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Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow

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Riparian ecosystems fundamentally depend on groundwater, especially in dryland regions, yet their water requirements and sources are rarely considered in water resource management decisions. Until recently, technological limitations and data gaps have hindered assessment of groundwater influences on riparian ecosystem health at the spatial and temporal scales relevant to policy and management. Here, we analyze Sentinel-2–derived normalized difference vegetation index (NDVI; n = 5,335,472 observations), field-based groundwater elevation (n = 32,051 observations), and streamflow alteration data for riparian woodland communities (n = 22,153 polygons) over a 5-y period (2015 to 2020) across California. We find that riparian woodlands exhibit a stress response to deeper groundwater, as evidenced by concurrent declines in greenness represented by NDVI. Furthermore, we find greater seasonal coupling of canopy greenness to groundwater for vegetation along streams with natural flow regimes in comparison with anthropogenically altered streams, particularly in the most water-limited regions. These patterns suggest that many riparian woodlands in California are subsidized by water management practices. Riparian woodland communities rely on naturally variable groundwater and streamflow components to sustain key ecological processes, such as recruitment and succession. Altered flow regimes, which stabilize streamflow throughout the year and artificially enhance water supplies to riparian vegetation in the dry season, disrupt the seasonal cycles of abiotic drivers to which these Mediterranean forests are adapted. Consequently, our analysis suggests that many riparian ecosystems have become reliant on anthropogenically altered flow regimes, making them more vulnerable and less resilient to rapid hydrologic change, potentially leading to future riparian forest loss across increasingly stressed dryland regions.

riparian vegetation | groundwater | streamflow | NDVI | California

Riparian ecosystems are hotspots for biodiversity, hosting a wide range of aquatic and terrestrial species. Yet, they are some of the most endangered ecosystems globally (1, 2) since they often exist at the epicenter of urbanization and intensive agriculture. Biodiversity and ecosystem functioning in fluvial environments are largely regulated by shallow alluvial groundwater and its interconnection with surface flow regimes. For many river systems, shallow groundwater is a critical ecological resource, sustaining baseflow throughout the year in perennial streams and supporting intermittent discharge in drylands when the groundwater table intersects the land surface. In addition to regulating flow, groundwater sustains aquatic ecosystems by providing thermoregulation and contributing minerals and oxygen. In terrestrial environments, groundwater provides a subsurface water source to deeply rooted plant species, enabling them to buffer the effects of dry periods (3). Since shallow groundwater along rivers interact with surface water, anthropogenic alteration of streamflow and pumping of local aquifers to meet high societal demand are often at odds with the flow needs for various species and can induce water stress to both aquatic and terrestrial species at critical life stages. Anthropogenic alteration is exacerbated in dryland regions, where small but persistent changes in the water balance may have large ecological impacts, further threatening the long-term sustainability of native riparian ecosystems (4, 5).

Phreatophyte trees are foundation species in riparian ecosystems that rely on groundwater and are effective indicators of ecosystem health, especially since they can be monitored using a variety of approaches at different scales (3, 6–8). Although documented instances of extensive tree mortality, crown dieback, growth decline, and poor recruitment exist within groundwater-dependent riparian ecosystems (9–11), there remain critical uncertainties in how strongly riparian woodlands respond to seasonal and interannual fluctuations in water table depth and how groundwater dependence varies across regions and between natural and altered surface water regimes (12). Riparian vegetation communities occurring within dryland regions are heavily reliant on low-flow and high-flow components of surface water and groundwater regimes (13, 14). This is because key life-history processes, such as propagule dispersal,

Significance

Riparian ecosystems are biodiversity hotspots under intense pressure from multiple stressors. In most water-limited regions, high human water use from agricultural and urban development eclipses environmental water needs and intensifies ecosystem water stress. In particular, adequate consideration of riparian water needs in water resource management is lacking. Here, we show that in California, riparian vegetation exhibit: 1) seasonal canopy stress responses to deeper groundwater, and 2) greater groundwater coupling along streams with natural flow regimes compared with anthropogenically altered streams. We conclude that water subsidies in altered stream systems reduce groundwater dependence of riparian woodlands, undermine their adaptations and resilience to natural hydrologic variation, and ultimately threaten their sustainability under dual threats of increased water demand and a changing climate.

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The authors declare no competing interest.

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germination, and establishment, are regulated by various characteristics of the flow regime and their interactions with geomorphic and biotic processes (15–17). For example, riparian tree recruitment typically occurs after large floods when propagules are transported onto point bars and the floodplains of naturally flowing rivers. As the river stage declines, the root networks of new germinants grow vigorously to maintain contact with the water table as it declines throughout the growing season. If spring flows are truncated or otherwise anthropogenically modified, or the water table recedes too quickly, new cohorts fail to recruit. Native riparian species that are adapted to these seasonal interconnections between surface water and groundwater are often outcompeted by nonnative or upland species where groundwater and surface flow regimes are strongly altered, thus contributing to habitat and biodiversity loss (18–20). In this context, we set out to: 1) characterize when and where riparian ecosystems exhibit stress responses to seasonal groundwater table declines; and 2) evaluate influences of natural versus anthropogenically altered surface flow regimes on riparian ecosystem groundwater reliance.

