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Vegetation responses to climatic and geologic controls on water availability in southeastern Arizona

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Abstract

Vegetation distribution, composition and health in arid regions are largely dependent on water availability controlled by climate, local topography and geology. Despite a general understanding of climatic and geologic drivers in plant communities, trends in plant responses to water distribution and storage across areas under different local controls are poorly understood. Here we investigate the multi-decadal interactions between spatial heterogeneity of geologic controls and temporal variation of climate, and their impacts on water availability to vegetation and plant responses (via normalized difference vegetation index, NDVI) in a monsoon-driven arid region of southeastern Arizona. We find that grasslands display low NDVI and respond directly to monsoonal rainfall. In the uplands, vegetation on west-facing slopes and in canyons share similar NDVI averages and variability, suggesting that they both use water from surface-groundwater flow paths through fractured rocks. Along the San Pedro River, streamflow, groundwater, and NDVI in deciduous riparian woodlands are strongly responsive to monsoonal rainfall, but water availability stratifies between wet (perennial), intermediate, and dry reaches, underlain by different local geologic controls that affect water table elevation. These controls interact with the driving climate to affect water availability in the shallow alluvial aquifer of the riparian zone, a primary water source to the gallery phreatophytes. A recent shift toward a strengthened monsoon in the region has led to an increase in water availability for grasslands and for dry reaches of the San Pedro, while the benefit is more muted along wetter reaches, where the riparian forest shows signs of having reached its maturity, with diminished trends in NDVI. These results have implications for the future vulnerability of dryland vegetation to climate change, which may be either dampened or intensified by local controls such as geology.

1. Introduction

Plants in dryland ecosystems may experience differential seasonal access to water and distinct long-term trends in their responses to water availability changes, based on rooting depth, as well as the local expression of hydrology and water storage at their rooting location. Thus, changes to the climatically controlled water cycle in an arid region, where water availability is the main limiting factor to plant growth, can have important consequences for vegetation distribution, health and functioning (Shafroth *et al* 2000, Loik *et al* 2004, Caylor *et al* 2005, Tietjen *et al* 2009, Stella *et al* 2013, Singer *et al* 2014). Precipitation brings water to the land surface where it may become available to vegetation as a function of local storage, yet the amount and distribution of water (in stream-flow, soil moisture and groundwater) depends on the rainfall intensity, duration, location and seasonal distribution throughout the year, as well as the fluxes in the hydrological cycle including evapotranspiration, infiltration of rainfall into the soil, runoff generation, and percolation to aquifers.

A key unknown is how spatial variations in subsurface geology along dryland riparian systems affect plant-water interactions and corresponding ecosystem responses to climate-controlled variations and shifts in water availability. In arid environments, where evapotranspiration exceeds precipitation, vegetation is typically concentrated at locations in the landscape where runoff accumulates and/or where the water table is close to the surface (Dawson and Ehleringer 1991, Patten 1998, Lite and Stromberg 2005, Rodriguez-Iturbe *et al* 2007), yielding potentially strong differences in vegetation types and density across a region with the same driving climate depending on the local geologic controls and geomorphology (Caylor *et al* 2005, 2009, Franz *et al* 2010). Lowland riparian forests in arid regions, for example, may have frequent access to water from multiple, seasonally mixed water sources (Singer *et al* 2014), in contrast to open grasslands, shrubs, and trees growing on slopes, which are prone to more seasonal dryness and susceptible to drought (Allen and Breshears 1998, Breshears *et al* 2005). Although lowland riparian forests have a small footprint in arid landscapes, they represent critical moisture and thermal refugia for a range of species, many of which may be considered threatened or endangered (Stromberg *et al* 1996, Seavy *et al* 2009, Albright *et al* 2017). However, dryland riparian forests are vulnerable to shifts in climate that affect root zone water availability to the key plant species because they cannot expand their range (Malagnoux *et al* 2007, Loarie *et al* 2009, Bertrand *et al* 2011, Reidmiller *et al* 2018), making them sensitive to climate change.

Our goal in this paper is to address how climate variation through time and/or geologic controls in space affect water availability to vegetation growing across a diverse landscape under the same climate regime by using various time series datasets including satellite-derived vegetation density, groundwater wells, as well as streamflow and rainfall gauges. We leverage these datasets to provide a general understanding of the controls on water availability and vegetation community responses across a dryland region. Our premise is that if we can better improve understanding of the climatic forcing on water availability to vegetation in the recent past, we can better predict how vegetation will respond to climate change in the coming years.

Conceptually, we consider how water from rainfall travels through the landscape in a mountain front recharge system, and how groundwater and surface flow (and soil moisture) affect vegetation communities distribution and composition (figure 1).

2. Data and methods

2.1. Study area

This study was conducted in the Sonoran Desert in SE Arizona (figure 2), in an area where low and flat stretches of desert are interrupted by isolated small mountain ranges called the Sky Islands, such as the Huachuca Mountains (figure 2(a)). Crossing this desert is the San Pedro River, a free-flowing river characterized by a series of perennial and intermittent reaches (Leenhouts *et al* 2006, Stromberg and Tellman 2012, p 377) fed by both local groundwater discharge from surrounding mountains and summer monsoon precipitation (Baillie *et al* 2007, Stromberg and Tellman 2012, p 292, Thomas and Pool 2006). Between the late 19th and early 20th centuries, the San Pedro underwent entrenchment, followed by channel widening (Heord and Betancourt 2009), which led to shifts in vegetation in some reaches. The studied stretch of river is around 60 km long and is part of the San Pedro Riparian National Conservation Area (SPRNCA), created in 1988, which resulted in removal of cattle grazing and agriculture from the riparian zone (Stromberg and Tellman 2012, p, 371). The SPRNCA is home to various riparian vegetation communities dominated by Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*) near the river, and mesquite (*Prosopis velutina*) forest and grasslands on an elevated relict floodplain (Leenhouts *et al* 2006).

