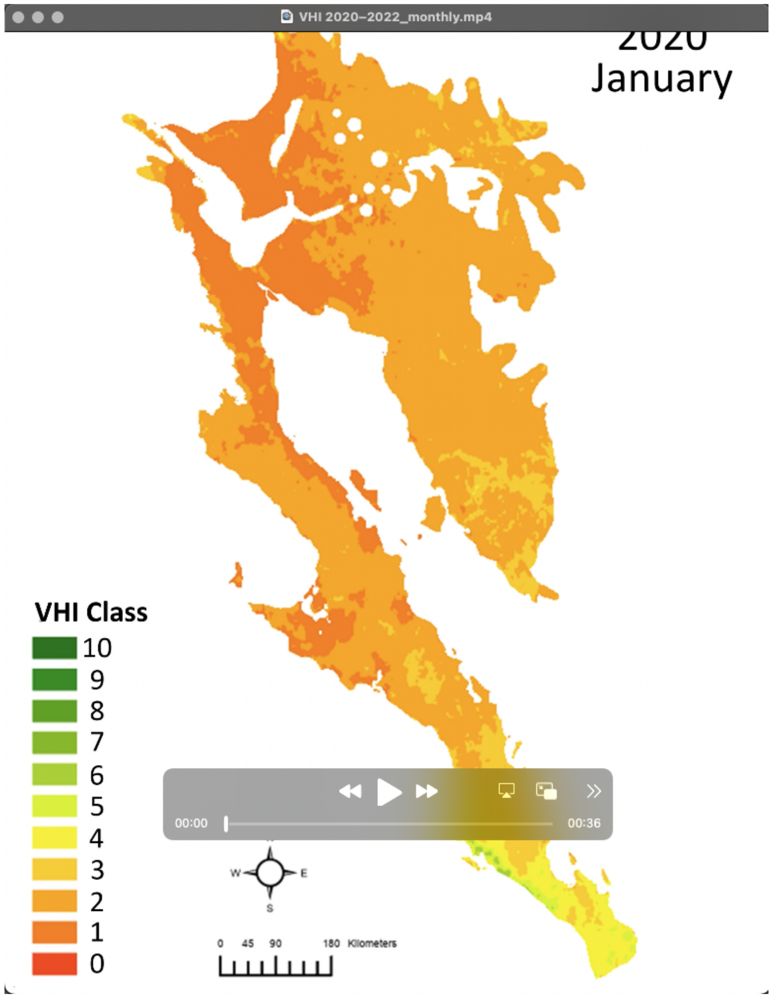

Figure 2. Monthly VHI maps 2020–2022 visualized as a short movie viewable here: https://youtube.com/shorts/ZEvW_B7pPPA

Average VHI values for the whole of the Sonoran Desert were consistently low (1–2) throughout the time period (Figure 3). Values did consistently increase with the onset of summer monsoons in the late summer months (August and September), with a much decreased signal in the weak monsoon of 2020. The variation of mean VHI values increased markedly in the summer months (Figure 4), indicating a scattered and localized geographic distribution of summer rain events.