Until recently, riparian woodlands have been difficult to study at the landscape scale because they are typically excluded from systematic ground-level forest and agriculture monitoring programs (21). However, remotely sensed indicators, such as the normalized difference vegetation index (NDVI), a measure of canopy greenness linked to water stress responses such as leaf functioning, growth, and mortality (22), show promise for detecting phreatophyte responses to groundwater. Studies linking NDVI to groundwater levels in northern China (23), the East Coast of the United States (24), Nevada (25), and California (26) have all observed NDVI declines with increasing depth to groundwater (DTG), but they are limited in regional scope and spatial resolution. This is because sensor resolution on Earth observation satellites such as MODIS (250 m) and Landsat (30 m), are too coarse to effectively monitor riparian woodlands, which are typically distributed along river networks in narrow and discontinuous patches (27). When pixels are large relative to vegetation patches and comprise a functionally diverse set of species, only some of which rely on groundwater, this "mixed-pixel" problem can obscure the detection of phreatophyte responses to groundwater availability (6, 23). In this study, we exploit the finer resolution (10 m) of the European Space Agency's Sentinel-2 satellite, launched in 2015, to link riparian ecosystem responses (NDVI) to groundwater levels and surface water flow regimes across a broad range of riparian systems in California (United States), and to estimate where and when riparian vegetation is most reliant on groundwater.

California is of global ecological interest since it is one of the world's top biodiversity hotspots (28), containing more species than the rest of the United States and Canada (29). Riparian ecosystems in California coexist with a multibillion dollar agricultural industry and 40 million people, epitomizing the ongoing global challenge of balancing social, economic, and environmental water needs. The state of California is a recent leader in sustainable groundwater management, since it is one of only four jurisdictions globally that legally require managers to consider ecosystem impacts when designing sustainability metrics and monitoring programs (30). California's water systems are highly altered and engineered to redistribute water across the state's hydrologic regions, from the water-rich Sacramento River region to the semiarid south where precipitation is low and evaporative losses are high (*SI Appendix*, Fig. S1). Due to intensive agriculture and urbanization, the riparian ecosystems that exist today within California's Central Valley represent only ∼5% of the floodplain habitat that was present nearly a century ago (31, 32). These remaining riparian habitats continue to be stressed by groundwater overdraft (33), climate change (34, 35), and a surface water system that is highly altered (36–38) and overallocated (39). With more than 90% of all freshwater species endemic to California already vulnerable to extinction within the next 100 y (40, 41), it is imperative that groundwater and surface water are managed to protect the broad ecohydrologic niches within natural riparian environments that support biodiversity and ecosystem function.

We coupled Sentinel-2–derived NDVI measurements (n = 5,335,472 observations) with field-based groundwater data (n = 32,051 groundwater depth measurements), and streamflow alteration indices for three major phreatophytic riparian woodland communities (n = 22,153 mapped vegetation polygons) over a 5-y period (2015 to 2020) across California. We focused on mapped vegetation types dominated by phreatophyte riparian species that are ubiquitous throughout the state: *Salix gooddingii* (Goodding's willow; "willow"), *Populus fremontii* (Fremont cottonwood; "cottonwood"), and *Quercus lobata* (valley oak; "oak"). By combining these large spatiotemporal datasets, we linked NDVI to groundwater and streamflow data to test whether canopy greenness varied with groundwater depth across different woodland communities, hydrologic regions, seasons, and surface flow regimes. We show that: 1) willow, cottonwood, and oak woodlands all exhibit stress responses to groundwater availability as evidenced by declines in NDVI with deeper groundwater; and 2) NDVI for vegetation along altered streams was elevated and the coupling of greenness with groundwater was weak, compared with natural flow regimes. We conclude that current water management and infrastructure have profoundly altered natural hydrology in a manner that has impacted riparian woodlands. This has manifested in subsidies to groundwater-dependent riparian ecosystems, which in turn, promote high aseasonal growth and function, but with little opportunity for regeneration or natural succession trajectories. These alterations have the potential to lessen the adaptive capacity of riparian vegetation communities in drylands, making them vulnerable and less resilient to climatic changes or water management decisions that affect subsurface water availability.