The Huachuca Mountains, with their highest peak ~1500 m above the surrounding desert, are covered by a mixed forest of conifers and oaks, and the canyons support a narrow riparian corridor. The riparian forest species composition is largely dependent on elevation and the presence of perennial water, as these canyons display a series of dry and flowing reaches along their length, due to fractures within the underlying rocks (Shaw 1999, Jaeger and Olden 2012). In between the mountains and the San Pedro River lies a broad area of grasslands: a mix of grasses and shrubs, dissected by ephemeral washes (arroyos). The geology under the San Pedro River is comprised of various units of varying permeability to water (figure 3). The southern reaches are underlain by deposits of sand with layers of silt and clay that act as confining beds, holding the water close to the surface and allowing for an upward flow along gaining reaches (Pool and Coes 1999, Blakemore 2006). Around Charleston, an outcrop of low-permeability granitic and volcanic bedrock keeps water at the surface and the river flows year-round reliably. In contrast, the north half of the study site

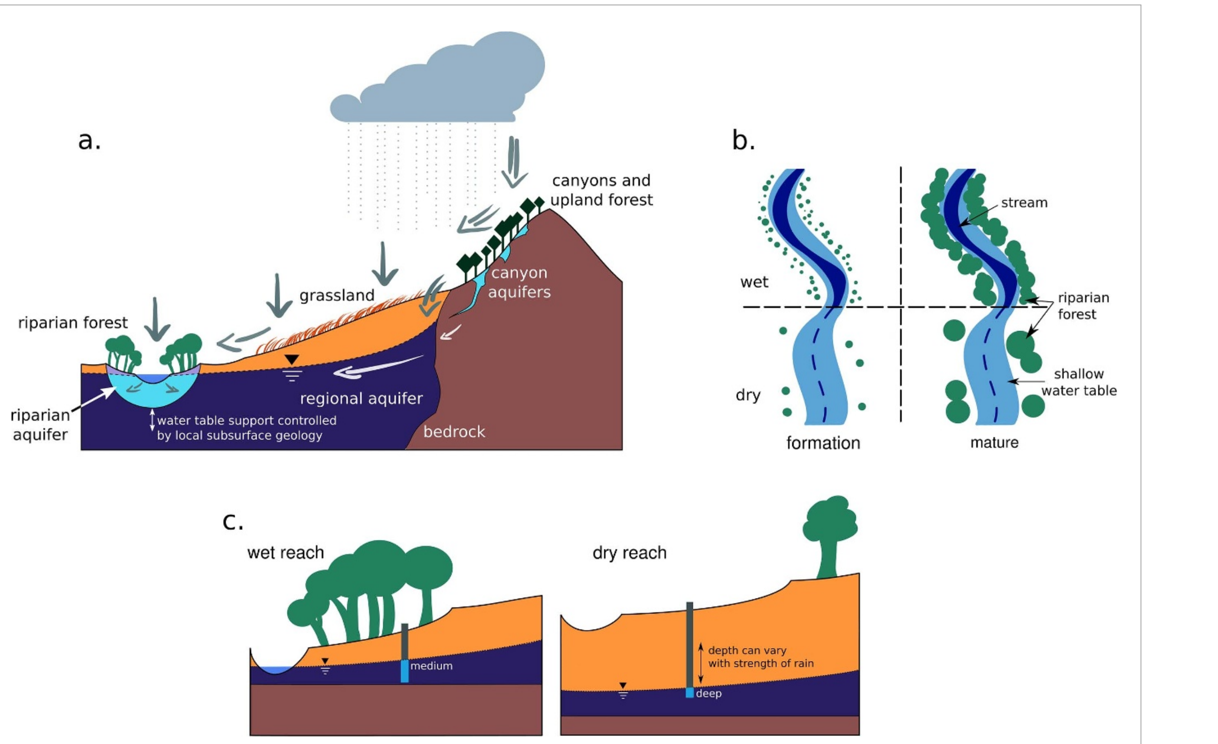

Figure 1. Conceptual model showing the path of water through the landscape and the location of each vegetation community studied (rainfall water going down the canyons and seeping in fractures to be used by upland and canyon vegetation, then reaching the deep regional aquifer before reaching the river and interacting with streamflow, providing a stable water source for the riparian trees while the grasslands have to rely on rainfall) (a), a view of the river showing the temporal changes experienced within the riparian forest along the stream (the growth of a riparian corridor for the wet reach, and scattered trees in the dry reach (b), and a view showing the underlying geology of the wet and dry reaches, as well as the response of water table depth to precipitation (depth reached during the drier month of the year) (c).

is underlain by sand and gravel, enabling high transmission losses under the stream, resulting in losing (intermittent/ephemeral) reaches (Pool and Coes 1999, Blakemore 2006, Quichimbo *et al* 2020).

This region is under the influence of the North American monsoon, which leads to large seasonal variations in precipitation (Loik *et al* 2004, Vera *et al* 2006). At a more local scale, topography and orography also affect precipitation patterns (Loik *et al* 2004). Rainfall mainly occurs during two distinct wet seasons: the monsoon (July to September) and during winter (December to March), whereas spring and autumn are largely dry. Only intense monsoon rainfall generates significant ephemeral runoff in this region, while winter streamflow in major streams is largely controlled by groundwater (Osborn and Lane 1969, Simpson *et al* 2013, Singer and Michaelides 2017).

2.2. Datasets and methods

We selected cloud-free images from the Landsat Earth Observation Satellite Program, contrasting those from summer (June) and autumn (October) (see supplementary table S1 for all dates used), to understand the impact of the summer monsoon and winter rains on vegetation. Pre- and post-monsoon time series were thus built from 1986 to 2017. To measure how vegetation changed over time (both as long-term changes and inter-annual responses to climate variability), we used the normalized difference vegetation index (NDVI; Rouse *et al* 1974), which provides information on canopy density and chlorophyll content (Bannari *et al* 1995, Kerr and Ostrovsky 2003, Yang 2007, Yang *et al* 2012, Lawley *et al* 2016):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}.$$

NDVI ranges between 1 and −1, where negative values represent water and higher positive values represent high canopy density. Data from Landsat-5 and Landsat-8 were homogenized after Goulden and Bales (2019), and all cloudy images were removed from the analysis.