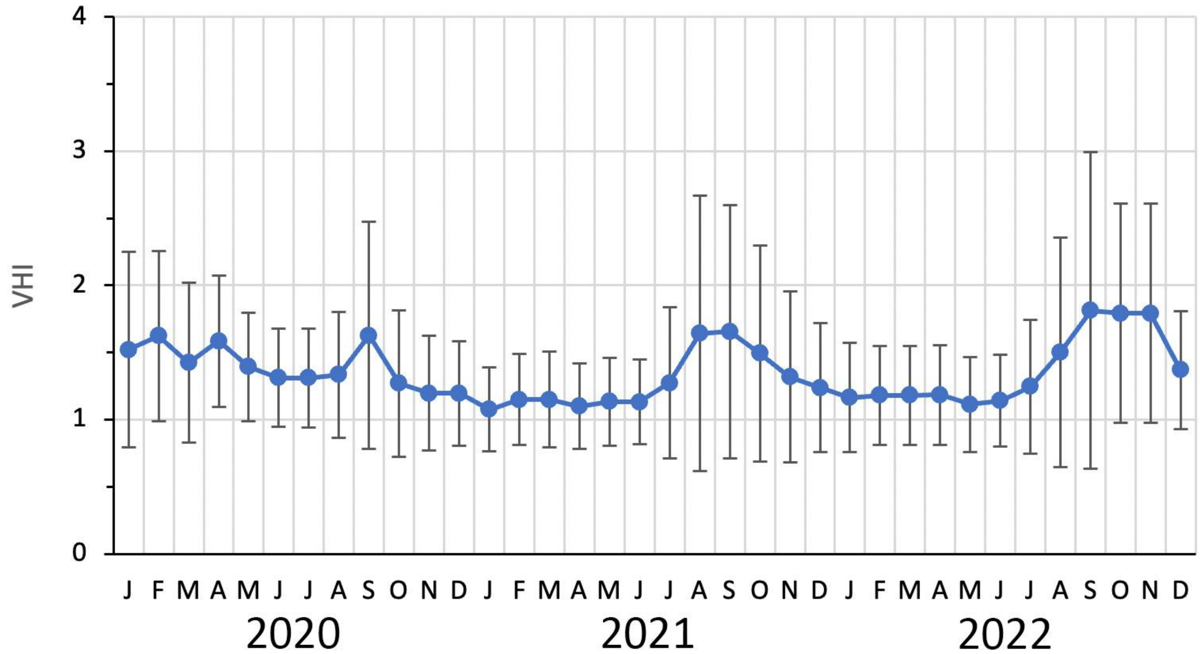

Figure 3. Average VHI values by month from the whole Sonoran Desert, 2020–2022.

