Project Information Submittal Form

Project Submitters/Owners: Tubb Canyon Desert Conservancy

~~Environmental Working Group of the Borrego Springs Watermaster [to be confirmed after review]~~

~~Tubb Canyon Desert Conservancy~~

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Project Name: Groundwater Dependent Ecosystems (GDE) Monitoring/Assessment Program

[Following the 1/26/22 Project Review Committee (PRC) meeting, the Tubb Canyon Desert Conservancy (TCDC) and the Watermaster (WM) representatives were asked to combine their respective GDE proposals into one proposal. This document represents the effort to date undertaken by TCDC and the WM to create a combined proposal to address GDE's in the Subbasin. This document replaces and supersedes TCDC's previous GDE proposal. The proposal as described in this document is subject to the review and approval of the WM board. If approved by the WM board, this proposal will be a joint proposal of TCDC and the WM to evaluate and monitor the potential GDE near the Borrego Sink known as The Mesquite Bosque.

It is worth noting that the cost of this proposal has been reduced by two thirds by removing significant scope.]

Contact Information

~~[Watermaster Board POC to be confirmed, and]~~

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Project Summary

Please provide a summary of the Project description. Use as much space as you need.

The technical work that supported the Watermaster's Groundwater Management Plan (GMP) ~~indicated~~ asserted that all existing GDEs within the Borrego Springs Subbasin (Subbasin) have never been, or are no longer, dependent on groundwater in the Subbasin. The major GDE identified as once dependent on the regional aquifer within the Subbasin was a honey mesquite community in the vicinity of the Borrego Sink (Mesquite Bosque).

The Watermaster's Environmental Working Group (EWG) contends that a GDE Monitoring Program is necessary to confirm/refute~~check/verify~~ the conclusions of the technical work that supported the GMP. For the Project proposed herein, a GDE Evaluation and Monitoring Program will be developed and implemented in a phased approach under the guidance of the GDE Scientific Implementation Subcommittee working in concert with the EWG and the direction of the Watermaster Board over an approximate three-year period concluding by June 30, 2025.

The~~It is also envisioned that a~~ GDE Scientific Subcommittee (Subcommittee) will be ~~convened~~ comprised of scientists from the Tubb Canyon Desert Conservancy, Watermaster Technical Consultant, UCI Ecology and Evolutionary Biology Department, the San Diego Natural History Museum, and others as recommended by the EWG. The Subcommittee will: ~~collaborate in the~~ prepare~~ation of~~ the ~~draft~~ GDE Evaluation and Monitoring Program Workplan (Task 1); implement the GDE Evaluation and Monitoring Program and provide interim reporting (Task 2); and prepare the final report and recommendations (Task 3).

The major tasks and subtasks are:

- **Task 1. Prepare the GDE Evaluation and Monitoring Program Workplan**. A GDE Evaluation and Monitoring Program Workplan (Workplan) will be prepared by the GDE Scientific Implementation Subcommittee, in concert with the EWG~~,~~ and the Watermaster Board. Subtasks to prepare the Workplan include:
    - *Task 1a – Review the technical work that supported the conclusions in the GMP*.
    - *Task 1b – Prepare a draft Workplan and distribute to the EWG for review and comment*. The draft Workplan will be prepared by the Scientific Implementation Subcommittee which will include: (i) a precise articulation of the gaps in the current understanding regarding all potential GDEs within the Subbasin and (ii) the detailed steps and costs to fill the gaps in understanding.
    - *Task 1c – Prepare a final Workplan based on the feedback from the EWG*. The final Workplan will be approved by the Watermaster Board.
- **Task 2. Implement the GDE Evaluation and Monitoring Program**. The GDE Evaluation and Monitoring Program Workplan will be implemented under the guidance of the Scientific Implementation Subcommittee, EWG, and the Watermaster Board. In this grant application, the Workplan is conceptual but will likely include the following activities:
    - *Task 2a – Update the mapping and characterization of the historical GDEs in the Subbasin*. This type of work was previously performed to support the GMP. The work proposed in this subtask will build upon the GMP, and may include:
        - Maps of the extent and health of the potential GDEs using air photos and remote sensing data (e.g., Normalized Difference Vegetation Index [NDVI]) to display the extent and health of GDEs over time.
        - Charts and data graphics that reveal/demonstrate the relationships between changes in GDEs and changes in those factors that could influence the GDEs (e.g., groundwater production, groundwater levels, surface water discharge, and climate).
        - A comparison of the history of GDEs in the Borrego Springs Subbasin to the GDEs in the Ocotillo-Clark Valley Groundwater Basin (which has not

experienced the same magnitude of groundwater-level declines).

A task memorandum will be prepared to document the results and conclusions of this subtask and will include recommendations for the subsequent subtasks. The recommendations will be used to update the GDE Monitoring Program Workplan that was prepared in Task 1.

- *Task 2b – Fill gaps in understanding*. In this subtask, the gaps in understanding as identified in the GMP will be filled through the implementation of~~and~~ the GDE Evaluation and Monitoring Program Workplan~~ will be filled~~.

Commented [MOU1]: It is not clear that this subtask is required to meet this project's objectives

Commented [DG2]: This task should be reduced to 1) "mapping the present extent of the potential subbasin-dependent GDE known as the mesquite bosque near the Borrego Sink, and 2) mapping the extent of the mesquite bosque at Clark Dry Lake.

The remaining subtasks described herein are not needed, helpful, or relevant to answering the question that is at the heart of this proposal: Is the mesquite bosque in the Borrego Subbasin presently groundwater dependent.

Personal correspondence with Dr. Huxman indicates that remote sensing data, on the scale that is currently available, is not applicable to areas as small as those on which this proposal focuses.

The GMP notes the considerable variation of the rooting depths of the dominant species of this once thriving phreatophytic ecosystem: the honey mesquite (Prosopis glandulosa, and potentially other Prosopis sp.) found throughout the southwestern United States. The GMP notes that the extent of understanding of this particular ecosystem in the Subbasin is limited by "the lack of ~~site specific~~site-specific information on the root depth of the honey mesquite community… (leaving us with a) very high uncertainty associated with these values." (GMP, Appendix D4, pg. 17). Thus, existing data is unable to determine if the remaining Mesquite Bosque is in fact sustained in whole or in part by the regional aquifer of the Subbasin.

This Project uses a two-prong approach to resolve this uncertainty. The first prong uses the established method of comparing the isotopic signature of the groundwater (primarily using isotopes of oxygen and hydrogen) to the predominant isotopes found in the plants themselves. The second prong is based on capturing several data sets that enable a calculation to determine if the plant assemblage and supported fauna at the proposed GDE could survive only with access to surface water. These data sets are: (i) a complete inventory of the plants and fauna in the potential GDE; (ii) a water needs assessment of that plant assemblage found at the potential GDE; and (iii) determining the availability of surface water at the potential GDE.

The work proposed in this subtask ~~may ~~includes:

- *Task 2b(i) – Isotopic Comparison*. Plant use of different water sources (e.g., near-surface water, perched groundwater, regional aquifer) will be measured using stable isotope abundance in water held within plant tissues. The mixing of water sources by plants can be partitioned by sampling water contained in plant tissue and comparing the signal to the differential isotopic composition of those sources using mixing model approaches. Measured across time, the differential use of water relative to periods of stress can be evaluated, whereby the presence of groundwater can identify critical need. Sampling four times over the year can reveal seasonal variations in water uptake fractions from different water sources.

  In summary, groundwater typically possesses a distinct oxygen and hydrogen stable isotope signature associated with the dominant period of infiltration and percolation within the hydrologic year (estimated from the global meteorologic line), while surface water originating from on-site and nearby precipitation is often influenced by the ephemeral nature of the rainfall, temperature, and evaporation such that the two water sources provide distinct isotope signals.

Water samples will be collected from soils, wells, and plant tissues, co-located sufficiently to assume root access, and then sealed in vials preventing evaporation. This requires approximately 2-3 ml of soil and well water (for repeated sampling) and typically 2-3 cm-long stems of ~1 cm diameter woody plants. Water will be cryogenically extracted or filtered (from liquid samples) prior to isotopic analysis at one of the major environmental isotope sampling laboratories (e.g., SIRFER at University of Utah, Salt Lake City, Utah). Where simple mixing models do not work, we will rely on published isotope sourcing models.

- *Task 2b(ii) – Inventory of Species Present and GDE Health Monitoring*. Flora: The second data gap will be filled by an inventory of the plant species in and around the Mesquite Bosque. The first step in filling this data gap will be to conduct special searches of the San Diego Herbarium (including the San Diego County Plant Atlas database) and the California Consortium of Herbaria (CCH2) to see what scientific specimens of plants have historically been documented from within the GDE polygons. Next comes the incorporation of those iNaturalist~~s~~ (iNat) observations that Dr. Rebman (Curator of Botany, San Diego Natural History Museum) has personally verified by spatially searching the downloaded database of iNat observations that document plant species from within the GDE. This process will provide a preliminary plant list for the GDE. Once this baseline is established, we will organize public iNat training in Borrego Springs to show volunteer botanists ("citizen" or "resident" scientists) how to appropriately use the iNat app and how to document plants in the potential GDE. This training will occur at the Steele-Burnand Anza-Borrego Desert Research Center and in the field at the site of the Mesquite Bosque. The training will focus on using the iNat app, how to properly document plants using the app, what resources are available to help observers in the field, etc. We will thereby create an iNat project focused on the Mesquite Bosque, so the curator of the app (Dr. Rebman) can easily see, identify, and verify all the observations that are already, and will be, made within the study site. The curator will personally travel to the site to survey for plants and document more difficult plant groups such as grasses, small and often overlooked plant species, and other graminoids that are more difficult to accurately identify using photography.

  Fauna: If the Mesquite Bosque is a GDE, measuring the health of the entire dependent "ecosystem" becomes important in assessing groundwater effects on the health of the GDE as a beneficial user. Establishing a baseline, quantitative measurement of fauna is an important metric, quantifying species up through the food chain/web, including insects, birds, reptiles, amphibians (if any), up through mammals, including rodents, bats, and any larger predators. Small changes in plant health can have a magnified effect on dependent fauna, and thus can sometimes be detected as a stronger integrated signal over time, than deterioration or improvement in plant health metrics alone.

To assess the fauna component of the health of the ecosystem as a whole, data-driven estimates must be made of the number of different species present, the number of members of each species present, the size, and apparent health of species members (to the extent easily visible on wildlife cameras). These measurements need to be made at different times of day to sample nocturnal and diurnal populations, and throughout the year, particularly to identify significant migratory species (e.g., some birds and some butterflies) that may be dependent upon the site. For this site, the best way to conduct a survey is with remote wildlife cameras, and automated video image analysis to dump images showing nothing of interest. Local and San Diego County students will be recruited, emphasizing disadvantaged communities, and trained under project scientist~~ce~~ supervision, and tested on known sample video imagery. Those students who pass testing on sample video imaging will be given supervised internships to extract the needed data. Data quality will be ensured by the supervising scientist using random review of students' and volunteers' counts and assessments and detailed in-person examination of reported unusual activity and species, along with other unexpected events or circumstances. Exact sites for wildlife cameras and solar/battery-powered support equipment will be selected during initial surveys with project scientists and cooperating landowners, including the State Park where sites are on Park land.

For GDE Health Monitoring, the data available from the differing types of measurements, such as depth-to-water in shallow wells, number of apparent species vs. time of year, and abundance of specific species vs. time of year, together make a better assessment of GDE health than any single measurement. Water level, for example, is an instantaneous measurement, while number of apparent species at points in the seasonal cycle (from which biodiversity can be derived) is a more integrative measurement, showing the results of accumulated changes in water availability, nutrients and other factors over time.

- *Task 2b(iii) – Water Needs Assessment of Extant Plant Assemblage*. The third data gap will be filled with a "water needs" assessment of the plant assemblage identified and cataloged by the task described above. This assessment of the water needs of the extant plant assemblage will be completed by scientists from the University of California, Irvine who published in May 2021 an assessment of declining desert vegetation, but on a regional scale. (See: Stijn Hantson, Travis E. Huxman, Sarah Kimball, James T. Randerson & Michael Gouldon (2021). "Warming as a driver of vegetation loss in the Sonoran Desert of California." Journal of Geophysical Research: Biogeosciences, 126, April 2021. e2020JG005942. https://doi.org/10.1029/2020JG005942).
- *Task 2b(iv) – Surface Water Availability & Evapotranspiration Environment Measurement*. The fourth data gap is to be filled by estimates of surface water

available to the extant plant assemblage at the Mesquite Bosque. We are fortunate to have on this Project scientists from UCI who have been measuring climate parameters, such as soil moisture, in the Borrego Valley since 2016. The data continuously collected since 2016 from the seven climate monitoring stations located throughout the valley, one of which is near the GDE in question, will be analyzed to create an understanding, both historically and currently, of the surface water available to the extant plant assemblage at this potential GDE.