We mapped the study area vegetation using the US Department of Agriculture's National Agriculture Imagery Program (NAIP) imagery (www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/), classified by communities that occur in different parts of the landscape and have potentially different access to water: (a) cottonwoods (*Populus fremontii*) of the San Pedro riparian forest, (b) open grasslands, (c) fir-oak forest in the Huachuca Mountains and (d) riparian forest along the canyons of the Huachuca Mountains. For each vegetation class, we defined a mask covering an area with a homogeneous land cover based on NAIP images and a cloud of random points was drawn in

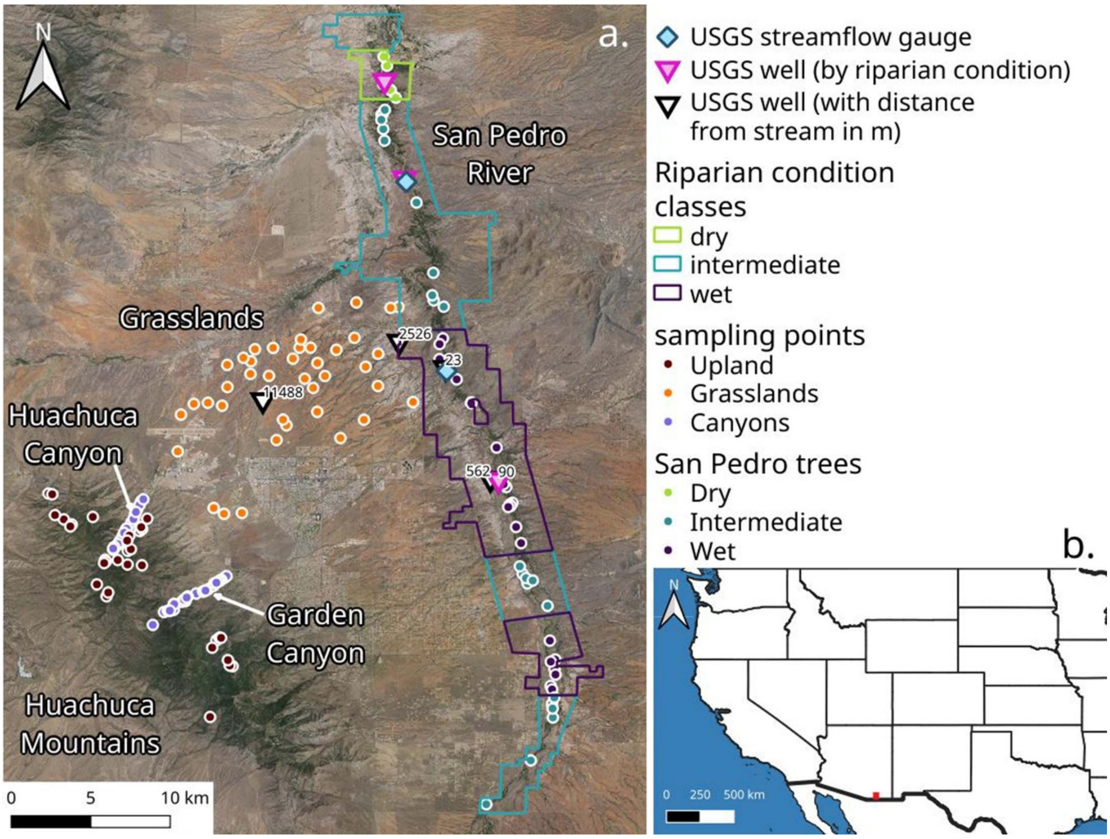

Figure 2. Study area (National agriculture imagery program image), hydrologic stations, and sampling points used for the NDVI analysis, split by vegetation community (a), location of the study site (b). Riparian condition classes are from Stromberg et al (2006).

this area (see supplementary table S2 for number of points for each class). NDVI values for the points were then extracted for each year (both pre- and post-monsoon). For the trees of the San Pedro corridor, we created separate masks to stratify the vegetation responses within different categories of flow permanence (wet, intermediate and dry reaches), based on the riparian condition classes mapped by Stromberg *et al* (2006) from vegetation traits sensitive to changes in streamflow permanence and/or groundwater levels (see supplementary methods S1 for details on the riparian condition index). Trends were quantified by linear regression of NDVI over time.

Local hydrology data came from two different datasets. Daily rainfall data came from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center's Unified Gauge-Based Analysis of Daily Precipitation (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html). This dataset is provided on a 0.5° × 0.5° grid and we used the grid cell covering both the Huachuca Mountains and the San Pedro River. Daily streamflow and water table depth data for the time period overlapping with the NDVI dataset were acquired for selected locations in the study area from the US Geological Survey's National Water Information System (https://waterdata.usgs.gov/az/nwis/) (figure 2 and see supplementary tables S3 and S4 for gauges and wells numbers). We also used interpolated monthly potential evapotranspiration (PET) data provided by the Climatic Research Unit (https://catalogue.ceda.ac.uk/uuid/89e1e34ec3554dc98594a5732622bce9). PET takes into account atmospheric parameters such as temperature and wind and their effect on water demand by plants. This dataset shows no trend in PET over the 1986–2017 time period for our study site (see supplementary figure S1), meaning that the variations in NDVI are not caused by a change in atmospheric demand.

NDVI data were used to produce violin plots comparing NDVI values and trends across vegetation communities, flow permanence and season. Wilcoxon–Mann–Whitney rank sum tests were performed between seasons and vegetation communities to highlight significant differences (see supplementary tables S5–S8 for all *p*-values). We plotted hydrological time series to identify the relative contributions of monsoon and non-monsoon precipitation, and we analyzed groundwater wells data to explore spatial patterns in water table elevation, variability, and temporal trends.