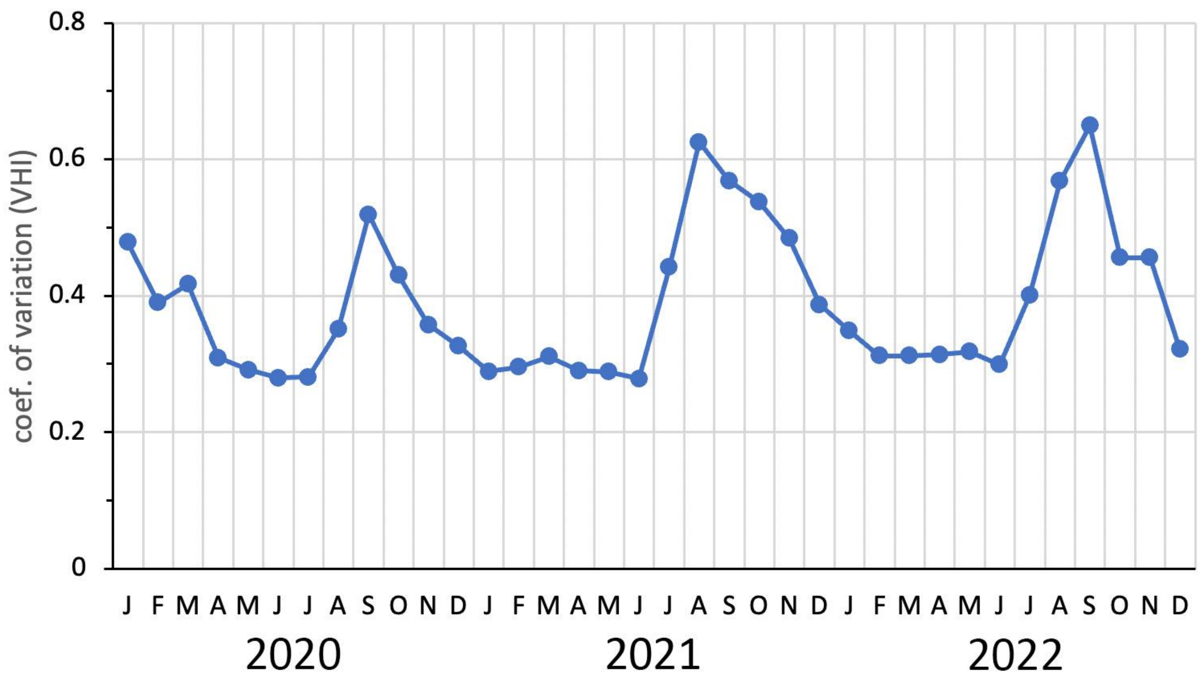

Figure 4. Coefficient of variations of average VHI values by month from the whole Sonoran Desert, 2020–2022.

Across the Sonoran Desert, the various subregions as defined by Shreve (1951) and modified for Baja California by González-Abraham et al. 2010, show variations in the VHI values within and between years (Figure 5). The subregions with consistent drought stress and low VHI values are the normally arid Lower Colorado River Valley, the Vizcaino portion of Baja California, and the Central Gulf Coast. Nearly all regions were especially stressed in 2021, with differential recovery in 2022. The La Paz and Plains of Sonora subregions consistently showed the least amount of drought stress.