- *Task 2b(v)* – Depth to Groundwater. The fifth data gap pertains to depth to groundwater at and around the remaining plant assemblage. This Project will use existing monitoring wells, as well as nearby abandoned wells, to capture data to reveal trends in the water table underneath this remnant GDE. As a contingency, if there are no monitoring wells or abandoned wells sufficiently near the study area, a shallow duel-nested monitoring well facility will be constructed and equipped near or within the Mesquite Bosque. [1]

The above tasks will answer the following questions:

- What are the correlations between the isotopic signature of groundwater and the moisture found inside the honey mesquite plants at the mesquite bosque?
- What flora~~plants~~ now compose the remnant mesquite bosque, and what fauna~~animals~~ depend on this?
- What is the "water economy" of this plant assemblage?
- In combination, these data sets will answer the question "Is this plant assemblage sustained by groundwater and/or surface water?"

This project has the unique opportunity to coordinate its activities with those in an adjacent subbasin, Clark Dry Lake. As an additional approach to determining whether the Mesquite Bosque east of Borrego Sink is indeed dependent on groundwater in the Borrego Subbasin aquifer, its conditions will be compared with those of the nearby Clark Dry Lake mesquite bosque, where there is no question that the mesquite trees are dependent on the water table there that is much closer to the surface and that aquifer is not significantly pumped to support other beneficial users. Evapotranspiration conditions driven by solar illumination, temperature, humidity, and wind conditions are similar between the two locations. Precipitation can vary significantly between the two locations, despite their proximity. Existing wells in the vicinity of Clark Lake may be available to be used to measure groundwater levels. Measuring comparative vegetation health through the seasonal cycle, along with weather conditions including precipitation, will enable determining with reasonable certainty if the mesquites in the Borrego Mesquite Bosque are dependent on a permanent root connection to an aquifer beneath them, or likely not. If the Borrego mesquites are heavily stressed compared to the Clark Lake mesquites at the same time

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[1] Budget for construction, equipping, and monitoring of groundwater and surface-water monitoring facilities are not included herein, but are included in the separate Watermaster Project Submittal for Monitoring, Reporting, and GMP Update.

of year, but healthy only after significant precipitation, then their connection to the Borrego Subbasin aquifer via roots is less probable. A comparison of older/larger trees (as measured by girth and exterior effects of age) that presumably could sustain deeper roots than younger/smaller trees will enable a more refined distinction between the aquifer connection of the Borrego vs. Clark lake populations.

Each of these evapotranspiration conditions will be measured at both the Borrego Sink and Clark Dry Lake sites, to the extent possible with existing sensors. New sensors, if needed, will be low-cost automated satellite-enabled data relay (available since late 2021 from Swarm.Space of Silicon Valley at $60/yr per sensor suite; see Fig.1) but will only be procured if sufficient existing data sources and datalinks aren't available.[1]

Figure 1 (above): Example ModuSense IIoT Weather Station communicates via Swarm.Space's new satellite constellation that began commercial operation under FCC license in 2021. Cost for data relay for up to hourly readout is $60/year. Source selection is not implied by use of this example figure; detailed requirements will be developed and vendors chosen during the Project Plan/Design/ Environmental Phase. Solar panel is ~1' square. (ModuSense photo downloaded 2022 January 14 from https://shop.modusense.com/products/ iiot-weather-station-satellite-swarm)

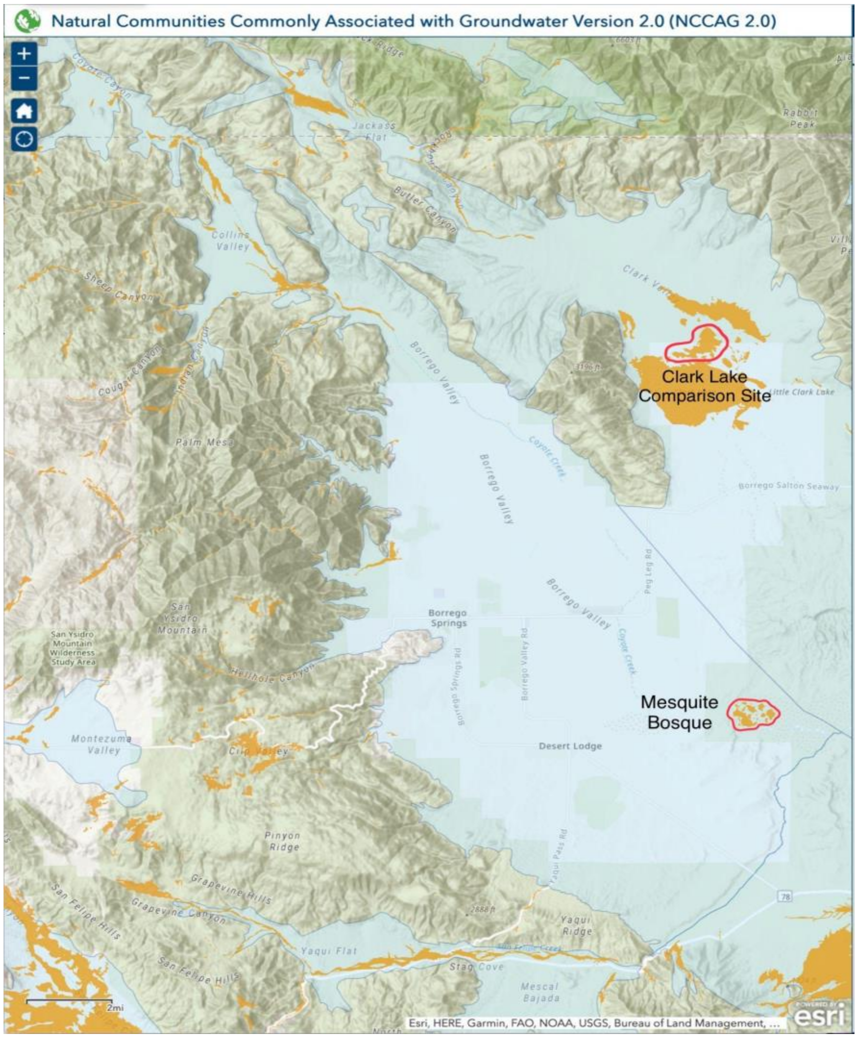
- **Task 3. Prepare GDE Identification and Monitoring Program Report and Recommendations**. A technical report will be prepared to describe the results, conclusions, and recommendations of the GDE Evaluation and Monitoring Program.
  - If the monitoring program indicates that GDE(s) ***are dependent*** on the regional aquifer within the Subbasin, then the EWG will provide recommendations to the Watermaster Board for revisions to the GMP to protect the environmental beneficial uses of groundwater pursuant to the requirements of the SGMA.
  - If the monitoring program indicates that GDE(s) ***are not dependent*** on the regional

aquifer within the Subbasin, then the GMP will not be modified. Any continuation of GDE monitoring will only be conducted at the recommendation of the EWG and at the discretion of the Watermaster Board.

- **Task 4. Stakeholder Meetings and Outreach.** The objectives of this task are to facilitate public outreach and communications of EWG and Scientific Implementation Subcommittee planned actions and provide a venue to receive public input prior to making decisions and recommendations to the Watermaster Board. This task also includes recruiting and/or employing local interns and volunteers to assist in implementation of the monitoring program.
  - *Task 4a – Conduct EWG and Subcommittee Meetings.* The EWG will meet at least two times per year to discuss the GDE Identification and Monitoring Program and make recommendations to the Watermaster Board. Detailed memos are prepared in support of each meeting on the subject matter and are posted to Watermaster's website and email list for distribution to interested stakeholders. The public is afforded an opportunity to provide comments to the EWG on items on each agenda item. All public input is recorded in meeting minutes. The Scientific Implementation Subcommittee is anticipated to meet at least six times in Year 1 and four times per year in subsequent years.
  - *Task 4b – Recruiting local Borrego Springs and/or nearby Native American students and broader San Diego County interns, and volunteers.* Employment of two interns in each of two ~10-week sessions per year, and associated broadening of their science, technology, engineering, art & mathematics (STEAM) skills in a manner that advances their education and enhances their opportunities for future higher education and professional employment. Recruitment of ~5 dedicated local volunteers each year as community scientists helping with gathering Project data that meets scientific quality standards.

Describe the project location, current conditions, and the benefitting areas. Please attach, separately, a regional and Project map depicting the site(s) location, current conditions, and benefitting areas.

The project location is the Borrego Springs Subbasin and the potential GDEs that exist or existed within the Subbasin. A "control area" in the Ocotillo-Clark Valley Groundwater Basin is also expected to be included in the project. Exhibit A (attached) is a map is from the GMP that shows the potential GDE areas within the Subbasin, particularly the Mesquite Bosque within the Borrego Sink. This potential GDE is the potential environmental user of groundwater, and hence, represents the benefiting areas. The map below also shows the location of the GDE at the Clark Lake control area.



Esri, HERE, Garmin, FAO, NOAA, USGS, Bureau of Land Management, ...

What is the nexus of the Project to the Sustainability Goal of the Borrego Springs Subbasin Groundwater Management Plan (GMP)? Is the Project listed in the GMP? How does the Project help achieve the goals of the GMP?

The Project is not listed as a standalone project or management action (PMA) in the GMP. However, the SGMA requires that all beneficial uses and users of groundwater, including GDEs, be considered in the development and implementation of Groundwater Sustainability Plans (GSP) (Water Code § 10723.2). GDEs are specifically defined under the SGMA as "ecological communities of species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" (23 CCR § 351(m)). The GSP Regulations include specific requirements to identify GDEs and consider them when determining whether groundwater conditions are having potential effects on beneficial uses and users.

The Watermaster's Groundwater Management Plan (GMP) is a repurposed GSP that is part of the Physical Solution under the Stipulated Judgment. The GMP is intended to avoid "undesirable results" as defined in the SGMA, such as adverse impacts to environmental uses/users of groundwater within the Borrego Springs Subbasin (e.g., GDEs). The GMP identified and characterized several historical and current GDEs overlying the Subbasin and within the tributaries of the mountain-front watersheds. However, the GMP concluded that all existing GDEs have never been, or are no longer, dependent on the regional aquifer of the Subbasin. The major GDE identified as once dependent on the regional aquifer of the Subbasin was a honey mesquite community in the vicinity of the Borrego Sink.

The main conclusions and recommendations of the GMP regarding GDEs are as follows [Appendix D4: Borrego Springs Subbasin Groundwater Dependent Ecosystems, page 26]:

> *"A review of available pertinent spatial datasets, historical data including stream flow and groundwater levels, satellite-derived vegetation metrics, and geology was completed to develop a robust HCM* [hydrogeologic conceptual model] *to evaluate nexus of GDEs with Subbasin regional groundwater levels. Because of the long-term imbalance of pumping with available natural recharge, an irreversible impact has likely occurred on the honey mesquite community from a decline in groundwater levels, an impact which, based on the best available science, was completed and became permanent sometime prior to 1985. The comprehensive assessment revealed potential GDEs identified within the Subbasin no longer have direct reliance on groundwater emerging from aquifers or on groundwater occurring near the ground surface, and instead are sustained by periodic stormwater flows, soil moisture, and potentially perched groundwater where present. These findings indicate that based on best available data there is no need for the GSP to address minimum groundwater level thresholds with respect to potential GDEs. Detailed mapping of vegetation is lacking for the area in the vicinity of the Borrego Sink. Groundwater level monitoring of wells located in the vicinity of the Borrego Sink should continue."*

Section IV.H of the Stipulated Judgment provides that:

> *An Environmental Working Group (EWG) will be established to advise the Watermaster on GDE and any other matters approved by the Watermaster.*

The EWG held its inaugural meetings in February and May 2021 to discuss and prioritize activities that the EWG could engage in pursuant to its purview and duties as defined by the Judgment. Some

EWG members contend that more study is necessary to determine if existing GDEs are dependent on the regional aquifer of the Subbasin, or not.

