Drought Stress of Riparian Woodlands from Groundwater Decline and Climate Change: Ecosystem Indicators at Multiple Scales

Stress Hydrique des Forêts Riveraines dû au Déclin des Eaux Souterraines et à la Sécheresse: Indicateurs Écosystémiques à Diverses Échelles

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RÉSUMÉ

Bien que l'on pense que les forêts riveraines des régions arides sont protégées contre le stress hydrique par leur position paysagère et leur hydrologie favorable, le changement climatique et l'extraction des eaux souterraines menacent leur durabilité à long terme. Nous synthétisons ici les résultats sur la réponse des forêts riveraines pendant et après la sécheresse exceptionnelle de Californie (États-Unis) de 2012–2019 à partir d'études à différentes échelles spatiales et temporelles. Nous avons couplé des études de cernes d'arbres de peupliers riverains sur la rivière Santa Clara avec une analyse de télédétection à l'échelle du bassin pour comparer le moment et la sévérité de la réponse des indicateurs. Les arbres individuels ont montré de fortes réductions de la croissance radiale et de la discrimination des isotopes du carbone ($\Delta^{13}C$), indiquant un stress hydrique sévère qui était davantage déterminé par le taux de déclin des eaux souterraines que par les facteurs climatiques. Ce modèle a été renforcé à l'échelle du paysage, où nous avons observé une diminution de la verdeur de la canopée et une augmentation de la biomasse morte progressant vers l'aval de 2012 à 2016. Dans l'ensemble, il y avait des relations cohérentes entre la profondeur des eaux souterraines, la santé de la canopée végétale et la fonction des arbres, indiquant que la condition de la forêt s'est détériorée de façon prévisible à mesure que la nappe phréatique diminuait à différents endroits et à différents moments. Ensemble, ces études permettent le développement d'indicateurs complémentaires de sensibilité au climat et aux eaux souterraines pour aider à gérer les forêts riveraines vulnérables confrontées au changement global.

ABSTRACT

Though riparian woodlands in dryland regions are thought to be buffered against water stress by their landscape position and favorable hydrology, climate change and groundwater extraction increasingly threaten their long-term sustainability. Here we synthesize findings on the water stress response of riparian woodlands during and after the exceptional California (USA) drought of 2012–2019 from concurrent studies at different spatial and temporal scales. We coupled tree-ring studies from riparian stands along the Santa Clara River with a basin-scale remote sensing analysis to compare the timing and severity among indicators. Individual trees showed strong reductions in radial growth and carbon isotope discrimination ($\Delta^{13}C$), indicating severe drought stress which was determined more by the rate of groundwater decline than by climate drivers. This pattern was reinforced at the landscape scale, where we observed decreased canopy greenness and increased dead biomass progressing in a downstream direction from 2012 to 2016. Overall there were consistent relationships between groundwater depth, healthy vegetation cover, and tree growth and function, indicating that woodland health deteriorated in a predictable fashion as the water table declined at different sites and different times. Together these studies pave the way for developing complementary climate and groundwater sensitivity indicators to help manage vulnerable riparian woodlands experiencing global change.

KEYWORDS

Drought stress indicators; riparian forests; groundwater dependent ecosystem; dendroecology; hyperspectral remote sensing

1 INTRODUCTION

1.1 Background

Though riparian woodlands are thought to be buffered against water stress by their landscape position and favorable hydrology, climate change combined with groundwater extraction increasingly threaten their long-term sustainability, particularly in dryland regions. Global trends toward hotter and drier conditions may contribute to groundwater declines that push these systems past a threshold of resilience. Over the last decade, California (USA) experienced its most extreme drought on record, with soil moisture depletion and severe reductions in groundwater availability during the peak drought period from 2013–2016. During this period, groundwater levels declined statewide, in some cases dropping 30 m or more over a few years.

The effects of drought on woodland ecosystems can be observed in water stress indicators at different levels of resolution and from different vantage points. The challenge is to understand, and then subsequently predict how trees and whole stands respond at the outset of drought, during its peak, and afterwards. At the individual tree level, we can study how growth and function respond using tree ring indicators, including annual radial growth and carbon stable isotope composition of the wood. Carbon isotope discrimination, expressed as Δ13C, provides a relative measure of water stress. Over the course of a drought, discrimination decreases with reduced transpiration induced by higher water stress, and radial growth also declines, because the reduced gas exchange limits photosynthesis.

At a much broader scale, canopy-level and river corridor scale indices are observed from remote sensing platforms such as airplanes and satellites (Rohde et al., 2021). With hyperspectral imagery, using many electromagnetic wavelengths, we can use mixing models to determine the proportion of a forest stand with green vegetation cover, or GV, versus non-photosynthetic vegetation, or NPV, which represents dead biomass. Canopy dieback events show as large reductions in GV and increases in NPV over time.