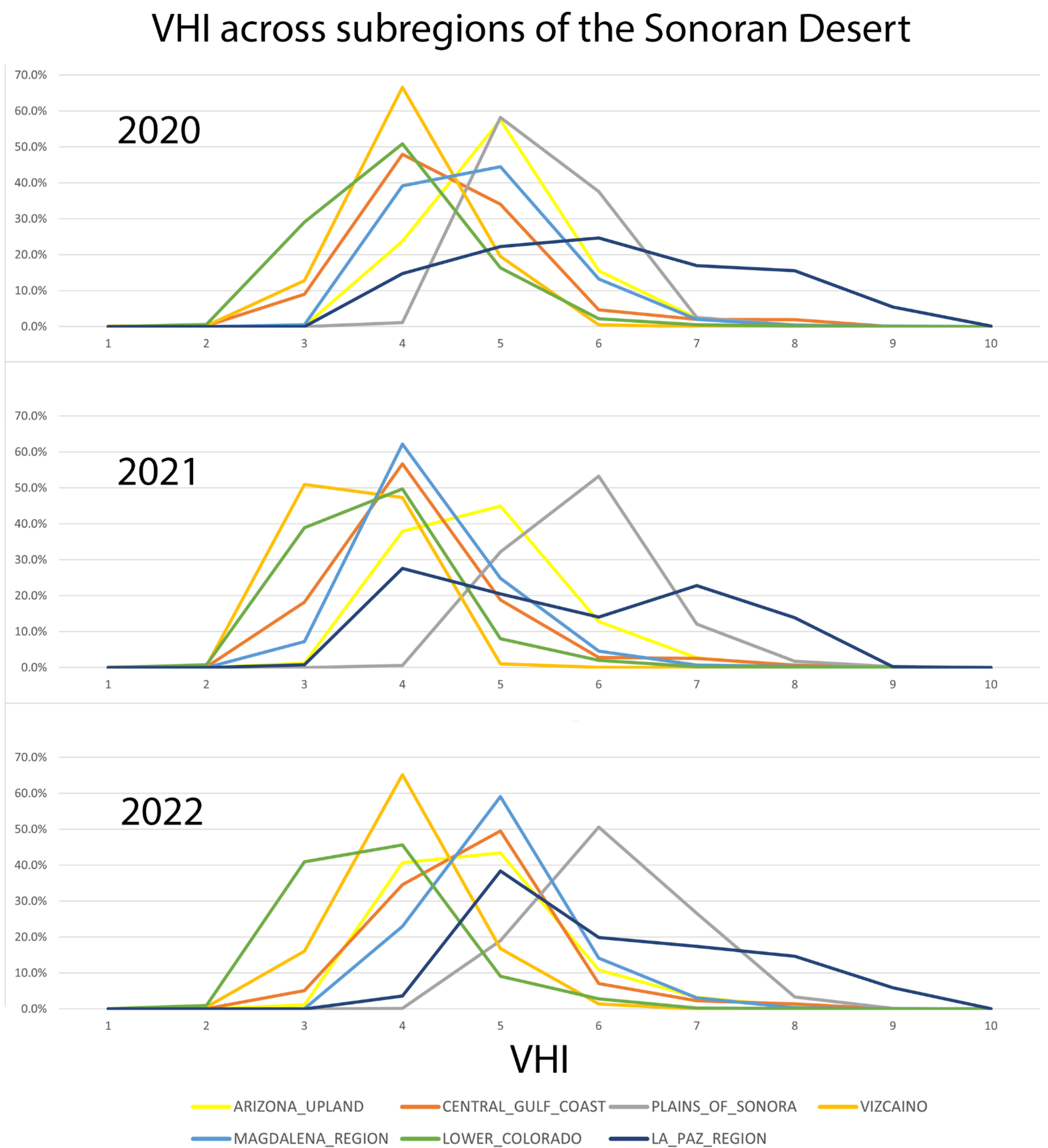

Figure 5. VHI values across subregions of the Sonoran Desert, 2020, 2021, 2022.

The long-term drought

Using the drought modified VHI data set (D-VHI) we were able to compile a longer-term time analysis of average VHI values across the Sonoran Desert (Figure 6). This 40 year data set helps provide a context for the two decade drought event that has been in place over the SW United States and NW Mexico since the year 2000. A general negative trend in average VHI values is detectable (dashed line in Figure 6). In the four decades that passed between August 1981 and December 2021, the mean D-VHI decreased from 4.9 to 3.7 D-VHI units, at an average rate of -0.31 D-VHI units per decade. The trend was highly significant (t-test for slope = 5.84, df 475, $P < 0.00001$), indicating a strong trend towards increasing drought spells throughout the Sonoran Desert during the last four decades.

Also apparent in this analysis is the presence of previous extreme drought periods (VHI<2) in 1989, 1996, 2002, 2012, 2017. The 2020–2022 period is one of the lower periods of VHI, though it does not stand out as unprecedented or the lowest in the timeseries. Likewise of note is the decrease in the average high VHI values (VHI>6) in the last 15 years.

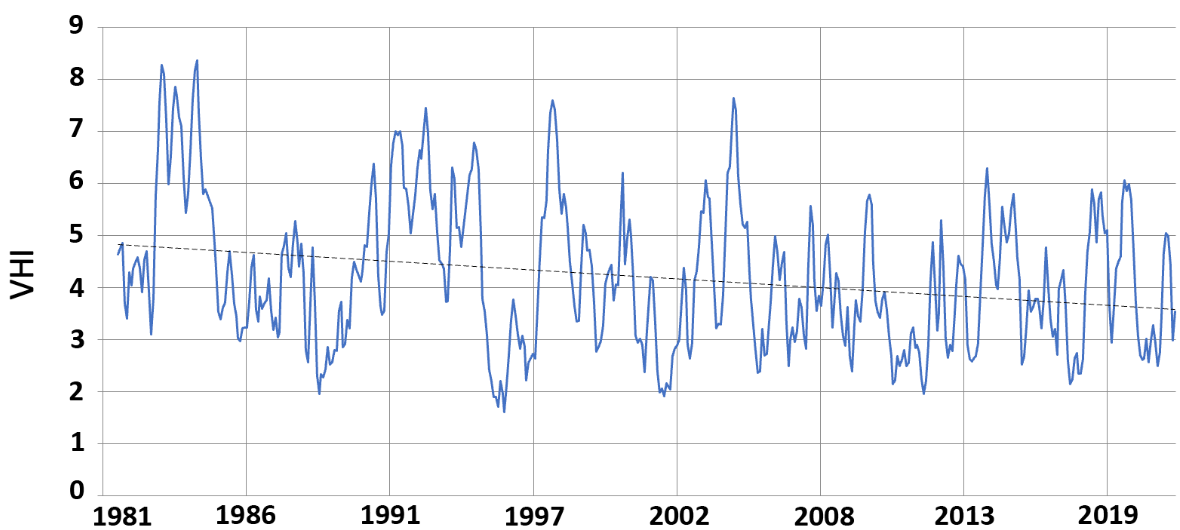

Figure 6. Average D-VHI (drought modified VHI) values by month from the whole Sonoran Desert, 1981–2021.