The Project proposed herein is intended to clarify this uncertainty through the development and implementation of a GDE Evaluation and Monitoring Program conducted by the Scientific Implementation Committee in concert with the EWG and the Watermaster~~ under the guidance of the EWG~~. If the results and conclusions of the monitoring program indicate that GDE(s) are dependent on the regional aquifer of the Subbasin, then the EWG will provide recommendations for revisions to the GMP to protect the environmental beneficial uses of groundwater pursuant to the requirements of the SGMA.

What are the specific goals and needs for the Project, and how will the project achieve the goals and meet the needs?

The main objective of the project is to determine if the potential GDEs within the Subbasin are dependent on the regional aquifer of the Subbasin, or not. A GDE Evaluation and Monitoring Program is needed to make this determination. A final technical report will describe the results, conclusions, and recommendations of the GDE Evaluation and Monitoring Program.

The GDE Evaluation and Monitoring Program will be developed and implemented under the guidance of the technical experts participating on the Scientific Implementation Committee in concert with the EWG. ~~Technical subconsultants, with demonstrated expertise in surface-water and groundwater hydrology, desert ecology, and GDEs, will likely be needed to execute the monitoring program.~~

If the GDE Evaluation and Monitoring Program~~monitoring program~~ indicates that GDE(s) ***are dependent*** on the regional aquifer within the Subbasin, then the EWG will provide recommendations to the Watermaster Board for revisions to the GMP to protect the environmental beneficial uses of groundwater pursuant to the requirements of the SGMA. If the monitoring program indicates that GDE(s) ***are not dependent*** on the regional aquifer within the Subbasin, then the GMP will not be modified.

What are the quantifiable benefits of the Project (e.g., protect or enhance water quality, water conservation, enhanced understanding of the groundwater basin, etc.)? How will those benefits be quantified and evaluated?

The project will enhance the understanding of the groundwater basin, and potentially, will result in revisions to the GMP to protect the environmental beneficial uses of groundwater pursuant to the requirements of the SGMA. These benefits will be quantified and described in the interim and final deliverables of the project.

In addition, there are monitoring facilities, such as monitoring wells, that are expected to be constructed in to support the project. These monitoring facilities will generate data and information to assist the Watermaster with other basin management initiatives, including the periodic Redetermination of the Sustainable Yield, groundwater-level and groundwater-quality monitoring programs, annual reporting to the DWR, etc.

Please describe the communities served by the Project. Will the Project benefit an Underrepresented Community, a Disadvantaged Community (DAC), and/or a Severely Disadvantaged Community (SDAC)? If so, please provide a map.

Exhibit B is a map of the Basin and the area defined as a SDAC. While the Project activities will be focus within the primary GDE within the Borrego Sink, the Project will serve the entire Basin, including the community of Borrego Springs and the area classified as a SDAC, because it is designed to better understand and (potentially) protect the natural resources within the Subbasin.

- A primary driver of the economy in Borrego Springs is ecotourism associated with the Anza-Borrego State Park and the flora and fauna of the region. The Project is designed to better understand and (potentially) protect the natural resources within the community, and thereby support economic activity within Borrego Springs.
- The Watermaster was officially formed in April 2021. Expenses to conduct Watermaster activities are relatively new costs that are ultimately funded by the residents and rate payers within the community. The grant funding will help offset the new costs and provide financial relief to the residents and rate payers.
- The community's water supply is solely dependent on the Basin. The Project is related to the larger project of implementation of the Judgment and GMP, which will ensure that the groundwater basin remains an affordable, high-quality source of water for the community in perpetuity.
- The project plan is to utilize student interns, actively sought from the local area and from nearby Native American communities. These interns are to be paid and trained in scientifically exacting observations and measurements, relevant environmental science, software and field techniques, current instrumentation and satellite networking techniques, clear record-keeping and data integrity techniques, and preparation and presentation of results. Young people and vulnerable constituencies can better protect and defend their limited resources when some of their cohort acquire awareness of water issues and skills associated with preserving their Human Right to Water. Beyond the student interns, community volunteers are also to be recruited who have an interest in measuring plants and animals of natural communities commonly associated with groundwater (NCCAG). The communities so served will center around the town of Borrego Springs and potentially the adjacent communities of the Los Coyotes Indian Reservation, Ranchita, Warner Springs, and Ocotillo Wells.

Will the Project or Component positively impact issues associated with small water systems or private shallow domestic wells (e.g., groundwater contamination vulnerability, drawdown, etc.)? If so, please provide justification such as water system maps or domestic well census results.

Small water systems and private shallow domestic wells share some similar hydrological characteristics with Groundwater Dependent Ecosystems. Chief among these characteristics is their dependence upon groundwater that is relatively near ground surface. If it is determined that there is a GDE in the Borrego Subbasin whose use of water must be "considered" in the management of the Subbasin's overdraft, other "shallow users" of groundwater will concomitantly be benefitted by this consideration.~~N/A~~

Does the Project address the needs of the State Water Board's SAFER Program, designed to ensure Californians who lack safe, adequate, and affordable drinking water receive it as quickly as possible, and that the water systems serving them establish sustainable solutions?

N/A

How does the Project address the Human Right to Water (AB 685 Section 106.3) which states that every human being has the right to safe, clean, affordable, and accessible water adequate for human consumption, cooking, and sanitary purposes?

N/A

Please describe how the project contributes to addressing the risks in the region to water supply and water infrastructure arising from climate change. If possible, please provide the amount of greenhouse gas emissions reduced and carbon sequestered resulting from the project.

GDEs can act to sequester carbon through the process of biosequestration, which is the capture and storage of the atmospheric carbon dioxide by natural vegetation. The Project is designed to better understand and (potentially) protect the GDEs and their function within the Earth's carbon cycle.

It will be possible from the data to be collected to estimate the amounts of carbon being sequestered in the GDEs, and to quantify what is being lost from these GDEs if GDE health deteriorates; or for that matter, how much carbon is being sequestered if GDE health improves.

A by-product of this project is that it will extend data collection capability in the Subbasin in such a way as to improve perceiving/monitoring Climate Change. This project will develop and rely on data streams that will capture the impacts of climate change such as changes in precipitation, soil moisture, evapotranspiration, temperature, and water table depth. These data streams will enable the Subbasin to better model its water economy on a continuous basis, which is a sine qua non for responding quickly and appropriately to the changing climate. Borrego cannot be a resilient community if it cannot perceive quickly and accurately alterations in local climate. This project provides the data streams that form the basis for resilience.

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~~It will be possible from the data to be collected to estimate the amounts of carbon being sequestered in the GDEs, and to quantify what is being lost from these GDEs if GDE health deteriorates; or for that matter, how much carbon is being sequestered if GDE health improves.~~

Work Plan

The Work Plan must contain descriptions of the anticipated tasks necessary to complete the project. Tasks should be organized by the five budget categories, as applicable: (a) Project Administration, (b) Planning/Design/Environmental, (c) Construction/Implementation, (d) Monitoring/Assessment, and (e) Interested Parties Outreach/Education. The Work Plan should also identify the anticipated deliverables for each task.

Add additional tasks and subtasks as needed to provide a detailed work plan. Some examples and suggested language have been provided.

Budget Category (a): Project Administration

Task 0 – Project Management. This task includes: preparation and submission of supporting grant documents and coordination with the Grantee; preparing invoices including relevant supporting documentation for submittal to DWR via the Grantee; tracking project budget and schedule progress; and coordinating with and performing project management task with partnering agencies and subcontractors.

Deliverables: Invoices and necessary documentation.

Budget Category (b): Planning/Design/Environmental

Task 1. Prepare the GDE Monitoring Program Workplan. A GDE Evaluation and Monitoring Program Workplan will be prepared by the GDE Scientific Implementation Subcommittee, the EWG, and the Watermaster Board. Subtasks to prepare the Workplan include:

Task 1a – Review the technical work that supported the opinions/assertions regarding Subbasin GDEs~~conclusions~~ in the GMP and noting the data gaps in the GMP.

Task 1b – For each of the subtasks noted in "*Task 2(b)–Fill Gaps in Understanding,*" of this project proposal, complete detail plans of the specific locations, all equipment necessary for the data chain from field sensors to science work stations to quality control to web-accessible archives and publication, timelines for equipment purchases, recruitment and staffing/contracting of scientific experts (where not already known and noted in the project summary), interns, and community volunteers. Prepare a draft Workplan and distribute to the EWG for review and comment.

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Task 1c – Prepare a final Workplan based on the feedback from the EWG.

Deliverables: Draft and final versions of the GDE Evaluation and Monitoring Program Workplan will be posted on the BWD and WM public websites.

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Permitting and CEQA. Obtain permits and prepare CEQA documentation for temporary installation of equipment for environment assessment and monitoring.

Deliverables: Permits and CEQA documentation.

Budget Category (c): Construction/Implementation

Task 2b – Fill gaps in understanding. In this subtask, the gaps in understanding as identified in the GMP and the GDE Evaluation and Monitoring Program Workplan will be filled. The work proposed in this subtask may include:

Task 2b(v)–Depth to Groundwater. If necessary c~~C~~onstruct and equip a dual-nested monitoring well near or within the Borrego Sink. Preference will be given to using existing wells if one or more are available to provide the needed information as determined by the technical experts of the Scientific Implementation Subcommittee.

Deliverables: Identification of existing wells to be utilized and any necessary modifications and equipment. If not existing wells are suitable, then d~~D~~raft and final technical specifications for the monitoring well; contractor bid documents; and final completion reports for the monitoring facilities.

Budget Category (d): Monitoring/Assessment

Task 2a – Update the mapping and characterization of the historical GDEs in the Subbasin. This type of work was previously performed to support the GMP. The work proposed in this subtask will build upon the GMP, and ~~may~~ include:

- Maps of the extent and health of the potential GDEs in the Subbasin and in Clark Dry Lake using ground-based assessment/mapping techniques.~~using air photos and NDVI to display the extent and health of GDEs over time~~.
- ~~Charts and data graphics that reveal/demonstrate the relationships between changes in GDEs and changes in those factors that could influence the GDEs (e.g., groundwater production, groundwater levels, surface water discharge, and climate).~~
- ~~A comparison of the history of GDEs in the Borrego Springs Subbasin to the GDEs in the Ocotillo-Clark Valley Groundwater Basin (which has not experienced the same magnitude of groundwater-level declines).~~

Deliverables: A task memorandum/public report on the BWD and WM websites will be prepared to document the results and conclusions of this subtask and will include recommendations for the subsequent subtasks. The recommendations will be used to identify the study locations for ~~update~~ the GDE Evaluation and Monitoring Program Workplan that was prepared in Task 1.

Task 2b. Fill gaps in understanding. In this subtask, the gaps in understanding as identified in the GMP and the GDE Evaluation and Monitoring Program Workplan will be filled. The work proposed in this subtask ~~may~~ includes:

Task 2b(i) – Isotopic Comparison.

Task 2b(ii) – Inventory of Species Present and GDE Health Monitoring.

Task 2b(iii) – Water Needs Assessment of Extant Plant Assemblage

Task 2b(iv) – Surface Water Availability & Evapotranspiration Environment Measurement

Task 2b(v) – Depth to Groundwater

Deliverables: Draft and final technical memos to document the investigations and technical work will be posted on the BWD and WM public websites.

Task 3. Prepare GDE Monitoring Program Report and Recommendations. A technical report will be prepared to describe the results, conclusions, and recommendations of the GDE Monitoring Program.

Deliverables: Draft and final GDE Monitoring Program Report and Recommendations will be posted on the BWD and WM public websites.

Budget Category (e): Interested Parties Outreach/Education

Task 4. Stakeholder Meetings and Outreach. The objectives of this task are to facilitate public outreach and communications of EWG and Scientific Implementation Subcommittee planned actions and provide a venue to receive public input prior to making decisions and recommendations to the Watermaster Board. This task also includes recruiting and/or employing local interns and volunteers to assist in implementation of the monitoring program. The work proposed in this task includes:

Task 4a – EWG and Scientific Implementation Subcommittee Meetings, including compensation for participating EWG and Scientific Implementation Subcommittee members.~~.~~

Task 4b – Recruiting local Borrego Springs and/or nearby Native American students and broader San Diego County interns, and volunteers.

Deliverables: Meeting agendas/packets; PowerPoint presentations; summary meeting notes; and memorandums with recommendations to the Watermaster Board. Recruited interns and local volunteers. All EWG/Subcommittee meeting deliverables will be posted to the BWD and Watermaster public ~~'s~~ websites.

Budget

DWR required budget categories have been included below. Add tasks as applicable; additional rows must be added under the applicable categories to present the cost of each task described in the Work Plan.