Results

NDVI and Groundwater Depth. The magnitude and variability of NDVI differ over time between the three riparian phreatophytic woodland communities and show strong spatial variations between hydrologic regions (Fig. 1 and *SI Appendix*, Tables S1–S3). DTG is a significant predictor of NDVI for all vegetation types, and in all cases greenness declines with deeper groundwater (Fig. 2 and *SI Appendix*, Table S4). The strongest effect (i.e., steepest negative slope) occurs in oak woodlands, in which the response is significantly different from willow, which has the most modest response to DTG (shallowest slope) among the three vegetation types (*SI Appendix*, Table S5). Cottonwoods exhibit an intermediate response, which does not differ significantly from either willow or oak. These rankings of groundwater dependence follow relative differences in maximum rooting depth among the three communities and their positions within the riparian landscape. As pioneer riparian species, cottonwood and willow colonize channel boundaries, young point bars, and low floodplains, with typical rooting depths of ≤2.5 m (42, 43) under natural conditions. The weaker NDVI response to DTG for willow woodlands compared with cottonwood and oak woodlands may reflect differences in fluvial niches. Riparian willows typically occur in locations with stable and shallow groundwater that support a narrower range of seasonal drought stress conditions than oak, and thus they lack deep root systems. Valley oak is a later successional species and is more drought tolerant in the riparian biome, occupying older and higher fluvial surfaces with rooting depths up to 24 m (44). The NDVI-DTG trends across vegetation types vary across hydrologic regions, with the most significant groundwater-dependent relationships occurring in the Central Coast, North Lahontan, Sacramento River, and South Coast (willow only) regions (*SI Appendix*, Fig. S2 and Table S6).

Surface Water Influences on NDVI and Groundwater Depth. Of the total statewide extent of riparian woodlands considered in this study (57,900 ha across all vegetation polygons), 30% of the

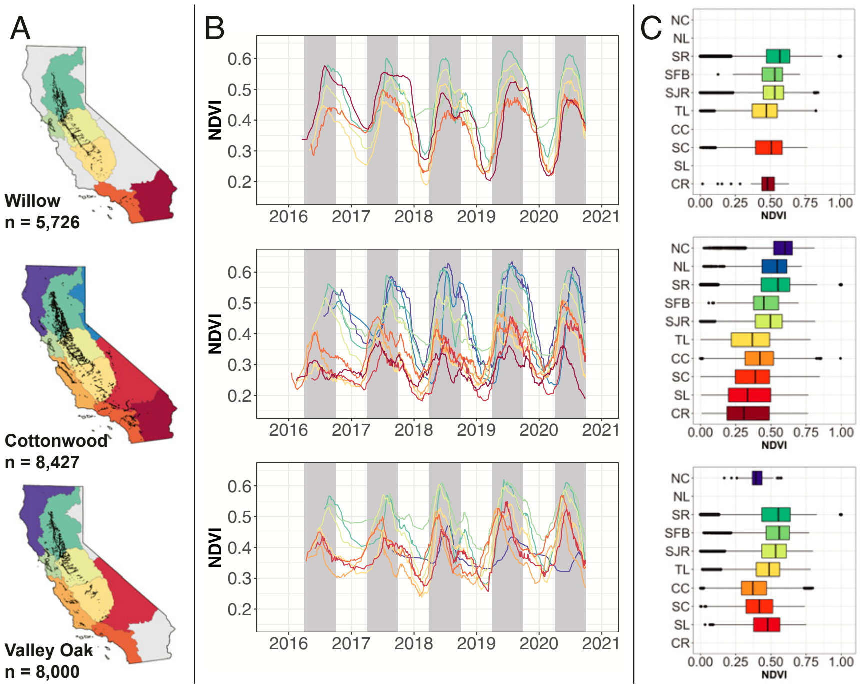

Fig. 1. NDVI trends by hydrologic region. (*A*) Spatial distribution of riparian vegetation types (black polygons) within each hydrologic region (colors). Hydrologic regions shaded in gray indicate those with no mapped polygons for that vegetation type. (*B*) NDVI time series with annual growing seasons (April–September; highlighted in gray) for willow (*Top*), cottonwood (*Middle*), and oak (*Bottom*) woodland vegetation types. Each line represents the median value for all mapped vegetation polygons within each hydrologic region. (*C*) Interquartile ranges (IQR; 25th to 75th quantiles) and median polygon values within the growing season. Outlying points beyond the minimum (Q1 − 1.5 × IQR) and maximum (Q3 + 1.5 × IQR) are plotted individually. Hydrologic regions include the North Coast (NC), North Lahontan (NL), Sacramento River (SR), San Francisco Bay (SFB), San Joaquin River (SJR), Tulare Lake (TL), Central Coast (CC), South Coast (SC), South Lahontan (SL), and Colorado River (CR).

woodland area occurs along natural stream reaches and 70% occurs along stream reaches with an altered regime (Fig. 3*A*). We compared the NDVI-DTG trends for each vegetation polygon that had locally available well data by its respective flow modification regime (natural or altered; $n = 582$ polygons). DTG was a significant linear predictor of riparian woodland NDVI in both natural and altered systems (Fig. 3*B*), but the effect was significantly stronger (steeper slope) for vegetation along natural streams (*SI Appendix*, Table S7). The more robust NDVI-DTG trend for natural streams, observed primarily in the Sacramento River, San Francisco Bay, and Central Coast regions, suggests a greater groundwater reliance. Specifically, we find that canopy water stress levels are directly linked to water supply via DTG, relative to altered streams where the relationship is weaker (*SI Appendix*, Fig. S3 and Table S8).