1.2 Research questions and approach

We set out to understand the effect of the 2013–2016 California drought on groundwater-dependent riparian woodlands. Specifically we asked:

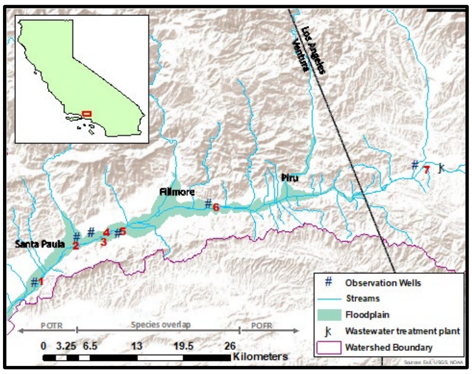
- *What are reliable indicators of drought stress for individual trees and landscape-wide?*
- *How does severity of drought effects vary in space and time across indicators?*
- *Are there lags and thresholds relevant to ecosystem recovery and management?*

We were especially interested in understanding which indicators express drought stress earliest, most dependably and how these may inform ecosystem predictions and protection. In the field, we selected riparian woodland sites distributed along a climate gradient that varied in impact severity. We cored trees and measured their radial growth and carbon stable isotope ratios for the decade spanning the drought. We coupled the tree and stand level measurements with hyperspectral imagery from the NASA HyspIRI airborne platform, and analyzed live and dead vegetation change using spectral mixing models (Kibler et al., 2021; Rohde et al., 2021). These studies together allowed us to observe riparian responses to drought in space and time through different indicators.

2 METHODS

2.1 Study system

Our study system was the Santa Clara River. the largest river in southern California that is largely natural, flowing from the Mojave Desert to the Pacific Ocean in Ventura and Los Angeles Counties. The basin has a Mediterranean climate with cool, wet winters and warm, dry summers, and many reaches of the Santa Clara River are ephemeral. The river corridor has been subject to extensive urban and agricultural development over the last century, but the main stem of the river has not been severely altered or diverted.



Santa Clara River study system in California.

For the tree-ring study, we cored 114 cottonwood trees (*Populus fremontii and P. trichocarpa*) from seven sites along a climate gradient throughout the river corridor varying in drought impact severity. The hyperspectral imagery covered the entire river corridor, and we analyzed vegetation change at sites that historically supported isolated forest stands (called *cienagas*).

3 RESULTS

3.1 Tree-ring study

During the drought, water table recession ranged 0.1—1.75 m/year with some of the fastest rates in 2015 and 2016. Groundwater decline induced drought stress in the riparian cottonwoods, with the strongest response as sites with the highest recession rates (Fig. 2A). Tree ring cellulose values of carbon isotope discrimination, Δ^{13}C, shifted from their pre-drought baselines in site-specific patterns that matched the local groundwater dynamics (Fig. 2B). The greatest change in tree growth and function occurred at sites with recession >0.5 m/yr. In addition, there was a depth threshold of approximately 4-5 m that initiated reductions in growth and function. This threshold matches published values of maximum rooting depth for cottonwoods.

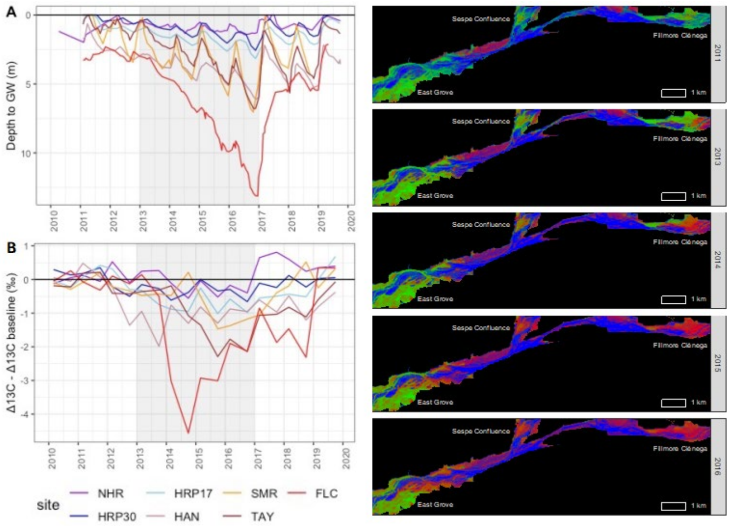


Figure 2. (A) Groundwater series from seven sites, with grey shading indicates the peak drought years. (B) Mean tree Δ^{13}C deviation from pre-drought baselines at each site. (C) Hyperspectral imagery showing progression of the drought each year, 2011-2016.

3.2 Remote sensing of canopy greenness

The hyperspectral imagery showed there was a progressive ‘brown wave’ of tree mortality, characterized by decreases in healthy vegetation cover, or GV in green, and increases in dead biomass, shown as NPV in red, which progressed downstream from east to west between 2013 and 2016 (Fig. 2C; Kibler et al., 2021). Blue regions are non-vegetated areas. There were significant relationships between groundwater depth and vegetation condition, which deteriorated in a predictable way as the water table declined at different sites and different times. The effects become most severe beyond approximately 5 m, where the fraction of dead vegetation area surpasses that of live plant cover.

4 KEY FINDINGS AND CONCLUSIONS

Water Stress Indicators at vastly different scales confirm the groundwater dependence of dryland riparian woodlands, particularly during drought. Reductions in leaf gas exchange, growth and canopy green vegetation follow groundwater level decline more than climate indicators. Numerous lines of evidence suggest that riparian woodland health declines when DTG > 4-5 m or when water tables recede faster than 0.5m per year (Kibler et al., 2021; Rohde et al., 2021)

The effects on growth, leaf function and canopy greenness occurred concurrent with, and sometimes following the start of water table recession. Importantly, there are no clear prior warning signals across any indicators. Therefore, riparian monitoring programs should focus on high-frequency water depth measurements at monthly intervals or less. Groundwater depth is a master driver for many aspects of riparian woodland health. Because many regions lack adequate shallow monitoring well networks, these should be prioritized wherever groundwater depletion is a threat.

5 ACKNOWLEDGEMENTS

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