		(a)	(b)	(c)	(d)
	Category	**Requested Grant Amount**	**Local Cost Share: Non-State Fund Source***	**Total Cost**	**% Local Cost Share (Col(b))/(Col(c))**
(a)	**Project Administration**				
	Task 0. Project Management	30,000		30,000	0%
(b)	**Planning/Design/Environmental**				
	Task 1. Prepare the GDE Monitoring Program Workplan	50,000		50,000	0%
	Permitting and CEQA	20,000		20,000	0%
(c)	**Construction/Implementation**				
	Task 2b(v) – Depth to Groundwater. Construct and equip a dual-nested monitoring well in the Borrego Sink[2]				
(d)	**Monitoring/Assessment**				
	Task 2a – Update the mapping and characterization of the historical GDEs in the Subbasin	50,000~~125,000~~		50,000~~125,000~~	0%
	Task 2b(i) – Isotopic Comparison	50,000		50,000	0%
	Task 2b(ii) – Inventory of	400,000		400,000	0%

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[2] Budget for construction and equipping of groundwater monitoring facilities are not included herein, but are included in the separate Watermaster Project Submittal for Monitoring, Reporting, and GMP Update.

	Species Present and GDE Health Monitoring				
	Task 2b(iii) – Water Needs Assessment of Extant Plant Assemblage	42,000		42,000	0%
	Task 2b(iv) – Surface Water Availability & Evapotranspiration Environment Measurement	75,000		75,000	0%
	Task 2b(v) – Depth to Groundwater[3]				
	Task 3 – Prepare GDE Monitoring Program Report and Recommendations	200,000		200,000	0%
(e)	**Interested Parties Outreach/Public Education**				
	Task 4a – Conduct EWG and Subcommittee Meetings	100,000		100,000	0%
	Task 4b – Recruiting local Borrego Springs and/or nearby Native American students and broader San Diego County interns, and volunteers	20,000		20,000	0%
(f)	**Grand Total (Sum rows (a) through (e) for each column)**	1,037~~112~~,000		1,037~~112~~,000	0%

* List sources of Local Cost Share funding:

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[3] Budget for monitoring of groundwater levels is not included herein, but is included in the separate Watermaster Project Submittal for Monitoring, Reporting, and GMP Update.

Schedule

The Schedule must be organized in a manner that is consistent with the Work Plan and Budget that will be contained in the Grant Agreement. The Schedule Table presented below is a template that must be completed for each project in the proposal. The required budget categories have been included below. Add additional rows for each task as described in the Work Plan and Budget.

Categories		**Start Date** (Earliest Start Date)	**End Date** (Latest End Date)
(a)	**Project Administration**	**4/1/2022**	**6/30/2025**
	Task 0. Project Management	4/1/2022	6/30/2025
(b)	**Planning/Design/Environmental**	**4/1/2022**	**8/1/2022**
	Task 1. Prepare the GDE Monitoring Program Workplan	4/1/2022	8/1/2022
	Permitting and CEQA	4/1/2022	4~~1~~/1/20223~~5~~
~~(c)~~©	**Construction/Implementation**	**7/1/2022**	**10/1/2023**
	Task 2b(v) – Depth to Groundwater. Construct and equip a dual-nested monitoring well at the Borrego Sink	4/1/2022	10/1/2023
(d)	**Monitoring/Assessment**	**4/1/2022**	**6/30/2025**
	Task 2a – Update the mapping and characterization of the historical GDEs in the Subbasin	4/1/2022	1/1/2023
	Task 2b(i) – Isotopic Comparison	8/1/2022	12/31/2024
	Task 2b(ii) – Inventory of Species Present and GDE Health Monitoring	8/1/2022	12/31/2024
	Task 2b(iii) – Water Needs Assessment of Extant Plant Assemblage	8/1/2022	12/31/2024
	Task 2b(iv) – Surface Water Availability & Evapotranspiration Environment Measurement	8/1/2022	12/31/2024
	Task 2b(v) – Depth to Groundwater[4]	8/1/2022	12/31/2024
	Task 3 – Prepare GDE Monitoring Program Report and Recommendations	1/1/2025	6/30/2025
(e)	**Interested Parties Outreach/Public Education**	**4/1/2022**	**6/30/2025**

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[4] Budget for monitoring of groundwater levels is not included herein, but is included in the separate Watermaster Project Submittal for Monitoring, Reporting, and GMP Update.

	Task 4a – Conduct EWG and Subcommittee Meetings	4/1/2022	6/30/2025
	Task 4b – Recruiting local Borrego Springs and/or nearby Native American students and broader San Diego County interns, and volunteers	4/1/2022	12/31/2024

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Ecology and Evolutionary Biology
University of California
Irvine, CA 92679

January 28, 2022

Dr. David Garmon, President
Tubb Canyon Desert Conservancy
230 West Palm Street
San Diego, CA 92103

Dear Dr. Garmon,

I am writing to you in my capacity as a scholar and as the Faculty Director of the Steele/Burnand Anza-Borrego Desert Research Center of the University of California, Irvine to show my support for your proposed project to identify, assess, and monitor groundwater dependent ecosystems in the Borrego Subbasin. I have worked collaboratively with your organization over the past decade on several important projects in the region, including a comprehensive approach to understanding the invasion of the non-native Sahara mustard in the US and working to develop a community engaged approach to strategic planning around important environmental and societal challenges. I have always been extremely impressed with the success / outcomes of these projects, the science produced, the decision-making outcomes, and importantly for my role, the professional development associated with trainees at UCI. The specific issue of understanding groundwater dependent ecosystems in the basin touches on my own academic strengths, having studied the patterns of desert plant water use over the last three decades and determining the ecohydrologic importance and consequences of these patterns. These ecosystems are critical to regional biodiversity and the ecosystem services critical to sustaining our societal practice in the region, and we lack a fundamental understanding of their dynamics in Borrego.

Please do not hesitate to contact me if I may provide you with additional assistance in this project.

Best regards,

Travis E. Huxman
Director Advisor, Steele/Burnand Anza-Borrego Desert Research Center
Professor and Chair, Ecology and Evolutionary Biology
University of California, Irvine

(949) 677-9929; thuxman@uci.edu; www.faculty.sites.uci.edu/huxman

ANZA
BORREGO
FOUNDATION

P.O. Box 2001 · Borrego Springs · CA 92004
760.767.0446 | theabf.org

1/27/2022

Groundwater Dependent Ecosystems
Borrego Springs Subbasin
Anza-Borrego Foundation
Letter of Support

To Whom it May Concern,

Anza-Borrego Foundation, the cooperating partner to Anza-Borrego Desert State Park, appreciates the opportunity to submit a letter of support in connection to our mission to protect and preserve the natural landscapes, wildlife habitat, and cultural heritage of Anza-Borrego Desert State Park for the benefit and enjoyment of present and future generations.

We support the Tubb Canyon Desert Conservancy's proposal to identify, assess, and monitor groundwater dependent ecosystems in the Borrego Subbasin. Over the past decade we have worked collaboratively with TCDC on previous projects such as coordinating volunteers and park resources to remove invasive Sahara mustard from ecologically sensitive and touristically valuable areas in our community.

Furthermore, as the cooperating association with the Park, we recognize the critical importance of groundwater dependent ecosystems in the Subbasin and Park and are very supportive of TCDC's proposal to increase our knowledge and understanding of the vital components of our environment.

Sincerely,

B. Fordem

Bri Fordem
Executive Director
Anza-Borrego Foundation

JGR Biogeosciences

RESEARCH ARTICLE

10.1029/2020JG005942

Warming as a Driver of Vegetation Loss in the Sonoran Desert of California

Stijn Hantson[1], **Travis E. Huxman**[2], **Sarah Kimball**[2], **James T. Randerson**[3], and **Michael L. Goulden**[3]

[1]Geospatial Data Solutions Center, University of California, Irvine, CA, USA, [2]Center for Environmental Biology, University of California, Irvine, CA, USA, [3]Department of Earth System Science, University of California, Irvine, CA, USA

Key Points:

- We detected a widespread decrease in Sonoran Desert vegetation density from 1984 to 2017 using Landsat satellite normalized difference vegetation index
- Vegetation loss was greatest in more xeric areas
- Recent increases in surface air temperature were critical for explaining the spatial and temporal patterns of vegetation decline

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Hantson,
shantson@uci.edu

Citation:

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Abstract

Dryland ecosystems cover large regions of the Earth and have important impacts on global biogeochemistry and the carbon cycle. The plant species that occupy dryland environments have traits that enable them to withstand harsh environmental conditions, and some researchers have hypothesized that dryland vegetation may be comparatively resilient to changing climate, while others have pointed out that dryland vegetation often operates close to the physiological limits of many species, implying a possible vulnerability to warming. Here we use the Landsat archive to analyze vegetation dynamics for part of the Sonoran Desert and adjacent mountains in southern California. We show that large decreases in vegetation cover occurred over the last 34 years (1984–2017), especially across the xeric portions of our study region, where we observed a normalized difference vegetation index (NDVI) decline of 1.1 ± 0.3% yr^{-1}. Changes in precipitation explain most of the year-to-year variation but are unable to fully explain the observed long-term decline in NDVI. Statistical models that combined summer temperature and mean annual precipitation explained more of the spatial and temporal structure of NDVI trends and implicate climate warming as an important driver of declining vegetation cover. The impact of warming contributed to a change in the precipitation-vegetation relationship through time for this desert region, indicating a structural change in ecosystem function during the study period. These results suggest that recent climate change has already had significant impact on these drylands and highlight the potential for future warming to increase risks for dryland ecosystems in other regions.

Plain Language Summary

Dryland ecosystems are widespread across much of the globe. Plants occurring in these drylands are adapted to prolonged periods without rainfall and it is often assumed that drylands will be relatively resilient under present and future climate change. Here we use 34 years (1984–2017) of satellite data to assess vegetation changes over part of the Sonoran Desert and adjacent mountain areas in southern California. We observed a strong decline in vegetation cover, with the drier locations showing the strongest decline. Changes in rainfall could only explain part of the observed trends, with the long-term vegetation trends closely related to warming climate. These results indicate that dryland ecosystems may be more susceptible to changing climate than previously thought.

1. Introduction

Dryland ecosystems cover about 41% of Earth's terrestrial surface, making them one of the most widespread ecosystems worldwide (Cherlet et al., 2018). Dryland systems are known for high numbers of endemic species and account for 20% of the major centers of global plant diversity (White & Nackoney, 2003). Drylands are characterized by extended periods when potential evapotranspiration exceeds precipitation input (Lal, 2004). Vegetation in dryland ecosystems is characterized by adaptations to endure stressful conditions (Smith et al., 2012). While annual primary productivity is low (Schlesinger et al., 2009), dryland ecosystems often react strongly to changing water availability, with plants rapidly increasing photosynthesis and growth after rain events and soils metabolizing carbon with minor wetting (Noy-Meir, 1973; Sala et al., 2012). This however depends on precipitation amount, timing, and duration, as well as vegetation characteristics, and as a consequence in some situations dryland ecosystems may have a dampened response to individual precipitation events (Fernández, 2007). Dryland systems are widespread and play a key role in global biogeochemical cycles and Earth's energy balance (Jickells et al., 2005; Okin et al., 2004). For example, the response of net primary production to interannual variability in precipitation in global dryland ecosystems explains much of the year-to-year variability in the growth rate of atmospheric CO_2 (Poulter et al., 2014). Across multiple continents, there is an accumulating body of evidence that dryland ecosystems have a high level of sensitivity to various drivers of global environmental change, including temperature, precipitation, nutrient deposition, elevated CO_2, fire, and invasive species (Burrell et al., 2020; Cherlet et al., 2018; Lovich & Bainbridge, 1999). Understanding the response of dryland vegetation dynamics to climate change is essential for understanding past and future changes in global biogeochemistry and the carbon cycle, and for protecting and preserving the biodiversity of these vulnerable regions.

It is currently unclear how dryland vegetation will respond to climate change. It is expected that CO_2 fertilization may increase photosynthesis and water-use efficiency (Farquhar, 1997), though observational and experimental evidence is mixed (e.g., Donohue et al., 2013; Shaw et al., 2005; Smith et al., 2000). Future climate projections also indicate shifts in precipitation across global drylands, with a general decrease in overall precipitation (but including localized increases) and increases in temporal variability (e.g., Dai, 2012; Feng & Fu, 2013; Swain et al., 2018). While it is well known that changes in precipitation can drive long-term dynamics in dryland systems, including shifts in overall vegetation density or the relative proportion of alternative life-history strategies (e.g., Goldberg & Turner, 1986; Hereford et al., 2006; Miriti et al., 2007; Tucker et al., 1991; Venable, 2007; Venter et al., 2018; Weltzin et al., 2003), it remains uncertain how projected changes in precipitation magnitude and interannual variability will impact dryland systems. Predicting future vegetation outcomes is challenging, in part, because compared with plants in other biomes, dryland vegetation is often adapted to drought conditions and interannual variation in precipitation (Kimball et al., 2012; Noy-Meir, 1973; Smith et al., 2012).