Distinct seasonal trends are evident in the NDVI-DTG relationships between the wetter northern regions compared with the drier regions in the south. In the Sacramento River region (*SI Appendix*, Fig. S4*A* and Table S9), for example, NDVI declines significantly with deeper DTG during spring and summer, and the negative NDVI-DTG slope is steeper in the summer. This suggests a stronger groundwater reliance later in the growing season when vapor pressure deficits (VPDs) are highest and soil moisture is low. The weaker influence of DTG on canopy greenness earlier in the spring may reflect both the lower VPDs, as well as greater water availability from prior precipitation and elevated snowmelt-driven streamflow along the Sacramento River and its tributaries. In contrast, the South Lahontan region in southeastern California has no significant NDVI trend with DTG in either season (*SI Appendix*, Fig. S4*B* and Table S10). In this region, riparian phreatophytes occur only as isolated patches of cottonwood woodlands along a portion of the Mojave River adjacent to a wastewater treatment facility. This facility provides a substantial perennial water source to the local river channel and its linked shallow groundwater aquifer (*SI Appendix*, Figs. S5 and S6). The lack of a relationship between groundwater depth and canopy greenness in this arid climate exemplifies the strong anthropogenic control over hydrology for riparian woodlands.

Flow alteration can be quantified by examining whether seasonal flows are inflated (subsidized) or depleted (abstracted) for riparian vegetation patches adjacent to streams with long-term gauge records. We investigated the effect of seasonal flow alteration by comparing the NDVI response of riparian vegetation patches along streams with inflated and depleted flows ($n = 1{,}891$ vegetation polygons; Fig. 3*C*). NDVI was lower in summer compared with spring for vegetation under both inflated and depleted flow alteration classes, which is consistent with the expected higher water stress in plants in summer due to reduced water availability ($\chi^2 = 744.21$, degrees of freedom [df] = 3, $P < 0.001$; *SI Appendix*, Table S11). However, in both seasons, riparian NDVI values along stream reaches with inflated flow were elevated, relative to depleted stream reaches. Seasonal differences in NDVI under both flow alteration classes suggest a tightly coupled vegetation response to the strong seasonal shifts in water availability from precipitation-derived soil moisture in spring toward perennial groundwater in this Mediterranean climate region. However, elevated NDVI along inflated streams (Fig. 3*C*) suggests more uniform water availability throughout the growing season, as a result of water subsidies associated with conveyance infrastructure and regulated streamflow regimes.

Discussion

Vegetation Greenness Decreases with Groundwater Depth. Across California, we found riparian woodlands to be very sensitive to groundwater depth both seasonally and across a wide range of regional hydrologic regimes. Riparian canopy greenness (NDVI), a