Predictive tool to identify geographic areas for further study

The Sonoran Desert Drought map has been made available to researchers and interested users in two manners. It has been added as a layer to the iAlumbra Plantas Nativas Afectados (BCS) ArcGIS working project, https://tgi.maps.arcgis.com/apps/dashboards/ce2592cec1424b99a63a26a3344b8c1f. This is available to all team members of this project space.

In addition, the drought map is publicly available as an ArcGIS story map where users can interact with the map and the 36 monthly VHI layers from 2020–2022, https://storymaps.arcgis.com/stories/bd55950db0f34d03a4e68a3cdaafec98.

The goal of making this data set available is to allow users to explore different regions of interest in the Sonoran Desert to see the extent of vegetation stress as identified by the VHI values during the 2020–2022 event. This will aid the identification of areas expected to be most severely impacted by the drought event and focus prioritization of areas on the ground for continued study.

Discussion

The development of a Drought Map for the Sonoran Desert based on the vegetation health index (VHI) with a focus on the 2020–2022 event allows us to visualize and quantify the extent and impact of this anonymously hot and dry period. It also allows us to better understand this event within the context of the two decades long drought within the region and to help us guide our future efforts to track how species, communities, and specific regions are faring in the face of these extreme events.

The Drought Map does reflect the declines in vegetation health throughout the Sonoran Desert, especially in the winter-spring of 2021 and 2022 and especially in the central portion of the Baja California peninsula. Nearly the entirety of the Baja California peninsula was facing extreme drought for a period of almost two years, which was not alleviated until the arrival of tropical hurricane storms in September 2022. The mainland of Mexico and Southern Arizona likewise faced an extreme drought from the period of April 2020 until July 2021, which was dominated by complete failure of the monsoon in southern Arizona and much diminished in Sonora in the summer of 2020 (Hoell et al. 2022). Extreme drought conditions were alleviated in this region with the arrival of a favorable monsoon in July through September 2021.

Interestingly, two areas within the peninsula experienced less severe decreases in VHI values, the mid-peninsular mountains and the Cape Region. In both of these cases, the high elevation habitats were likely able to attract the scant moisture that was present in the region to help ameliorate the drought conditions. The more persistent influence of tropical moisture in the Cape Region in the summer periods is also likely in helping maintain relatively elevated VHI values.

However, the desert lowlands throughout the Peninsula, especially in the mid-Peninsula south towards Loreto and beyond, experienced a bit over two years of no rain and high temperatures. The drought map reflects this with consistently low VHI values from the beginning of 2020 through the summer of 2022.

One of the main findings of the drought map analysis is that when the VHI is low, the whole region is uniformly stressed (Figures 3 and 4). However, as the VHI increases due to precipitation events in August-to-December (monsoon and tropical storm events), the recovery is spatially patchy; some areas recover but others do not. This finding reflects an inherent and core characteristic of desert habitats, which is the patchy distribution of resources in time and space (Polis 1991). In fact, this fundamental characteristic of unpredictable productivity has likely led to the existence of divergent life history strategies within the “feast or famine” nature of primary productivity and food availability in deserts (Polis 1991). A mechanism for plant and animal communities to cope with this uncertainty is the “pulse-reserve” strategy wherein reserves (e.g., tubers, fruits, water storage, offspring) are developed in pulse times, which help maintain an individual as dry conditions set in (Noy-Meir 1973)

The implications of the patchy recovery of VHI across the region are concerning for an area or community’s ability to withstand or recover from severe drought conditions. Climate models are increasingly consistent and certain in their prediction and assessment that the greater Southwest is in a process of aridification (Seager et al. 2023). Within the depths of a severe drought there is a relatively low degree of likelihood for a patch of land to receive an influx of moisture (Knapp et al. 2015), even during the normally predictable and dependable summer rainy seasons. The extension of these “famine” periods, compounded by extreme heat, could have significant impacts on a species tolerance for extreme physiological conditions. The stress response of the species could be seen in direct (e.g., stem mortality or photosynthetic decay, to death in plants) or indirect ways (reduced resources for defenses and vulnerability to pathogens or predation).