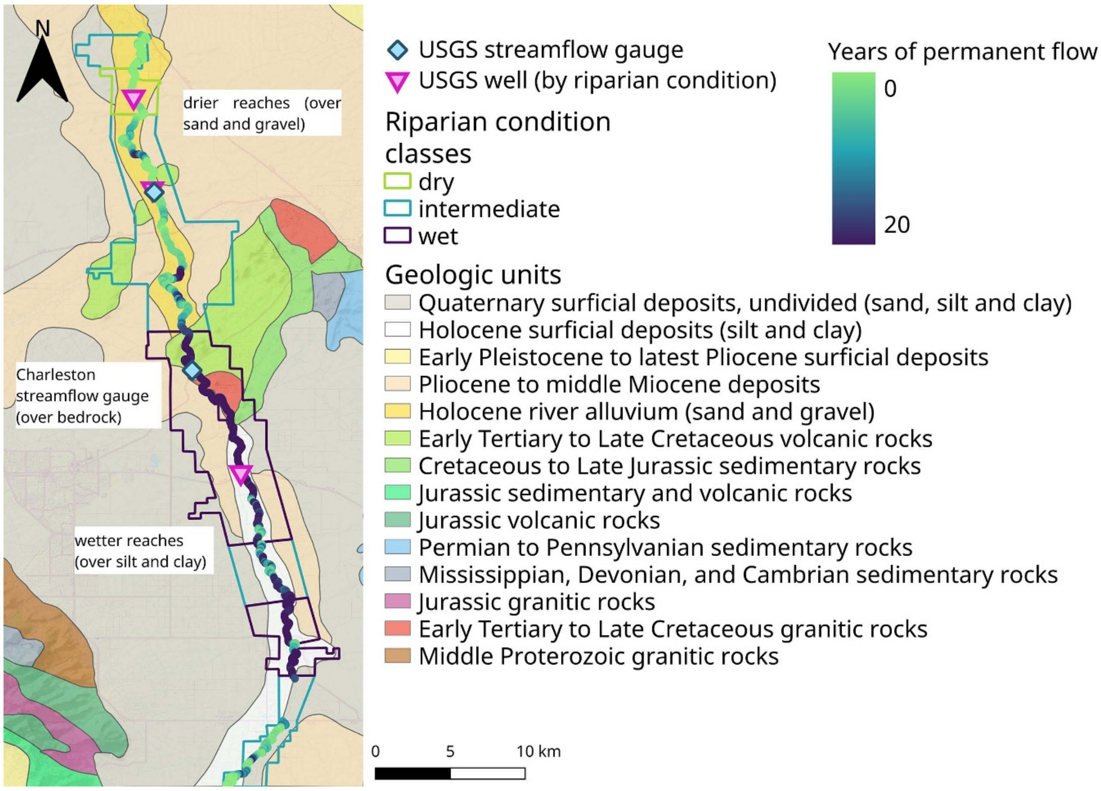

Figure 3. Geologic map of the San Pedro River and its surroundings showing the geologic units (from https://mrdata.usgs.gov/geology/state/), the riparian condition (from Stromberg *et al* 2006; see supplementary methods S1, available online at stacks.iop.org/ERL/16/064029/mmedia) and the flow permanence (provided by Lisa McCauley from The Nature Conservancy, more information available here: https://azconservation.org/projects/water/wet_dry_mapping).

3. Results

3.1. Vegetation

The distribution of NDVI values for each vegetation class highlights the difference between sparse, small vegetation in the grasslands (NDVI median under 0.2) and trees (median always above 0.4) (figure 4(a)). Some vegetation communities display a strong response to the monsoon rains with an important green-up mostly noticeable for the grassland, the upland forests and the canyons ($P < 2 \times 10^{-16}$), while the San Pedro riparian forest is less responsive ($P = 8.6 \times 10^{-5}$) (figure 4(a)). Examining the San Pedro riparian cottonwoods more closely in relation to flow permanence, trees in all reaches show a significant increase in NDVI values after the monsoon, though the wet reach display the smallest increase ($P = 6.8 \times 10^{-6}$) while the intermediate and dry reaches show a stronger increase in canopy density or chlorophyll content ($P = 2.7 \times 10^{-8}$ and $P = 6.2 \times 10^{-8}$, respectively) (figure 4(b)).

A linear trend analysis was performed over the 30 years of the time series as a means to examine the long-term changes in vegetation over the whole study area (figure 5). This analysis highlights multi-decadal differences between the various vegetation communities. Riparian areas along the San Pedro River tend to have increasingly dense vegetation through time, with rising NDVI values (median annual trend of $\sim 10^{-5}$). In contrast, grasslands and mountain vegetation (both upland and canyons trees) show no annual trend, or a negative trend for upland forests (median of -6×10^{-6} for pre-monsoon upland) (figure 5(a)). Along the San Pedro, the NDVI trends depend on flow permanence, with wet and intermediate reaches characterized by a wide distribution but an overall increase (median $> 10^{-5}$) and dry reaches displaying a narrower range of values and a median $< 10^{-5}$ (figure 5(b)). The wet and intermediate pre-monsoon values are also significantly different from the dry reach values.

3.2. Hydrology

Total rainfall in the study area does not show a trend ($r = 0.005$; $p = 0.239$), but the seasonal distribution of rainfall during the year appears to be shifting (figures 6(a) and (c)). Monsoon rains are slightly increasing ($r = 0.005$; $p = 0.08$), while winter precipitation is significantly decreasing ($r = -0.01$; $p = 0.004$). Furthermore, monsoon precipitation exceed winter precipitation since 2005 (figures 6(a) and (c)), based on means of 250 mm and 109 mm, respectively. This precipitation shift can also be seen in the San Pedro

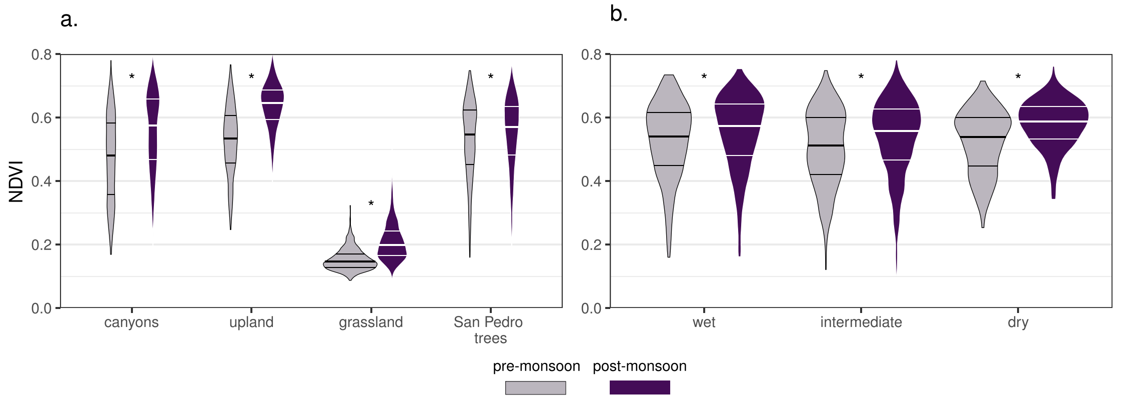

Figure 4. Distributions of pre-monsoon and post-monsoon NDVI over time (1986–2017) for the Huachuca Mountains canyon riparian vegetation, upland forest, riparian trees along the San Pedro River and grasslands (a) and flow permanence (b). Violin plots showing median and interquartile range, asterisks indicate significant differences between pre- and post-monsoon ($P < 0.05$).