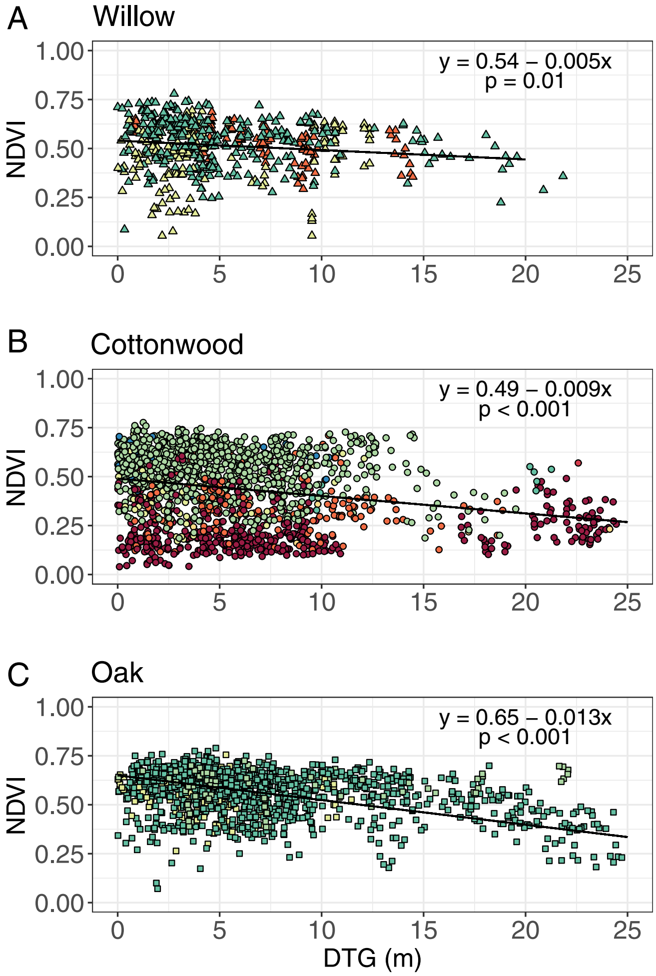

Fig. 2. Linear mixed-effects regression models of NDVI and DTG for (*A*) willow, (*B*) cottonwood, and (*C*) oak vegetation types. Each data point represents a vegetation polygon's spring or summer median NDVI value and the corresponding DTG data for a given year. The colors correspond to hydrologic regions (see Fig. 1).

measure of vegetation health, varied systematically with DTG during the growing season for willow, cottonwood, and oak woodlands (Fig. 2). In locations where deeper groundwater depths coincide with lower NDVI, decreased greenness can be attributed to a wide range of physiological responses, such as reduced transpiration and photosynthesis, increased intrinsic water use efficiency, drought-induced leaf abscission, branch and canopy dieback, and cavitation-induced mortality (6, 10, 11, 17). We observe a strong coupling of NDVI with DTG, particularly along natural streams, which is consistent with other studies that found positive correlations between NDVI and precipitation (25) and negative correlations between NDVI and groundwater depth (23–26). However, this study also identifies the influence of surface water flow regimes on mediating the NDVI and DTG relationship, which can be explained by the same processes of focused recharge through riverbeds that are common in drylands (45).

Riparian Vegetation Relies on Groundwater, but Some Are Being Subsidized by Managed Water Sources. Under natural conditions, groundwater reliance within California's Mediterranean climate biomes is expected to be highest in the late summer when precipitation is absent, soil moisture is low, evaporative demand is high, and surface water flow in rivers and streams is diminished (46). However, natural groundwater reliance may be disrupted by hydrologic subsidies due to anthropogenic alteration of streamflow. As human water demand and concerns about water security intensify, natural hydrology is increasingly altered through surface water diversions into canals and regulated rivers, extensive groundwater pumping, and significant discharges of recycled wastewater downstream of treatment facilities (36, 37). The consequences of groundwater pumping on deepening water tables and loss of water access by riparian plants are well documented (10, 47). What is less well understood is to what degree altered flow regimes that redistribute water in the dry season augment local shallow alluvial aquifers and provide a supplemental water supply for riparian vegetation (45).

Here, we show that along altered streams, NDVI is higher during the growing season with all other factors equal, and the adverse effect of groundwater depth on NDVI is diminished compared with natural stream systems (Fig. 3*B*). This strongly suggests that stream alteration, particularly inflated flows, subsidizes riparian phreatophytes, enabling them to maintain high photosynthetic function and water status even during periods of high VPD (Fig. 3*C*). This is especially the case in drier regions of California (e.g., San Joaquin River, Tulare Lake, South Lahontan), where there is a long history of groundwater depletion due to pumping, and most extant stands of phreatophytes occur along streams with inflated or perennial flow conditions due to human activities (e.g., wastewater treatment discharge or summer water deliveries). These results further suggest that a large proportion of California's native riparian woodlands are at least partially maintained by altered surface water regimes and built water infrastructure rather than by the historical and natural seasonal groundwater cycles to which they are adapted.

We provide a graphical conceptual model (Fig. 4) illustrating how NDVI varies seasonally across natural versus altered hydrologic regimes as a function of available subsurface water. Along natural streams, NDVI shows strong seasonal changes associated with greater net water deficit in summer (Fig. 4*B*) versus spring (Fig. 4*A*). Along altered streams, where baseflow discharge is often augmented by agricultural and municipal water conveyance schedules or perennial inputs of treated wastewater from urban areas, NDVI remains relatively high despite deeper regional groundwater levels in the summer (Fig. 4 *C* and *D*). These managed water regimes alter interactions between surface and groundwater, artificially subsidizing deeply rooted plants, enabling greater canopy function and productivity than would otherwise be possible during the annual dry season.