Drylands are dynamic, undergoing large changes in plant cover in response to interannual, decadal, and centennial changes in precipitation (Gherardi & Sala, 2015; Huxman et al., 2004; Sala et al., 2012). Most of this change is associated with large interannual changes in abundance of annual species (Ehleringer, 2001), with seasonal and interannual variability in precipitation influencing vegetation structure (Gherardi & Sala, 2015; Lauenroth et al., 2014). Increases in woody vegetation has been observed in mesic drylands (Brandt et al., 2017), with perennial vegetation shifts caused mainly by changes in the size of individual plants and canopy expansion or loss, rather than whole plant mortality or recruitment. As such, the relative abundance of perennial species composition does normally not change drastically over long time periods in these more arid drylands (Goldberg & Turner, 1986). This seems at odds with the observations over the last two decades in the Southwestern US where large-scale mortality has been documented during recent drought (Bobich et al., 2014; Breshears et al., 2005; Hereford et al., 2006; McAuliffe & Hamerlynck, 2010; Miriti et al., 2007; Van Mantgem et al., 2009). These vegetation mortality events seem to exceed natural variability in background mortality rates, as some species have experienced up to 100% mortality (McAuliffe & Hamerlynck, 2010; Miriti et al., 2007), possibly leading to local extinction, and differential impacts that may depend on life-history strategy (Winkler et al., 2019). The effect of the local disappearance of a species may ultimately go beyond a decrease in local biodiversity, with possible implications such as nutrient cycling and water redistribution within soil (Maestre et al., 2012) making the changes possibly irreversible over a period of decades to centuries.

Precipitation has received the main focus as the driver of dryland vegetation dynamics, and comparatively few studies have explored secondary climate drivers of dryland vegetation dynamics. Some studies have looked at the impact of VPD on vegetation dynamics (Yuan et al., 2019) and another set of studies has shown that some desert plant species exhibit sensitivity to long-term changes in air temperature (e.g., Li & Yang, 2014; Munson et al., 2012, 2013). Interactions between precipitation and temperature have been shown to be important too, with rising temperatures on their own increasing drought risk (Diffenbaugh et al., 2015).

Moreover, desert areas are heavily influenced by anthropogenic disturbance, such as overgrazing by livestock, wildfires, off-road recreational vehicles, and agriculture (Brandt et al., 2017; Lovich & Bainbridge, 1999). All of these influence vegetation dynamics and recovery, and all are potentially sensitive to interannual variability and long-term trends in climate.

Here we study regional vegetation change across a swath of dryland ecosystems in Southern California, including a section of the Sonoran Desert and adjacent mountains. Within the Sonoran Desert, field studies

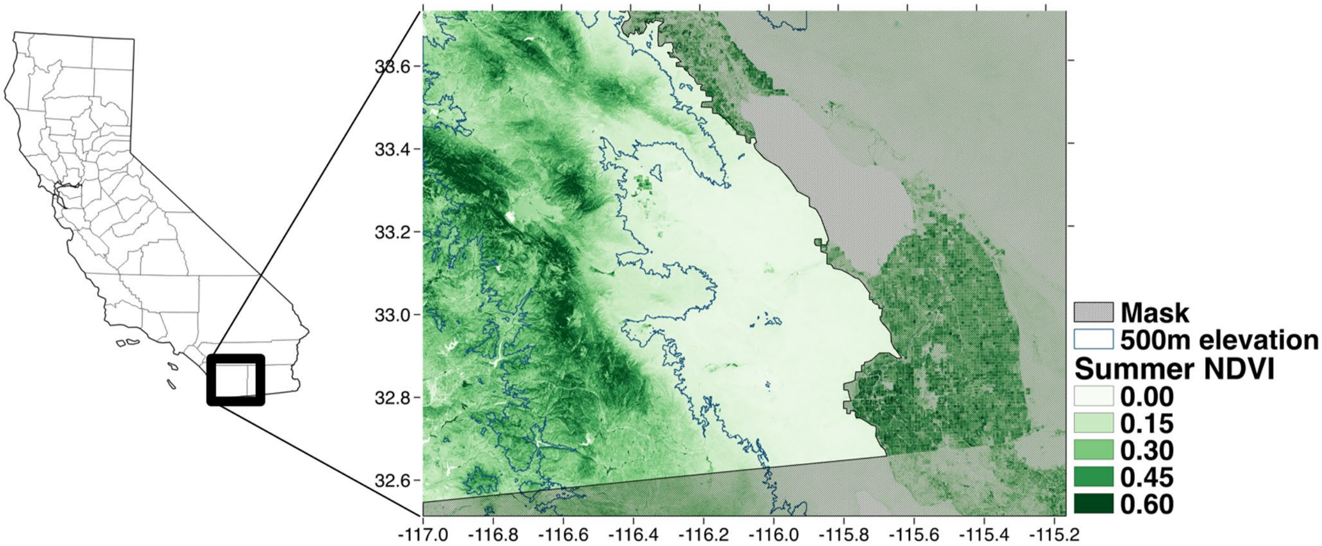

Figure 1. Location of the study domain within southern California, USA. Mean summer normalized difference vegetation index (NDVI) across the study site is presented where the gray shading indicates areas that were not considered for analysis such as croplands, water bodies (Salton Sea) and areas for which climate data were unavailable. The 500 m elevation separation (in blue) indicates the border between the lowland desert in the eastern part of the domain and the mountain area to the west.

have documented important perennial vegetation mortality events over the past several decades (McAuliffe & Hamerlynck, 2010; Munson et al., 2013). However, the magnitude, spatial extent, and drivers of these events are not well understood. We hypothesized that warming over recent decades has had a disproportional impact on the driest ecosystems within our study domain given the effect of increasing potential evapotranspiration and subsequent declining moisture availability. We focused our analysis on changes in perennial vegetation, as changes in water balance should have a more pronounced effect on perennial vegetation compared to annual vegetation as a consequence of differences in life-history responses to climate variability (e.g., Venable, 2007).

We examine long-term changes in perennial vegetation cover from Landsat imagery during 1984–2017, using the multidecadal satellite time series to attribute trends to long-term changes in environmental drivers. Recent improvements in the intercalibration and stability of satellite imagery time series, including Landsat, allow for the exploration of ever more detailed ecological questions (e.g., Robinson et al., 2019). The 34-year Landsat time series is powerful for differentiating the impacts of variable and decreasing precipitation and increasing temperatures on the desert perennial vegetation. Questions we address include: (a) What are the magnitude of vegetation changes across our study domain?, (b) Do hotter and drier lowland desert areas show larger decreases in NDVI than the more mesic ecosystems in adjacent mountains?, and (c) What are the drivers of interannual variability and long-term trends in vegetation change? In a final step, we explore the implications of a changing climate-vegetation relationship that is revealed from our analysis for changes in ecosystem function during the remainder of the 21st century.

2. Materials and Methods

2.1. Study Site

We assessed changes in vegetation cover over an area of Southern California encompassing the Anza Borrego State Park, on the border with Mexico (Figure 1). Our study domain covers 1.27 million hectares and includes a large part of the Colorado Desert, part of the Sonoran Desert, and peninsular mountain range (Laguna, Palomar, and Santa Rosa Mountains). The study region is bounded to the east by the change in land cover from natural systems to agricultural areas adjacent to the Salton Sea and to the south by the border with Mexico due to the lack of climate data (indicated by the mask in Figure 1). Elevation ranges from −70 to 1,660 m across the study domain, with a large 1984–2017 mean annual precipitation gradient from

73 mm y^{-1} in the desert to 770 mm y^{-1} in the mountains, and large interannual variability. Precipitation occurs during the winter and early spring, with occasional summer monsoons contributing additional precipitation across the lower elevation desert areas. Mean annual temperature also varies with elevation, from 10.7 °C in the mountains to 23.9 °C in the lowland desert.

A wide range of vegetation types occur across the study domain, in line with the large climatic gradient present. These can be largely divided in two groups (Keeler-Wolf et al., 1998), with higher elevation areas covered by montane woodlands, juniper and pinyon woodlands, chaparral and high desert vegetation. Areas in the lower elevation are covered by various lowland desert vegetation types, with the most abundant species being creosote bush (*Larrea tridentata*). A variety of cactus species are present, and some areas are dominated by mesquite (*Prosopis sp*.).

2.2. Remote Sensing Data Processing

We analyzed the historical Landsat archive across our study domain from Landsat 4, 5, 7, and 8 over the 34-year time period from 1984 to 2017, processing 2101 Level-2 surface reflectance Landsat scenes (Claverie et al., 2015; Vermote et al., 2016) were downloaded from USGS archives using the EarthExplorer interface (https://earthexplorer.usgs.gov). Clouds, cloud shadows, radiometric anomalies and missing data were masked (Foga et al., 2017). Landsat satellites provide imagery at 30-m spatial resolution in the optical spectrum since Landsat-5 with a 16-day return interval. Because of the radiometric differences between the Landsat 8 OLI detector and the previous Landsat detectors, we performed a bias correction on Landsat 8 imagery using a linear regression between the reflectance values of each band between Landsat 7 and Landsat 8 (Roy et al., 2016). This regression was developed using data from 30 pairs of images that were sampled within 10 days of each other. The resulting normalizations applied to the Landsat 8 imagery were 1.0257 × red band and 0.96349 × near infrared (NIR) band. This step normalized the reflectance values in the red and NIR band and reduced the difference in normalized difference vegetation index (NDVI) between Landsat 7 and Landsat 8, resulting in limited differences between the different sensors throughout the time period (Figure S1), except for a deviation in the red band of Landsat 5 at the end of the sensor's lifetime from about 2008-2011, especially for bright surfaces. We did not correct for potential biases between Landsat 4, 5, and 7 as radiometric differences between these sensors are relatively small (Chander et al., 2009).

Changes in vegetation cover were assessed by analyzing changes in NDVI time series (Tucker, 1979). NDVI represents the relative difference in reflectance between the NIR and red bands, normalized by the sum of reflectance in the two bands. High NDVI values are found in regions with dense vegetation (and high levels of leaf area index), as a consequence of high levels of light absorption in the red from the presence of chlorophyll and high levels of reflectance in the NIR from scattering off mesophyll leaf cells. As such, NDVI is sensitive to changes in vegetation cover and characteristics (Carlson & Ripley, 1997; Zhang et al., 2016). Other spectral indexes which are sensitive to vegetation dynamics include enhanced vegetation index (EVI), which differs from NDVI by means of the use of an additional blue band in the denominator to correct for aerosol impacts on the red band. EVI was calculated as $\mathrm{EVI} = 2.5 \times ((\mathrm{NIR}–\mathrm{Red})/(\mathrm{NIR} + 6 \times \mathrm{Red}–7.5 \times \mathrm{Blue} + 1))$. While the overall trend patterns derived from NDVI and EVI were similar (see Figure S2 for EVI analysis), we focused our analysis in the main text on NDVI in order to simplify the presentation. Likewise, additional analyses are possible, such as ones based on satellite-derived data products for vegetation class or plant functional type. We did not perform analysis on such data products as the underlaying classification algorithm can introduce arbitrary breakpoints in the data, especially when data density evolves over time, as it does here from Landsat 4 to Landsat 8.

The median NDVI over a monthly or seasonal time period was used to increase the robustness of the time series analysis and minimize the impact of possible coregistration errors of individual satellite images. We used summer NDVI (median NDVI during the period from 1 June through 30 September) for analysis (except if indicated otherwise), as this interval provides a quantification of perennial vegetation cover and excludes the significant variation that occurs due to annual plants contributing to springtime NDVI measurements as shown for an example pixel in Figure S3. We focused on changes in perennial vegetation because these plants play a key role in maintaining the stability and functioning of the ecosystem (Berg & Steinberger, 2012). Analysis of trends in peak spring growth from NDVI is more challenging (and not undertaken here) because satellite overpass frequencies are not daily, leading to the potential for aliasing when sampling the narrow spring peak. Further complications are introduced by a changing sampling frequency over time, which would complicate trend detection.