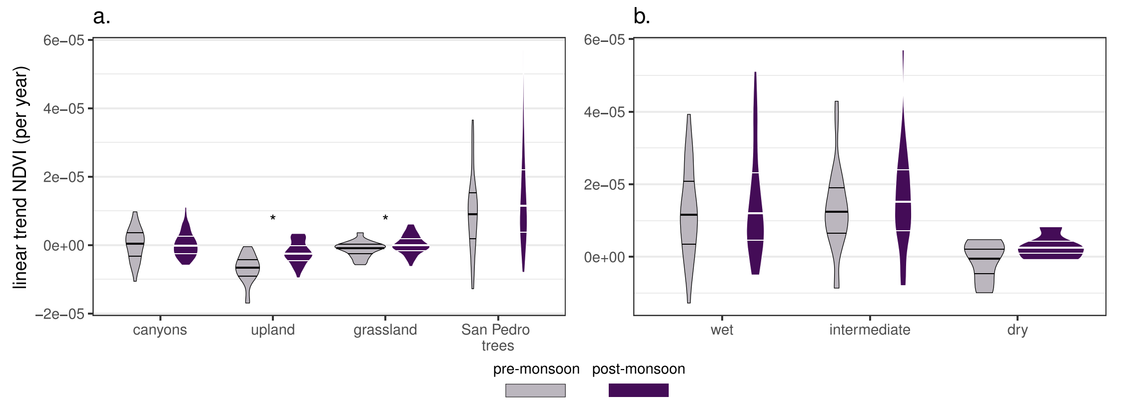

Figure 5. Distributions of time series trends. The values used are the slope of a linear model fitted to the 1986–2017 time series for each sampling point in the following classes: Huachuca Mountains canyon riparian vegetation, upland forest, riparian trees along the San Pedro River and grasslands (a) and flow permanence (b). Violin plots showing median and interquartile range, asterisks indicate significant differences between pre- and post-monsoon ($P < 0.05$).

River discharge (figure 6(b) and (c)). Before 2004, high volumetric discharge was recorded both during the monsoon (mean of 7.15 × 10^6 m^3 yr) and during winter (10.52 × 10^6 m^3 yr). Since 2004, however, streamflow volume is higher during the monsoon (16.0 × 10^6 m^3 yr), than during winter (5.9 × 10^6 m^3 yr). These results are confirmed by a changepoint analysis, using the At Most One Change method and run on annual monsoon rainfall for the 1986–2017 time period showing a shift in precipitation distribution in 2006 (see supplementary figure S2), which in turn has impacted runoff and streamflow generation.

In terms of groundwater, we observe a shallow water table (<2 m deep) directly under the river (figure 7(a)) with brief and substantial rises (to <1 m deep) during monsoon months and more prolonged but lesser increases during the winter, expressing strong streamflow-groundwater interactions under and around the streambed (figure 7(b)). However, the water level in these near-stream wells has been steady through the years of this analysis (figure 7(b)), suggesting consistent support by a deeper groundwater system across the study area (Ajami *et al* 2012, Meixner *et al* 2016). The water table becomes progressively deeper with much lower seasonal variability with distance from the San Pedro River (down to 90 m deep in the farthest well, with no seasonal variations), reflecting less streamflow-groundwater interactions (figure 7(a)). Interestingly, the wells located >2000 m from the San Pedro under the grasslands display a slow and steady decline in water table depth (figure 7(b)). Therefore, although there may be good support for the shallow alluvial aquifer along the San Pedro from mountain front recharge and streamflow, this benefit seems to bypass the aquifer below the grasslands.

We further investigated how streamflow and water table depth vary within flow permanence classes (wet, intermediate, dry) along the San Pedro River, focusing on the cases of a strong monsoon in 2008 (positive 98 mm anomaly from 1986 to 2017 average) versus a weak monsoon in 2009 (negative 65 mm anomaly). The rainfall anomaly for the whole time