Despite the hydrologic stability that these subsidies provide to extant riparian woodlands, they disrupt natural ecological processes and life history stages of species that are adapted to the fluvial disturbance regime and seasonally variable hydrology of this Mediterranean climate region (17, 27). For example, seed release and dispersal success of native pioneer trees depend on spring flood timing (16), and low summer baseflows allow for them to establish and outcompete nonnative species with less-adaptive life histories (18, 19). Flood-driven channel migration and cutoff events, which are greatly reduced in altered systems, are critical processes for maintaining native riparian forests over time (48, 49). Although modified surface flow regimes that recharge aquifers can promote short-term growth and function of existing woodland trees, these flow subsidies promote the homogenization of forest age and size structure (in the absence of recruitment and succession processes), greater invasion by nonnative species, divergent forest succession, and ultimately the transition to novel ecosystems (50, 51). In addition, faster growth induced by water subsidies may promote earlier mortality, a phenomena that is observed globally across many biomes (52), in particular for broadleaf trees in dryland regions where drought mortality is common (53). Fast growth is associated with low wood density and high hydraulic conductivity, among other traits that make trees vulnerable

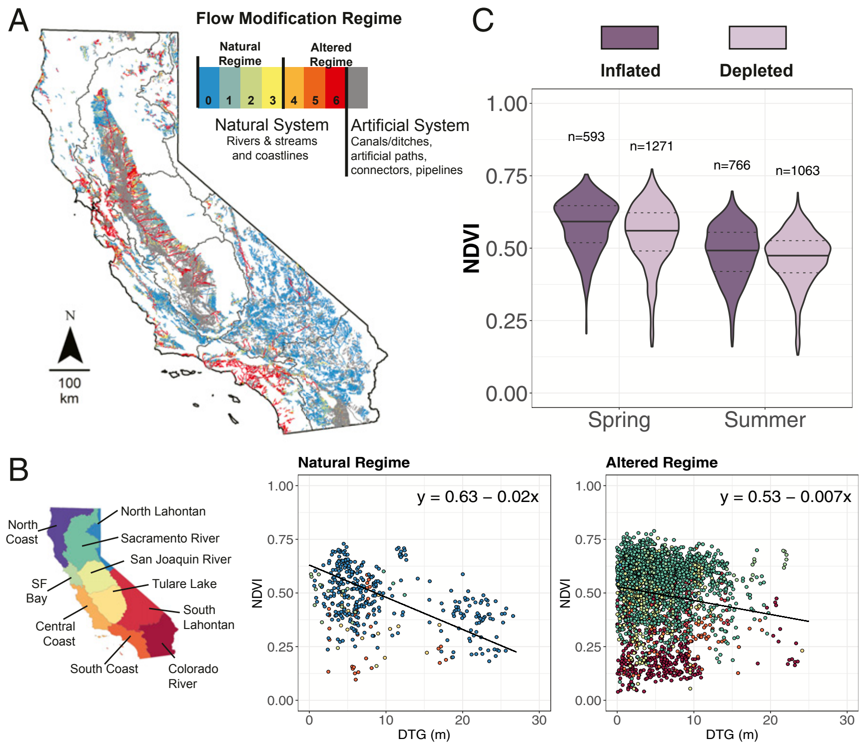

Fig. 3. Riparian vegetation responses (NDVI) to groundwater and flow regimes. (*A*) Flow modification regime for all waterways within California's groundwater basins ($n = 82,504$ waterway segments) (37, 59). (*B*) NDVI and DTG trendlines by flow modification regime (*A*) for vegetation ($n = 582$ polygons) within 1 km of a well included in this study. The NDVI-DTG trends are significantly different between flow regimes, with steeper slopes in natural versus altered regimes ($P < 0.001$). The colored points correspond to hydrologic regions indicated on the *Inset* map. (*C*) Median seasonal NDVI violin plots classified by flow alteration (inflated and depleted) for vegetation ($n = 1,891$ polygons) within 1 km of a stream gauge with observed and estimated flow data (60). The dashed lines denote the 25th and 75th percentiles and the solid line denote the 50th percentile. All groups were significantly different from each other ($P < 0.001$).

at an early age to drought cavitation, attack by pathogens and insect pests, and mechanical damage (53). Together, with other human stressors, including climate change, widespread hydrologic alteration in California, and other dryland regions, the long-term fate of native riparian woodlands is threatened, especially where there are ongoing tradeoffs between water diversions, water recycling, and instream ecosystem flow needs (4, 5). In light of the combined legacy of large-scale riparian woodland conversion to agriculture, groundwater overdraft, and weakened abiotic/biotic ecosystem linkages through flow alteration and water subsidies, the