The stress response of plants to these drought events marked by extreme temperatures can also have a time-lag, especially for long-lived species such as columnar cacti, which may not be noticeable until several years after the triggering event. In addition, the layering of these drought events from subsequent occurrences such as experienced in the summer months of July through October 2023 in Arizona, may compound stress responses. It is also possible that desert plants, while impacted by these drought events, have the capacity for re-growth and to rebound with the return of favorable conditions. The reality is most certainly a combination of the two, though the degree of impact and if physiological thresholds are reached can only be ascertained by on the ground studies of specific plants and areas.

Local adaptation is also a key consideration when assessing the impact of these drought events and the capacity of individual plant species to withstand them, or not. Within the geographic range of an individual species is a diversity, and often gradients of, different biotic and abiotic conditions. Accordingly, the qualities of the direct impacts of a drought event will be different for say, a species accustomed to a relatively high rainfall regime compared to a nearby drier area of desert (such as a saguaro in Tucson as opposed to the hotter and drier Phoenix area, or an organ pipe cactus at Rancho El Áncon as opposed to the more arid Vizcaino region). The individual plants in the drier area may be able to withstand the drought event to a greater degree due to local adaptations to dry conditions. Or conversely, individuals that experience less severe extremes may fare better. Another layer to consider are individuals at the edges of their range with less experience and adaptations to such dry and hot conditions, which may fare less well.

The plant stress responses observed and documented at Rancho El Áncon (Arnold et al. 2023) may be explained by these individuals occurring at the southern margin of their range in areas that normally do not experience such dry and hot conditions. Even though the drought map shows this area to have been relatively buffered from the most severe drought conditions experienced further north, the period of extreme heat and lack of moisture could have disproportionately negatively affected these individuals. In El Sargento and Los Planes, near El Ancón in the Cape Region, year 2020 was the driest year in the meteorological record, with an estimated recurrence time of around a century. However, in Loreto, some 200 km north, both 2020 and 2021 were the driest years on record. The joint probability of two years in succession being as dry as these was estimated to be close to $P = 0.0004$, or a recurrence interval of two thousand years. While the dry spell in Los Planes was unique on a scale of centuries, the dry spell in Loreto was, indeed, extraordinary on a scale of millennia.

Another important element of local adaptation in the Cape Region and the Central Gulf Coast subdivisions of the Sonoran Desert is humidity. One of the primary influences of the Gulf of California is an elevated humidity in the coastal deserts, reflected in the swollen and exaggerated stem diameters (succulence) that defines the vegetation of these areas (Shreve 1951). The drought events greatly lower these humidity levels and create extended periods of time of extreme stress for plants generally unaccustomed to such conditions.

It is our intention that the drought map and interactive tool allows scientists and land managers to better understand the nature of the 2020–2022 drought event. Perhaps even more important, this effort is meant to enable us to better focus on specific areas we expect to show the impacts of this and future events and track the recovery and/or loss of individuals and species across the landscape.

Suggested citations

Wilder, B.T., E. Ezcurra, W. Dorshow. 2023. Sonoran Desert Drought Map, Initial Report. Unpublished report submitted to iAlumbra.

Wilder, B.T., E. Ezcurra, W. Dorshow. 2023. Sonoran Desert Drought Story Map. ArcGIS Story Maps, https://storymaps.arcgis.com/stories/bd55950db0f34d03a4e68a3cdaafec98

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