Vegetation is sparse across large parts of the study domain, leading to an important soil signal in the satellite observed reflectance. While NDVI largely separates out the vegetation signal from the spectral signature, absolute values of NDVI are still influenced by the soil characteristics, which complicates comparison of NDVI values between locations with different soils in dryland areas. Changes in vegetation were assessed by performing linear regression between NDVI and year, to avoid the impact of the soil signal to a large extent. We used the slope of the regression to estimate the rate at which the vegetation changed over the study period. As the soil within a given pixel stays the same over the study period, the observed trends in NDVI are almost exclusively vegetation related and these trends can hence be compared between different areas. This analysis and all posterior analysis were performed at the native 30-m Landsat pixel resolution.

2.3. Climate and Burned Area Data

Daily climate data used to examine relationships with the NDVI time series was extracted from the gridded interpolated climate data produced by the Parameter-elevation Relationships on Independent Slopes Model (PRISM; PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, last accessed 01/03/2019; Daley et al., 2002) at 4 km spatial resolution. Climate data was bilinearly interpolated to the spatial resolution of the Landsat data. Annual climate data for precipitation was calculated over the hydrologic year (1 October–30 September) and mean summer temperature was used. Using winter precipitation or mean annual temperature did not qualitatively change the outcomes of our attribution analysis. We analyzed specifically whether summer precipitation explained some of the pattern in summer NDVI across the lowland desert area but found no significant relationship.

Fires have influenced many parts of the study domain, and have occurred more frequently across the wetter, western half of the domain (Figure S4). As vegetation disturbance from fire and post-fire vegetation recovery strongly influence temporal trends in NDVI, we accounted for fire disturbance in our analysis. Fire perimeters for 1950–2017 were obtained from California's Fire and Resource Assessment Program (https://frap.fire.ca.gov/frap-projects/fire-perimeters/, last accessed 01/03/2019). We used the last date of fire disturbance for each 30 m pixel individually (Figure S4) to assess the impact of fire disturbance on the observed trends in NDVI.

2.4. Data Analysis

The role of different environmental and climate drivers in explaining the observed NDVI trends was assessed both spatially and temporally. The large-scale spatial pattern of the trend in NDVI was assessed using a Generalized Additive Model (GAM) from the "mgcv" package in R 3.6.1 software (Wood, 2011). A GAM was used because it does not have a priori determined shape of the relationship between the response variable and the covariates; it is derived purely from the data (Guisan et al., 2002). We used spatial estimates of the linear trend in annual precipitation and summer temperature, as well as mean annual precipitation and time since last fire (Figure S4) as covariates to explain the observed spatial pattern in NDVI trends. Due to computational constraints a random sample of 20,000 30 × 30 m points (0.14% of the domain) was extracted to build the GAM model. Results of the GAM model might be impacted by unaccounted spatial autocorrelation. To assess the robustness of the results from the GAM models, and further explore in-depth the drivers of NDVI change we performed a set of additional a set of analyses as described below.

In a separate analysis, linear regression models were developed for each individual Landsat pixel to assess which variables explained the interannual variability in the NDVI time series and its long-term trend. This analysis was also performed using the mean NDVI time series constructed from the entire mountain area in the western part of the study domain and the lowland desert area in the eastern part of the study domain, to better understand the response of these contrasting ecosystems to environmental drivers. The two regions were separated along a 500-m elevation contour shown in Figure 1. We used annual precipitation, mean summer surface air temperature, and previous 1-, 2-, and 3-year integrated precipitation as variables to explain the summer NDVI time series. We also explored whether interactions between precipitation and temperature could explain part of the temporal variance. We estimated the relative contribution of each

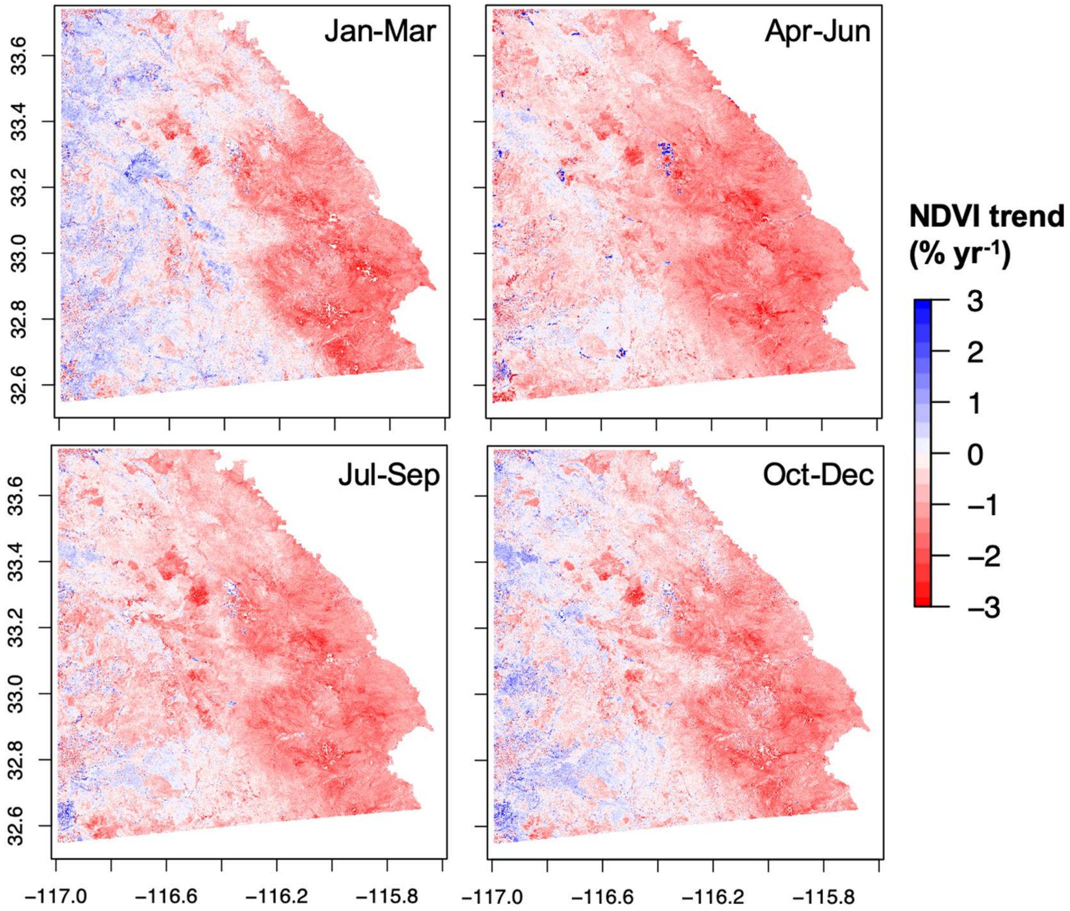

Figure 2. Normalized difference vegetation index (NDVI) trend during 1984–2017 for different seasons. The linear NDVI trend for each 30 m pixel was calculated from the median seasonal NDVI for each year. Blue indicates increasing NDVI and red indicates decreasing NDVI.

variable within the linear model by decomposing the linear model using the Lindeman, Merenda and Gold ("lmg") method as implemented in the "relaimpo" R package (Gromping, 2006; Lindeman et al., 1980). All analyses were performed using R 3.6.1 software (R Core Team, 2019).

3. Results

3.1. Vegetation Trends

Large declines in NDVI and apparent losses in vegetation cover occurred over the last 34 years (1984–2017) across the study region (Figure 2). The long-term NDVI decline was most widespread in the July-September summer period, with 87.1% of the study domain showing a downward trend. The observed negative trends in NDVI were highly significant in most 30 m pixels, with the exception of areas within recent fire scars (Figures S4 and S5). The most striking change was the strong reduction in NDVI across the lowland desert area in the eastern part of the study domain (Figure 2, Table S1). Mean summer NDVI across the lowland deserts decreased by 1.11 ± 0.26% yr^{-1} (Figure 3; Table S1). In accordance with the change in NDVI, we observed significant increases in the red reflectance ($p < 0.01$; Table S2). NDVI declines were apparent throughout the year in lowland deserts (Figure 2), which suggests they were associated with a structural change in perennial vegetation.

A widespread decrease in NDVI was observed in the mountains during the summer months with a mean reduction of −0.37 ± 0.18% yr^{-1}. The relative decrease was less extreme in the mountains than the lowland desert area, while the opposite was true for the absolute change (−0.049 NDVI vs. −0.029 NDVI), as a

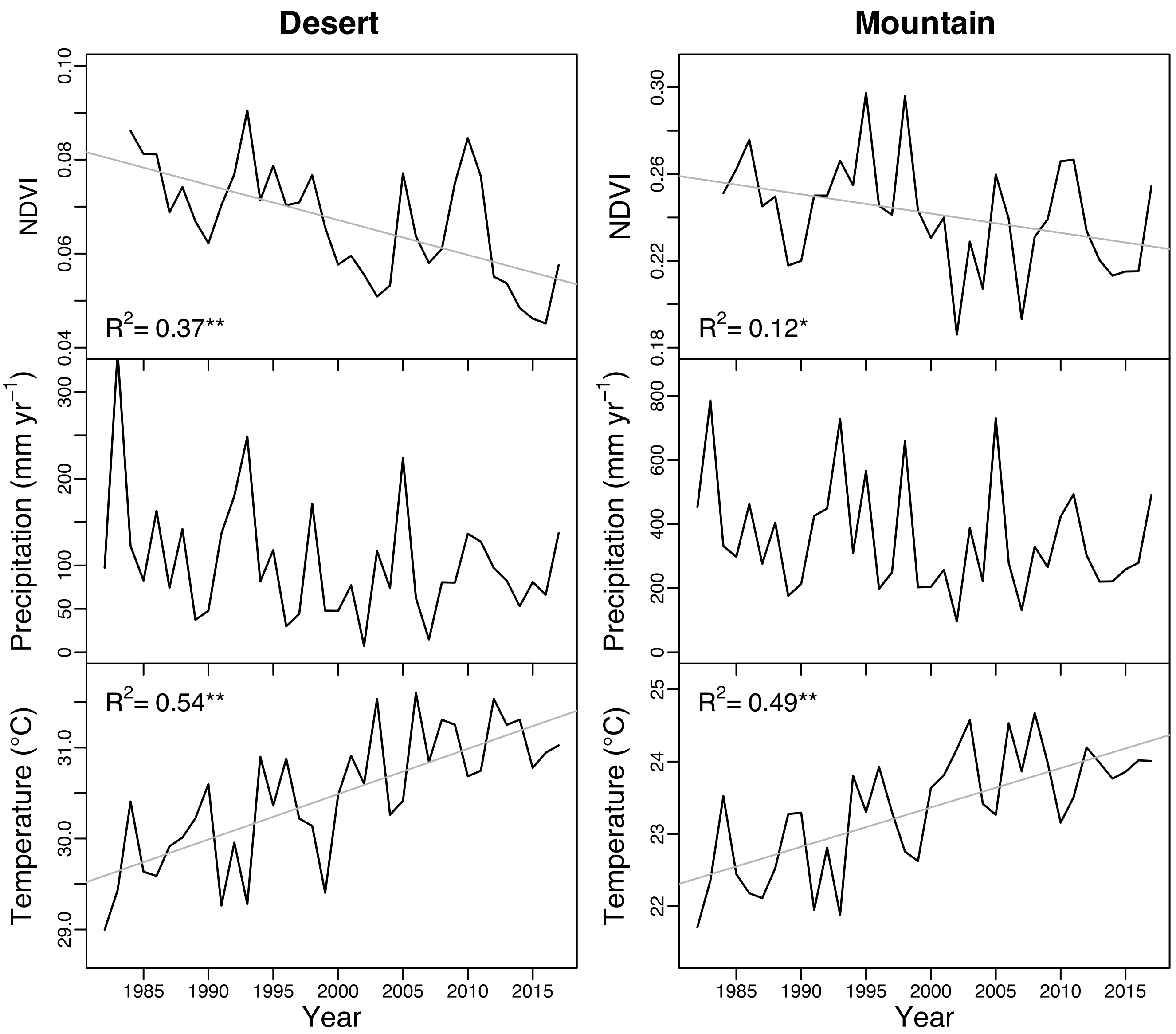

Figure 3. Time series of mean summer normalized difference vegetation index (NDVI) (June–September), annual precipitation, and mean summer temperature for lowland desert and mountain areas of the study domain. Linear trend lines are shown where significant and slopes are presented in Table S1. As an indicator of statistical significance, * denotes $p < 0.05$ and ** denotes $p < 0.01$.

consequence of the higher NDVIs in the mountains (0.241 NDVI) than deserts (0.067 NDVI). Most of the mountain region showed a decline in NDVI, with isolated areas showing a slight increase. The NDVI trends were variable during autumn and winter (October–March), showing a mixture of areas with increasing, decreasing, or no trend.