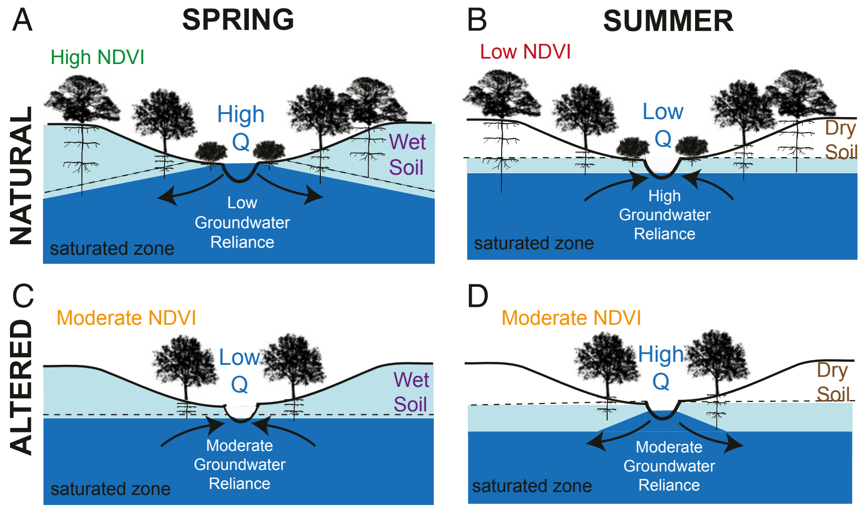

Fig. 4. Conceptual model of riparian vegetation reliance on groundwater under different seasonal and surface water influences: (*A*) natural streams, spring; (*B*) natural streams, summer; (*C*) altered streams, spring; and (*D*) altered streams, summer. Seasonal hydrologic variability of natural streams results in greater NDVI differences between spring and summer, compared with altered streams in which water subsidies minimize seasonal NDVI changes. Surface flow (Q) and groundwater are depicted in dark blue, soil moisture in light blue, and the capillary fringe is represented by the dashed line.

preservation of these crucial habitats for rare and endemic species now relies on the deliberate, coordinated management of resource and government agencies.

Remote Sensing Is a Promising Tool for Ecosystem and Resource Management. Prompted by the recent historic drought, California passed the Sustainable Groundwater Management Act (SGMA) in 2014 to minimize groundwater depletion and regulate its use (54). Under SGMA, local groundwater sustainability agencies are required to achieve sustainability by 2040 by bringing basins into balance and preventing adverse impacts to groundwater-dependent ecosystems (GDEs). There are significant theoretical and data gaps on the ecohydrology of GDEs across broad regions, including California, where the management challenges mirror those of many water-limited regions globally (30).

Achieving sustainable water management in California (and elsewhere) requires a science-based approach that is feasible and efficient to inform water allocation decisions and support multiple objectives. The coupling of high spatial and temporal resolution of Sentinel-2 satellite imagery with the powerful computing capacity of the Google Earth Engine platform (55) offers a new opportunity for practitioners to monitor regional changes in riparian vegetation in response to water availability, which can integrate ecological considerations into water resource planning and management decisions. By pairing Sentinel-2–derived NDVI data with concurrent field-based DTG measurements, water agencies can infer how groundwater conditions are affecting riparian vegetation communities in their basins so that appropriate thresholds and objectives are established in groundwater sustainability plans.

Conclusion

In this study, we found that vegetation greenness (NDVI) was decoupled from groundwater dynamics for riparian woodlands occurring along hydrologically altered streams compared with those along natural streams. This suggests that native riparian woodlands are opportunistic in their water use, but vulnerable to changes in water management that may subsequently threaten their long-term sustainability. Although altered flow regimes can offer supplemental water sources that alleviate seasonal drought stress, they also undermine the ecological processes and life history stages that are adapted to the hydrologic variability inherent in Mediterranean climates. Thus, the elevated canopy greenness and aseasonality evident in hydrologically altered riparian woodlands may be masking their extreme vulnerability to rapid hydrologic shifts or changes to water management. In the absence of restoration of natural hydrologic processes, the long-term sustainability of remnant native riparian woodlands in California may require extensive floodplain reforestation and similarly intensive water management approaches. The compound legacy of extensive conversion of riparian woodlands to agriculture and urban land uses and the wholesale disruption of natural surface and groundwater flow regimes, create major challenges for preserving and restoring remnant riparian habitats and their ecohydrologic functioning.

Materials and Methods

Vegetation Data Acquisition and Processing.

Vegetation data. The study comprised riparian vegetation throughout California dominated by phreatophytic woody species as delineated in the California Department of Water Resources' Natural Communities Commonly Associated with Groundwater (NC) dataset (56). The NC dataset contains 98,275 delineated polygons that correspond to vegetation types commonly associated with groundwater (phreatophytes), and we identified three deciduous vegetation alliances (n = 22,153 polygons) representative of riparian environments along large-order streams throughout the state: 1) *P. fremontii* (cottonwood); 2) *S. gooddingii* (willow); and 3) *Q. lobata* (valley oak). Details of the dataset are provided in *SI Appendix*.