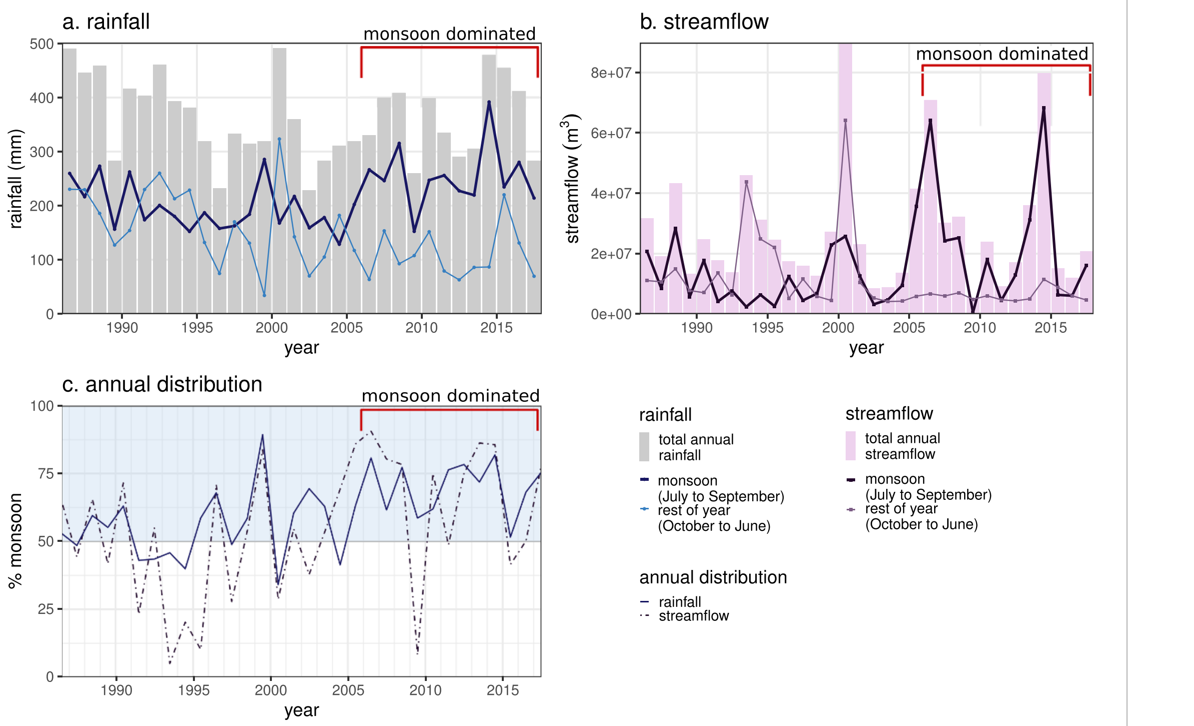

Figure 6. 1986–2017 time series of precipitation and streamflow. Precipitation panel includes total annual rainfall, total annual monsoon rainfall (July to September) and total rainfall for the rest of the year (October to June) (a). Streamflow includes total volumetric annual streamflow, total monsoonal streamflow and total streamflow for the rest of the year (b). Panel (c) shows the annual proportion of rainfall and streamflow measured during the monsoon. When above 50%, this means that more than half of the annual precipitation or streamflow has been measured during the monsoon season. Locations of streamflow stations and groundwater wells are shown in figure 2.

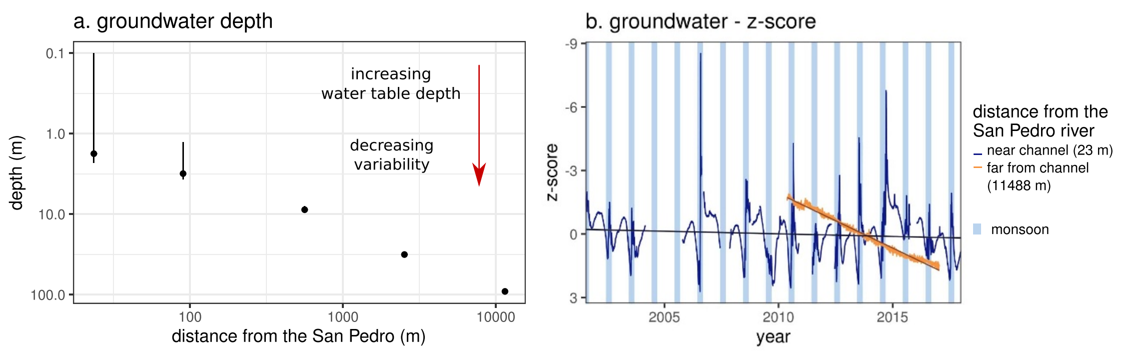

Figure 7. Water table depth over recent decades for several wells at various distances from the San Pedro River, showing median depth, as well as minimum and maximum (a), and time series of daily groundwater z-score for two of these wells: the closest to the channel and the farthest, with the corresponding linear regressions (b). z-score = (daily value − overall average)/overall standard deviation. Both figures use a reversed y-axis to show changes in depth as larger positive values when the water table is deeper.

series is shown in supplementary figure S3. In the wet reach, the river is flowing all year round (figure 8(a)), the minimum value is reached right before the monsoon while the highest peaks are usually during the monsoon. The water table in the wet reach rises ∼1.5 m during the monsoon, but it is otherwise nearly constant at ∼3 m below the surface, even during weak monsoon years (figure 8(b)). In the intermediate reach, streamflow variability is high, as there is generally only flow during monsoon and winter rains (in years with a very strong monsoon, both streamflow and groundwater stay high all year round), when discharge approaches values of the wet reach (figure 8(c)). Groundwater has a flashy response to streamflow (figure 8(d)) with similarly high variability (2–3 m fluctuations) and lengthy dry periods of very low water table depths (below the sensor). During a weak monsoon, levels remain low for the whole summer.

Streamflow from the USGS gauge in the dry reach was only recorded from July 2001 to June 2002, so it is challenging to draw conclusions. The water table here again has no consistent elevation, but instead rises and falls with the streamflow regime during monsoon