3.2. Drivers of the Spatial Pattern of Vegetation Trends

Climate and fire occurrence explained part of the spatial pattern of the observed trends in summer NDVI (median June–September NDVI). Precipitation was highly variable from year to year, exhibiting a weak, nonsignificant decline by approximately −17 ± 11 mm per decade in this lowland desert area and by −37 ± 27 mm per decade in the adjacent mountain areas over the 1984–2017 study period (Figure 3, Figure S4, Table S1). Summer temperatures increased significantly by 0.5 °C ± 0.1 °C per decade in the low

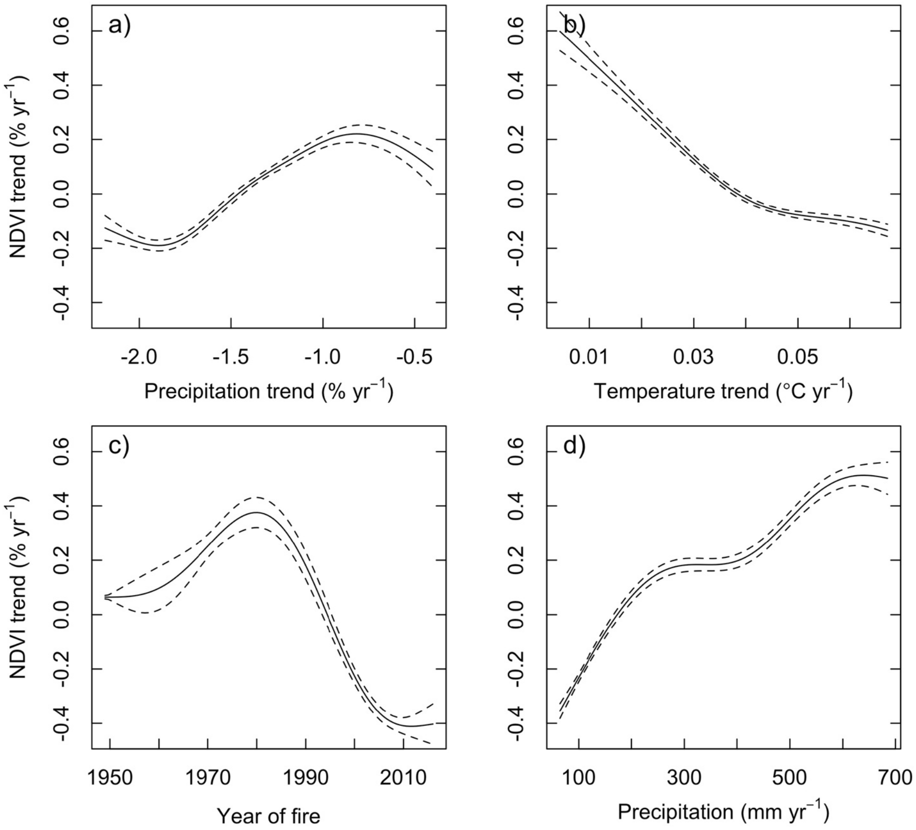

Figure 4. Generalized Additive Model response curves for a set of explanatory variables used to predict the spatial structure of summer normalized difference vegetation index (NDVI) trends (% yr^{-1}). The solid line in each panel is the estimate of the smooth function and the dashed lines indicate 2 standard errors above and below the estimate. The *x*-axis shows 99% of the data range. The values on the *y*-axis are centered so that the sum of the covariate values is equal to zero.

elevation desert and in the mountains. Wildland fires occurred frequently and were especially prevalent in the wester, higher elevation part of the study domain (Figure S4).

A GAM model incorporating temperature and precipitation trends, mean annual precipitation, and time-since-fire explained about 37% of the spatial variability in the summer NDVI trend. Regions that experienced more substantial declines in precipitation had larger decreases in summer NDVI (Figure 4a). Similarly, regions with larger more pronounced temperature increases also had stronger summer NDVI decreases (Figure 4b).

Wildland fires are an important driver of spatial patterns of NDVI change. Areas that recently burned had strong negative NDVI trends as at least part of the vegetation was killed and removed by the fire. Areas that burned around the start of our study period showed an increase in NDVI related to vegetation recovery after fires, while later-occurring fires did not demonstrate such recovery. The response to fire yielded a hump-shaped response in which positive NDVI trends were largest for fires that burned during the 1980s and 1990s, and most strongly negative for recent fires (Figure 4c). Considering these drivers together, there is still a large part of the observed variance in NDVI change which remains unexplained across the precipitation gradient in our study domain (Figure 4d), with drier areas showing a much stronger decrease than expected when compared to wet areas.

3.3. Can We Explain the Observed Trends?

A simple linear regression model using annual precipitation was able to capture part of the variance in summer NDVI time series (Figure 5; Table S1) for both the lowland desert (34%) and mountain areas (61%). Another simple model with only summer air temperature explained 32% of the variance in the lowland

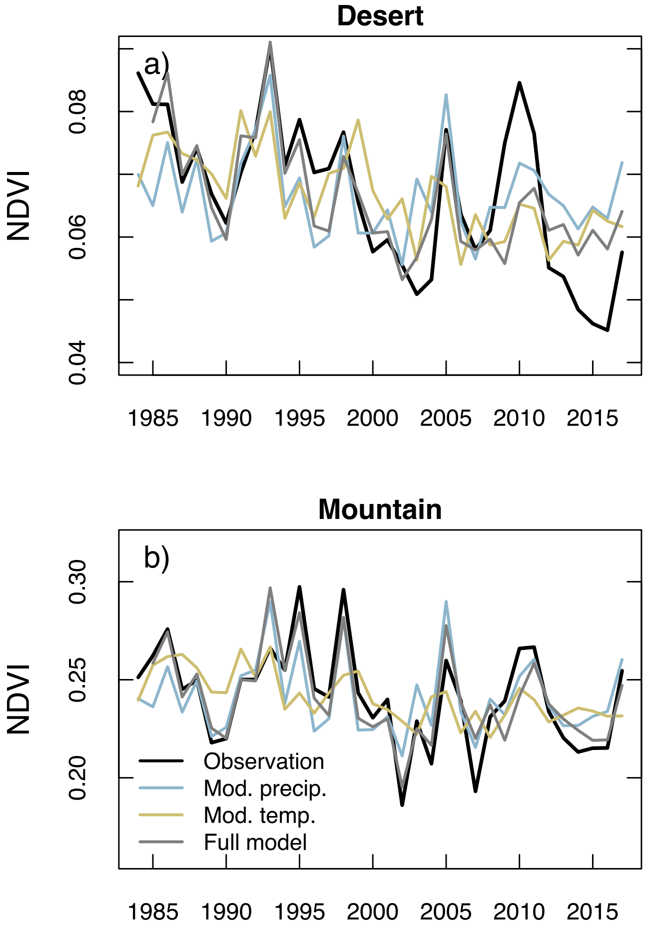

Figure 5. Annual mean summer (June–September) normalized difference vegetation index (NDVI) for lowland desert and mountain areas with predicted summer NDVI from a linear model based on annual precipitation, summer temperature, or a model including precipitation, temperature, and precipitation of the previous 3 years (Full model). R^2 values for each model are given in Table S1.

desert and 24% in the mountain region. In the case of the lowland desert temperature explained more of the variance than precipitation.

A full linear model, including precipitation, temperature and summed precipitation during the previous 3 years, explained 58% and 79% of the variance in annual summer NDVI for lowland desert and mountain areas respectively (Figure 5). This means that changes in NDVI in the higher elevation region were better explained by the variables included in the model than changes in NDVI across the lowland desert. This was especially evident toward the end of the desert time series, when the linear models were unable to represent the strong decrease in NDVI during the 2012–2016 period. A relative importance variable analysis revealed summer temperature and annual precipitation contributed about equally as drivers in the lowland desert region, and that annual precipitation was more important in the mountain region (Figure S6). Precipitation of the previous year did explain a small amount of variance, with precipitation 2 and 3 years before increasing in importance the longer the time lag considered, and they seem slightly more important for drier areas (Figure S6). Including an interactive term of precipitation and temperature within the linear regression to explain the temporal trend in mean summer NDVI was not significant for both the lowland desert and the mountain region and not further included in the analysis.

When fitting linear regression models for each pixel individually we found that the per pixel model using precipitation alone was largely unable to reproduce the observed long-term trend in summer NDVI across most of the study domain, while the model that included only temperature explained considerably more of the overall spatial pattern (Figure 6). Much of the total variance in the annual summer NDVI time series across the lowland desert region was explained by temperature alone (Figure 5, Figure S7). The full model, including precipitation, temperature, and the previous 3 years of precipitation, explained a large portion of the variance across the entire study region (Figure S7). Exceptions for this general pattern are recently burned areas ($R^2 = 0.44$ for areas burned after 2000 and $R^2 = 0.53$ for areas not burned are burnt before the year 2000). There was also heterogeneity in the eastern, lower elevation region, with some areas showing relatively low R^2 values. The full regression model predicted the magnitude of the decrease in summer NDVI for the higher elevation areas but underestimated the magnitude of the decline in lowland desert areas (Figure 6).

To investigate whether the relationship between annual precipitation and annual NDVI changed over time, as might be expected for a structural change in vegetation composition, we separately computed regression relationships for the first half and second half of the time series. For the higher elevation areas, there was a consistent positive linear relationship between annual precipitation and annual summer NDVI, with almost identical relationships between early and late periods in the 34-year time series (Figure 7). However, for the lowland desert region the intercept of the precipitation-NDVI relationship shifted downwards after the start of the drought in 1999. This means that for the same precipitation input amount there was higher mean NDVI prior to 1999 as compared to after, which is consistent with a structural change in ecosystem functioning over the study period and a loss of canopy cover (Ehleringer, 2001).

4. Discussion

4.1. Large-Scale Vegetation Loss

Here we provide evidence for a widespread decline in perennial vegetation cover in lowland deserts of southern California over the past four decades (Figure 2). Vegetation cover also declined in surrounding

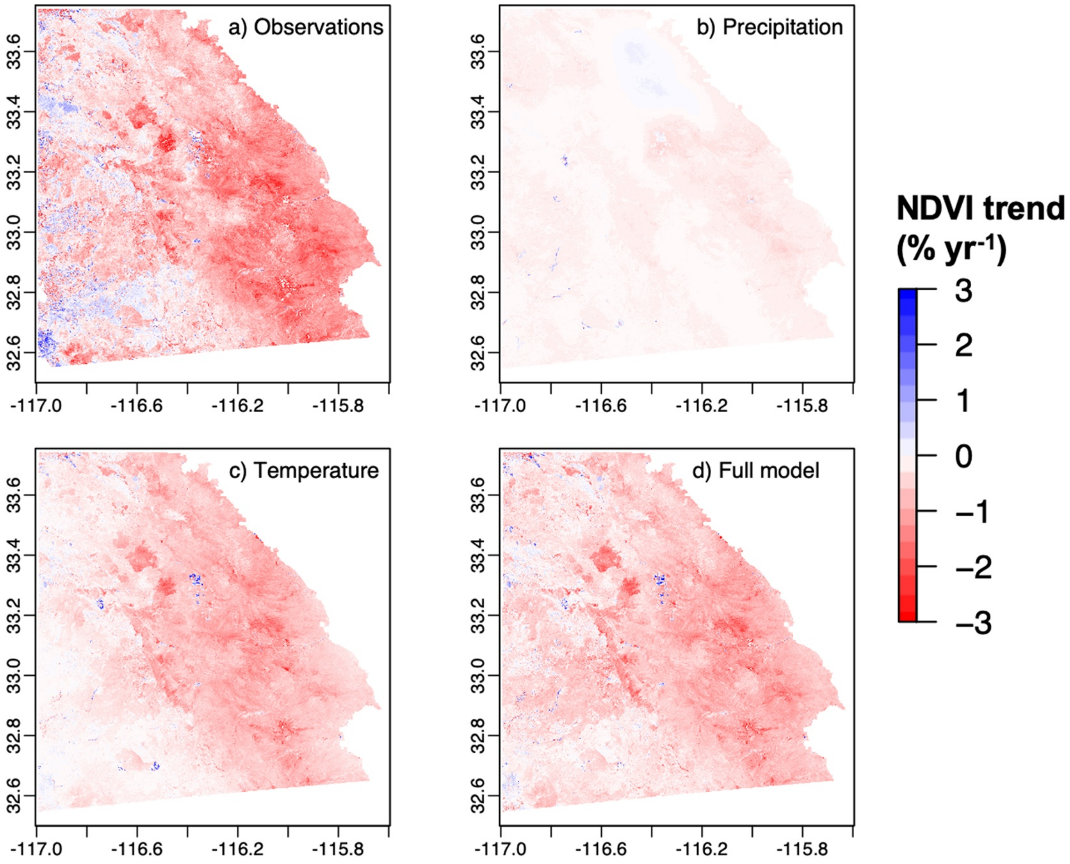

Figure 6. Trend in summer normalized difference vegetation index (NDVI). (a) observed trend in summer NDVI, (b and c) predicted trends in summer NDVI from linear regression model using (b) precipitation, (c) temperature, and (d) a model including precipitation, temperature and precipitation of the three preceding years. See Figure S6 for significance of the observed summer NDVI trend.

higher elevation areas, but to a lesser extent. The observed trends are consistent with the hypothesis that warming temperatures have caused a long-term increase in water limitation. This is especially clear across the lowland deserts, which are the driest areas of the study domain, and is superimposed against high levels of interannual variability in precipitation. Previous findings by Williams et al. (2020) indicate how warming increases drought severity, and here we show that this may result in a loss of vegetation cover.