Satellite imagery processing. We compiled, processed, and analyzed Sentinel-2, level-1C satellite imagery acquired between June 23, 2015 and September 30, 2020 for the riparian woodland polygons using Google Earth Engine (55). A supervised classification was performed to include only vegetation canopy pixels by masking out those dominated by bare ground. NDVI, a common index used in remote sensing to quantify vegetation "greenness," was calculated for crown-classified pixels within the vegetation polygons; data processing and analysis details are presented in *SI Appendix*. NDVI is a dimensionless index that ranges from −1 to 1, where values closer to 1 indicate vegetation with a higher density of green leaves, values close to zero (<0.20) indicate no vegetation, and values <0 denote the presence of surface water.

Hydrology Data Acquisition and Processing.

Groundwater. Groundwater level data from observation wells (n = 3,951) were downloaded from the California Department of Water Resources' SGMA Data Viewer (57). Wells that monitor groundwater within shallow unconfined aquifers were selected because roots of riparian phreatophyte species typically do not penetrate confining layers or extend >30 m below the ground surface (42, 58). DTG was calculated for riparian vegetation by subtracting the groundwater elevation at the closest shallow monitoring well from the averaged land surface elevation of each vegetation polygon; data processing details are presented in *SI Appendix*. After selecting vegetation polygons that met our selection criteria of being <1 km from a shallow groundwater monitoring well with measurements within the study period (June 23, 2015 and September 30, 2020), 747 polygons from the NC dataset were selected for evaluating recent trends between groundwater and vegetation.

Because the groundwater level and NDVI data were collected on different dates and at different frequencies (e.g., biannual groundwater levels versus NDVI ∼10 d), NDVI data were linearly interpolated to derive a daily NDVI measurement for each vegetation polygon, which could then be matched with observed groundwater level data. To avoid temporal autocorrelation due to polygons sampled repeatedly within a season, median values of NDVI and DTG were calculated for each polygon according to season for all years in the study (2016 to 2020) for spring (April–June) and summer (July–September). Because all three vegetation types in this study are winter deciduous, only NDVI and groundwater data with paired dates within the growing season (spring and summer) were included in this study. These comprised 3,560 paired observations from 591 vegetation polygons.

Streamflow data. We designated all stream reaches adjacent to riparian woodland polygons into two groups—natural or altered flow regimes—based on the National Hydrography Dataset (NHD) drainage features (e.g., rivers, streams, canals/ditches, and pipelines) (59) and the US Geological Survey national flow modification dataset (e.g., high and low flow magnitude, variability, and duration) (37); data processing and analysis details are presented in *SI Appendix*.

Statewide streamflow data were accessed from The Nature Conservancy's Natural Flows Database (60), which contains observed streamflow data from stream gauges (n = 1,241 stream segments) and estimates of natural flows (expected streamflow in the absence of human modification) for all streams and rivers in California (n = 171,167 stream segments) from 1950 to 2015 (36). We identified 1,891 vegetation polygons included in this study that were within 1 km of a river reach and had at least 5 full years of monthly observed and estimated flows between 1996 and 2015 (n = 89 stream segments). To quantify the degree of flow alteration by stream reach, we calculated a monthly ratio of observed/estimated streamflow. Data processing and analysis details are presented in *SI Appendix*. We then classified the streamflow within each stream reach as "depleted" if the median observed/estimated ratio was <1, indicating that more than half of the recorded observed flows within a season were less than the expected value for that location. Streamflow was classified as "inflated" if the median observed/estimated ratio was >1. This conservative approach tests whether differences in NDVI can be explained by the degree of flow alteration and whether these differences are distinct for inflated (subsidized) versus depleted (abstracted) flows. If flow alteration is not an important explanatory variable of NDVI, all these distributions should be equivalent (statistically similar).

Statistical Analyses. All data analysis and statistical tests were performed using the programming language R (R Core Team, version 3.6.1) (61). Comparisons of NDVI and DTG relationships among vegetation types, hydrologic regions, and seasons were made using linear mixed models (*lme4* and *lmerTest* packages) with random effects for polygon (to account for repeat measurements in multiple years) and for hydrologic region (to account for similar climate and environmental conditions). Post hoc pairwise comparisons were made using Tukey's estimated marginal means (*emmeans* package). NDVI and DTG relationships were determined using a linear mixed model (*lmer* function) by designating season as a fixed effect and polygon identification (ID) as a random effect. Wilcox and Kruskal tests were used for a pairwise comparison of median NDVI across seasons and flow alteration classes (inflated and depleted). Goodness of fit for linear mixed models (62) was determined using the (*MuMIn* package); see *SI Appendix* for details. Our analyses utilize a statistical significance threshold of $P < 0.05$.

Data Availability. Data inputs from public sources, code and statistical analyses used in this study are all publicly available in the Environmental Data Initiative repository (DOI: 10.6073/pasta/0a599dd64ae648a2de6c3d57069b0b5c). The code are also publicly available in a GitHub repository (https://github.com/melrohde/CA_RiparianGDE).

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