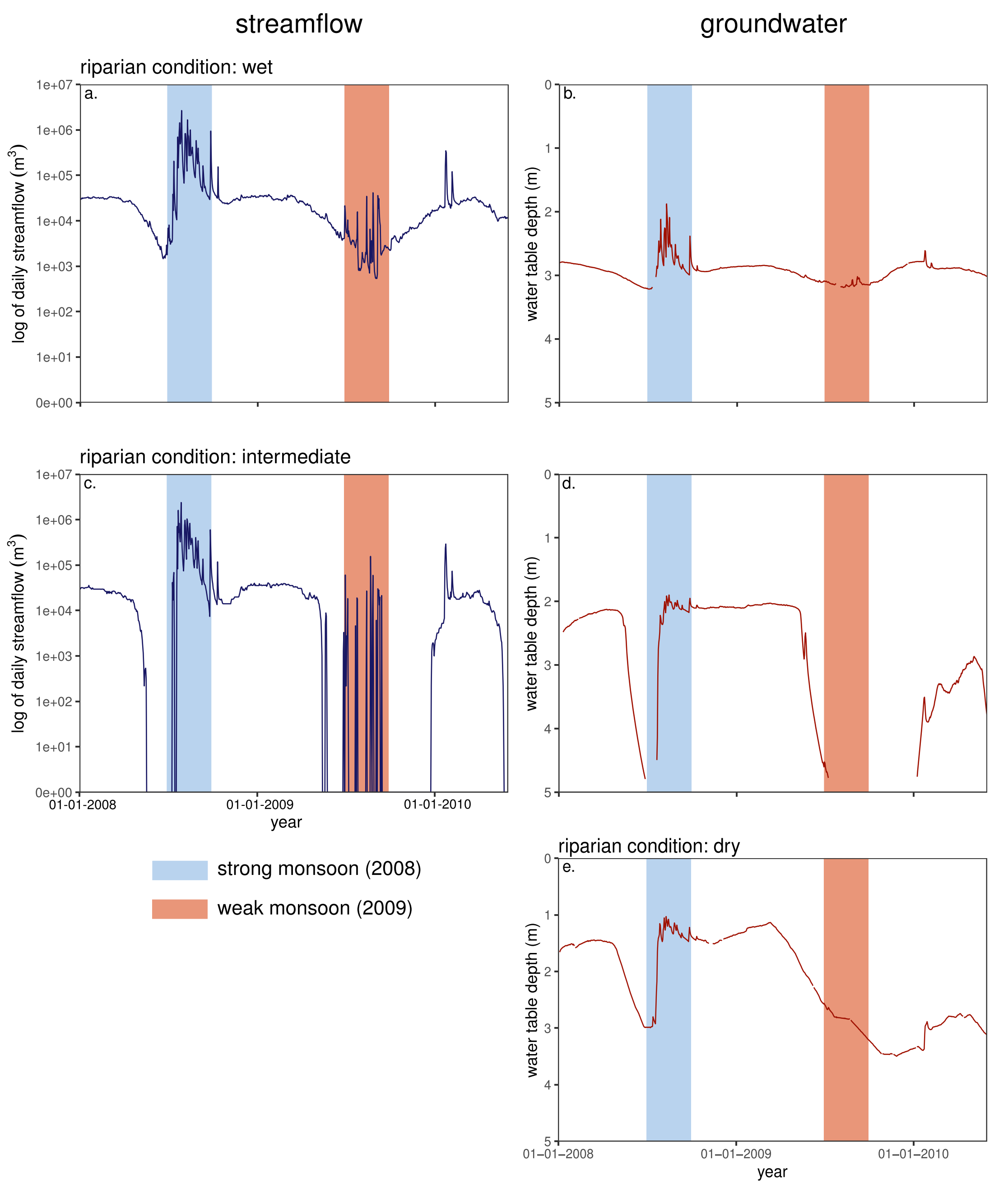

Figure 8. Time series (2008–2010) for streamflow and groundwater under the San Pedro for each flow permanence class: wet (a) and (b), intermediate (c) and (d), dry (e). Strong and weak monsoons are shown as blue and red vertical stripes, respectively.

and winter rains (figure 8(e)), apparently supported by a geologic control at a minimum value of 4 m below the surface. A strong monsoon keeps water table depth above 3 m all year round, with a high at 1 m during the summer, but a year with a weak monsoon will see the water table drop under 3 m, and even the winter rains will not be able to bring the water back up.

The years since 2006 are dominated by the monsoon (figure 6). The annual amount of water has not changed but at least half of this water is falling/flowing during the monsoon, meaning that vegetation receives more water in a smaller time step and water distribution is shifting, with potential consequences on water storage and accessibility to vegetation. Grasslands and the San Pedro riparian forest show a significant increase in NDVI values, with the San Pedro trees displaying the strongest increase (figure 9(a), median value goes from 0.55 to 0.61), mostly due to an increase in vegetation greenness in the wet and intermediate ranges (figure 9(b)). When looking at trends, the opposite patterns are apparent, with a significant shift from weak negative trends to strong positive trends for all the vegetation communities except the San Pedro trees (figure 9(c)). Along the San Pedro, wet and intermediate reaches

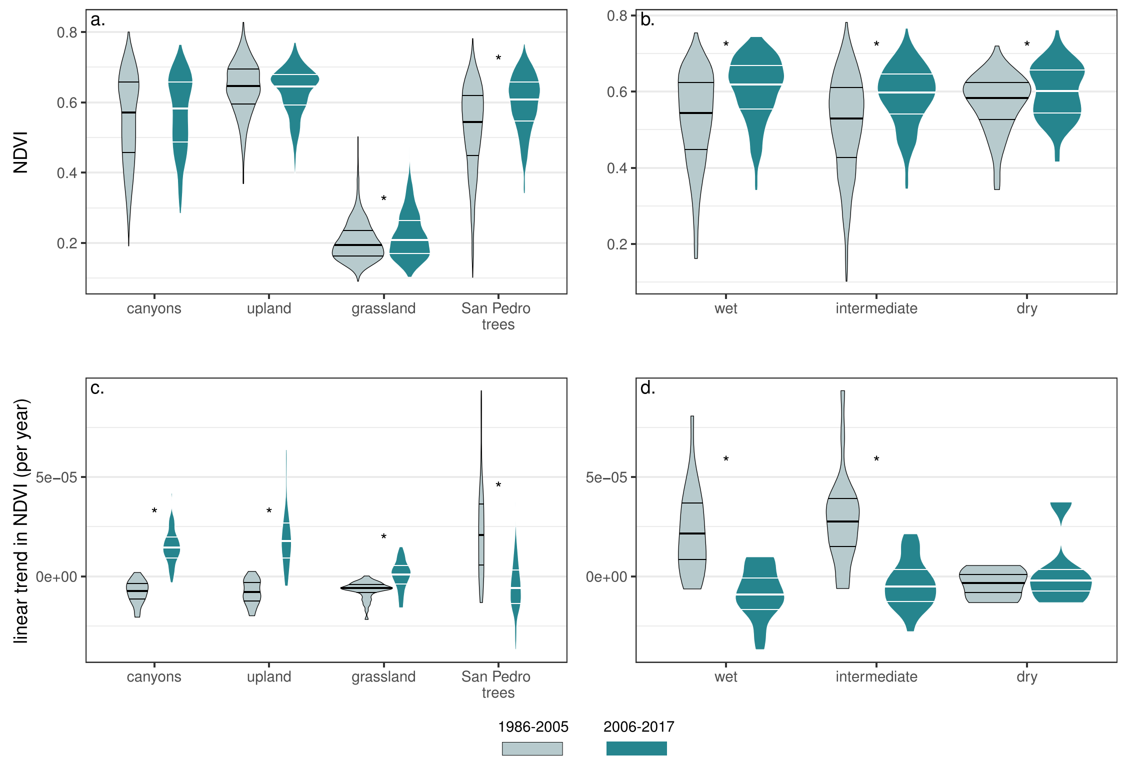

Figure 9. Distribution of pre-2006 and post-2006 NDVI for the canyon riparian vegetation, upland forest, San Pedro riparian trees and grasslands (a) and flow permanence (b). Distribution of time series trends before and after 2006 for canyon riparian vegetation, upland forest, San Pedro riparian trees and grasslands (a) and flow permanence (b). Violin plots showing median and interquartile range, asterisks indicate significant differences between pre- and post-monsoon ($P < 0.05$).

went from strong positive trends before 2006 to negative trends after 2006, while the dry reaches showed no significant change in a trend that stays negative before and after 2006 (figure 9(d)).