Although we observed widespread decreases in vegetation cover throughout our study domain, the responses of the lowland desert and higher elevation mountain areas to climate warming and precipitation variability had different magnitudes and were likely modulated by different processes. The more mesic higher elevation areas experienced smaller relative decreases in NDVI and the relationship between mean annual precipitation and NDVI did not appear to appreciably change over time (Figure 7). Hence, this is a straightforward way to predict the potential changes in vegetation for these systems, at least within the range of climate variability observed for the study period.

In contrast, the lowland desert areas experienced a stronger relative decline in vegetation cover (Figure 2) in line with large-scale mortality events that have taken place over the last 2 decades (McAuliffe & Hamerlynck, 2010; Miriti et al., 2007). Precipitation is an important driver of vegetation patterns and trends in dryland ecosystems (Goldberg & Turner, 1986; Hereford et al., 2006; Knapp et al., 2015; Miriti et al., 2007; Poulter et al., 2014; Tucker et al., 1991; Weltzin et al., 2003). Our attribution analysis is consistent with this past body of work, but also shows that temperature is as important as precipitation in explaining interannual variability in vegetation cover and is even more important for explaining multidecadal trends (Figure 6). Many plant species in desert ecosystems have adaptations that allow them to withstand high

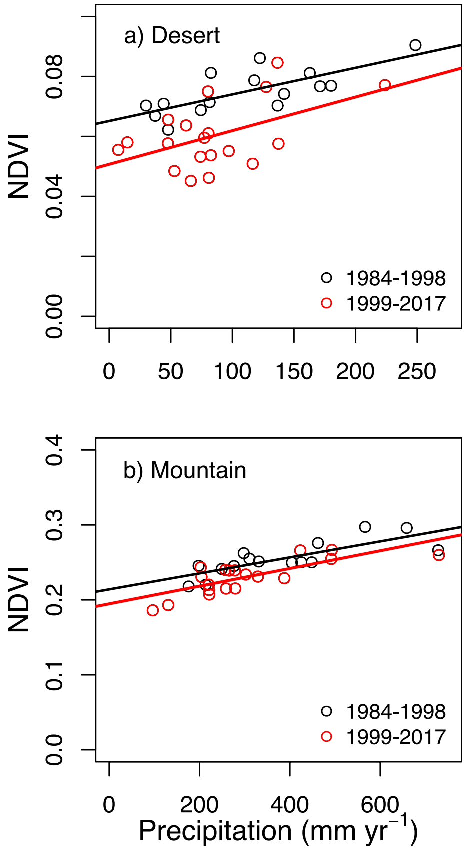

Figure 7. Relationships between annual mean precipitation and summer normalized difference vegetation index (NDVI) for lowland deserts (a) and mountain areas (b). Separate linear regression lines were drawn for the period 1984–1998 (black) and 1999–2017 (red).

temperatures, making this observation somewhat unexpected. Previous research has indicated some temperature sensitivity of certain perennial desert plant species (Munson et al., 2012, 2013). However, these findings are in line with observations of photosynthetic productivity in drylands, with lower gross ecosystem productivity under higher temperatures, both interannually and spatially (Biederman et al., 2017). Higher temperatures can increase evapotranspiration, which in turn, may lead to a reduced water availability and greater moisture stress for perennial plants during dry summer months. An important challenge in future work is to further assess whether the link between surface air temperature increases and vegetation decline operates through a water stress mechanism as described above, or by means of the direct effects of heat stress on plant physiology and mortality. In this context, it is also important to recognize that some of the temperature stress may arise by means of biophysical feedbacks with variability in the hydrological cycle (Humphrey et al., 2021).

For lowland desert areas, our analysis suggests these ecosystems may have crossed an ecological threshold, leading to shift in the precipitation versus NDVI relationship over the study period (Figure 7). Although NDVI is often linearly related to precipitation, we observed that the intercept of this relationship declined after the onset of the drought period in 1999 (Dai, 2013), coincident with rising temperatures. We find a lower NDVI after the year 1999 than before for a given level of annual mean precipitation. This suggests that the vegetation is undergoing or has undergone a restructuring through large-scale mortality in response to new temperature extremes. The break in the relationship suggests climate warming has not just contributed to a reduction in overall vegetation cover but has induced a reorganization of species composition, a consequence of varying increases in plant mortality between species. McAuliffe and Hamerlynck (2010) found that Ambrosia species has experienced up to 100% mortality in desert regions around our study region, while L. Tridentata has experienced lower mortality rates. For drylands, such reductions in year-to-year rainfall-use efficiency is indicative of degradation in other settings (Ehleringer, 2001). As these systems may be governed by thresholds, one potential implication is that it will be very difficult to predict future responses to changing environmental conditions. This could pose an important limitation to our ability to understand how drylands will be affected by future climate change.

There are several processes that could reduce or slow the recovery of desert vegetation. Many perennial desert plant species are long-lived, resulting in slow plant turnover times, frequently greater than 100 years (Cody, 2000; Vasek, 1980). Shrubs that are able to survive drought do so by a combination of factors, including cavitation-resistant xylem, deciduousness, photosynthetic stems and a broad range of plant water potential, water uptake depth and gas exchange behavior (Pivovaroff et al., 2016). Many of these strategies could be impacted by high temperatures, when evaporative demand increases. This, in combination with a recruitment bottleneck (e.g., Turner, 1990) where seedling establishment only occurs during rare, multiyear wet periods, results in very slow regeneration (Shriver et al., 2019). On the other hand, desert annual plants will simply not germinate in dry years or will germinate in very low numbers and will remain very small in stature during dry years (Venable, 2007). Increased temperatures will influence the suite of species that germinate along with their ability to survive and reproduce (Kimball et al., 2010). Over time, reduced reproductive rates of desert annuals would deplete the seed bank. Once vegetation decreases, recovery is further limited because few species can colonize bare soil directly but depend on existing adults ("nurse plants") for protection from adverse environmental conditions during the first few years following germination (McAuliffe, 1988). Vegetation recovery after disturbance can take a century in some desert ecosystems (Carpenter et al., 1986; Webb et al., 1988), and we may have entered a long-term state characterized by reduced vegetation cover for these lowland desert areas.

4.2. Precipitation Legacy Effects

Studies of the importance of time lags between precipitation occurrence and vegetation response have often indicated that the legacy of precipitation in prior years influences productivity and other ecosystems processes in the present (Bunting et al., 2017; Kimball et al., 2018; Ogle et al., 2015; Sala et al., 2012). We observed this type of legacy effect in the Landsat record (Figure S6), and that the importance of precipitation legacy increased at longer timesteps, underscoring the importance of long-term precipitation regime in driving vegetation trends.

Another factor that has been hypothesized to influence vegetation response to drought is the increase in atmospheric CO_2. While increases in atmospheric CO_2 have the potential to reduce the impact of temperature and drought on desert vegetation (Hamerlynck et al., 2000), our results imply that any positive effect of rising CO_2 over the last 30 years was overwhelmed by the competing negative effects imposed by climate variables observed here, leading to a net decrease in NDVI. This is in line with previous findings that climate drivers can overwhelm the atmospheric CO_2 effect (Brookshire & Weaver, 2015).

4.3. Spatial Heterogeneity

While we observed a reduction in NDVI over the entire lowland desert area, there were important local differences in magnitude between nearby pixels, showing the value of performing vegetation trend analysis at relatively high resolution (30 m). This type of fine scale information may be useful to land managers, as they develop conservation and management plans. This local spatial heterogeneity within the overall large-scaled patterns also explains the relatively low explanatory power of the GAM model. As the input climate drivers have a coarse resolution (4 km) we were limited to describing large-scaled patterns of vegetation change. However, important local differences also occur, and are likely tied to fine scale differences in topography, hydrology, and species composition. Such differences between nearby pixels (30 m) are in line with previous findings that contrasting species have differential sensitivity to changing climate conditions, depending on structural, physiological, and life-history characteristics (e.g., Miriti et al., 2007; Munson et al., 2012). Other environmental factors such as slope, orientation, and soil depth and type will influence the impact of changing climate conditions on ecosystem function and vegetation dynamics (Munson et al., 2015). Unfortunately, no detailed soil maps exist for this region, and so we were unable to quantify the impact of soil characteristics on the vegetation trends we observed in the Landsat time series.

Much of our study domain is public land that is protected from development, though historical and current anthropogenic impacts nonetheless have influenced vegetation dynamics (Lovich & Bainbridge, 1999). For example, off-road recreational vehicles may disturb biological soil crusts and perennial plants (Lovich & Bainbridge, 1999). Most of these effects are local, and it is unlikely that past and present anthropogenic disturbances explain the large-scale vegetation decline described here, though they clearly drive some changes, as observed for fire (Figure 4).

4.4. Implications for Dryland Conservation

Desertification and the large-scale degradation of productive areas across global drylands remains a global concern (Millennium Ecosystem Assessment, 2005). Much of this attention has focused on the degradation of dryland grazing lands, where transitions from grassland to woody, less productive systems carry implications for livestock (e.g., Venter et al., 2018). Here we show that more xeric systems also have undergone large-scale vegetation changes during the satellite era. While part of this reduction may be attributed to a reduction in perennial vegetation LAI, ample field data confirms an important contribution of perennial plant mortality (e.g., McAuliffe & Hamerlynck, 2010; Miriti et al., 2007). Perennial plant species are considered more sensitive to drought than annual species (Schwinning & Ehleringer, 2001), and a shift in plant community composition toward a larger dominance of annuals compared to perennials with climate warming appears possible. This may help explain the pattern of increasing spring NDVI and decreasing summer NDVI we observed (Figure 2). Such changes would have important implications for ecosystem functioning and carbon, water, and nutrient cycling, as well as for food webs and higher trophic levels. For example, a shift from perennial to annual vegetation has been related to an acceleration of the N-cycle and increasing inorganic N availability (Booth et al., 2003). Furthermore, as the nutrient cycles in dryland systems depend largely on precipitation, increasing drought may lead to a decoupling of C-N-P cycles (Delgado-Baquerizo et al., 2013), with subsequent impacts on ecosystem function.

Precipitation is expected to decrease in many dryland areas including Southern California (Dai, 2012), which, in combination with increasing precipitation variability (Swain et al., 2018), will likely result in more frequent droughts (Williams et al., 2020). However, we found that the desert perennial vegetation is also sensitive to temperature change, which means that dryland vegetation may be more susceptible to climate change than expected (Hoover et al., 2019). This is consistent with the findings of an experimental warming study on desert vegetation, where a 2°C increase in temperature caused significant declines in photosynthesis (Wertin et al., 2017) depending on plant functional traits (Valencia et al., 2016). While we have quantified the decrease in desert vegetation that already has taken place, our findings indicate further, potentially important restructuring of desert vegetation with future warming.

Data Availability Statement

Landsat Level-2 surface reflectance data are available at https://earthexplorer.usgs.gov. Fire perimeters are available from the California's Fire and Resource Assessment Program (FRAP; https://frap.fire.ca.gov/frap-projects/fire-perimeters/). The climate data used is available from the PRISM Climate Group, Oregon State University (http://prism.oregonstate.edu; Daly et al., 2002).

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