4. Discussion

We set out to explore variations in water availability and vegetation responses within this subregion of the San Pedro River basin based on diversity in landscape attributes (e.g. topography, subsurface geology). This analysis is particularly important considering climate change projections for the Southwest USA that portend more prolonged and extreme drought conditions, which may affect vegetation in profound ways (Cayan *et al* 2010, Parolari *et al* 2014, Cook *et al* 2015, Asner *et al* 2016, Ault *et al* 2016, Choat *et al* 2018).

4.1. Hydrology and water availability

Most of the annual precipitation in this region of SE Arizona is partitioned by season and elevation into rainfall or snow accumulation on the Huachuca Mountains, but it is only the intense monsoonal rains that generate significant runoff in ephemeral streams, which deliver flow to the San Pedro River (Thomas and Pool 2006, Goodrich *et al* 2008, Singer and Michaelides 2017). Rainfall in the mountains infiltrates into fractured rocks as temporary aquifer storage (Coes and Pool 1984) before periodically emerging at the surface in ephemeral and intermittent canyon channels, which are bounded by canyon riparian forests, on their downslope journey to the lowlands (Shaw 1999, Jaeger and Olden 2012, Meixner *et al* 2016). At lower elevations, the water table dips far below the surface in the grasslands, before becoming shallow again near the San Pedro River, where there are strong streamflow-groundwater interactions (Coes and Pool 1984). These interactions, expressed largely during the summer monsoon, recharge the shallow water table around the channel, briefly raising the water table level (figures 7 and 8) and saturating the soil close to the surface. Once the water table declines again, the residual moisture in the soil pores is available to vegetation for at least part of the remaining growing season. The reasons for the slow water table decline over time under the grasslands (figure 7) are unclear, although it could have to do with pumping for water supply to Fort Huachuca and Sierra Vista (Gungle *et al* 2016, Stromberg and Tellman 2012, p 299) and/or a deeper plunging of the water table below the grasslands, for example due to lower mountain front recharge under declining snowpack.

The other major factor controlling the distribution of water along the San Pedro River is flow permanence along the channel, which reflects the presence of subsurface geologic layers (bedrock and clay layers) that support a locally perched alluvial aquifer in some reaches (figure 3). However, depth to bedrock (e.g. figure 1(c)) is not the main factor governing water table characteristics in this and many other riparian systems (except around Charleston); the spatial distribution of alluvial deposits play a dominant role. There is evidence for a diversity of such sedimentary controls along the SPRNCA, which essentially stratify this area into wet, intermittent, and dry reaches (figure 3). Wet reaches are over bedrock or river alluvium layered with clay and silt that maintain the alluvial aquifer close to the surface, sustain perennial flow, and enable flashy responses to streamflow-groundwater interactions to monsoonal rainfall (figure 8). Relatively dry reaches (intermediate and dry) are more over stretches of sand and gravel alluvium (figure 3), providing limited benefits to moisture retention, so the flow series at these locations only responds to significant rainfall events, dropping back to zero flow for extended periods. The water table responses in these drier reaches are also flashy with several meter variations depending on the driving flow. When the flow is low or zero, the water table drops down to its minimum, again supported by deeper geologic controls. There might also be a difference in lateral underground flow from the surrounding mountains, with wet reaches receiving more water than dry reaches.

In wet years, high monsoonal rainfall may minimize the importance of geologic controls by, for example, creating higher sustained flows, strong streamflow-groundwater interactions, and a shallower water table, even in the drier reaches (figure 1). These would generate high water storage in the riparian zone similar to that in wet reaches. In years of very low monsoonal rainfall, however, the apparently strong geologic support to the water table in wet reaches creates large differences in water availability compared to drier reaches, where the streamflow is low or zero and water table drops substantially. Thus, if climate change trends toward a stronger monsoon, we would expect an equalizing in moisture availability across all reach types in the riparian zone. However, if the monsoon becomes weaker, it could exacerbate the moisture storage differences between reaches (figure 1).

4.2. Vegetation responses to water availability

With differences in water distribution and storage in the landscape, there are also differences in vegetation communities, species as well as vegetation density. At high elevation, oak-sycamore forests of the canyon riparian corridor and the oak-fir forests on slopes share similar seasonal NDVI distributions (figure 4(a)), suggesting that they use similar sources of water (seasonal flow passing through fractured rock, figure 1(a)), though differences in trends (figure 5(a)) might be explained by their difference in position in the landscape (bottom of canyons vs steep slopes). In lower elevation grasslands, vegetation relies on rainfall-derived soil moisture, as the water table is below the rooting zone (figure 1(a)), producing notable green-up after monsoon rains (figure 4(a)).

Along the San Pedro, the deciduous trees of the riparian forest green-up earlier than other vegetation communities in the study area, perhaps because they are phreatophytes that have access to groundwater before the monsoon starts and grow their leaves early with little change in leaf area or chlorophyll content over the growing season (Brock 1994). However, there are strong spatial differences in water availability and associated riparian forest use of subsurface water (Mayes et al 2020). The monsoon rains generate significant streamflow, which recharges the shallow water table, thus increasing hyporheic soil moisture within the riparian corridor. In perennial flow reaches, the riparian corridor is dense, with a closed canopy of cottonwoods and scattered willows, so the vegetation water requirements are high (Leenhouts *et al* 2006, p 140). This community is supported by a sustained, shallow water table and strong interactions with streamflow, even during years of low monsoon (figure 1(c), Leenhouts *et al* 2006). In drier stretches of the river, sparse patches of old cottonwoods, mesquite (*Prosopis velutina*) and tamarisk (*Tamarix* sp.) (Stromberg *et al* 2006, 2010) (figure 1(c)), subsist on moisture in the unsaturated zone generated during brief flow events and water table rises, which appear to be favorable to adult trees in small numbers, but apparently limit the establishment of a denser forest.

4.3. Trends

The relationships between water fluxes and vegetation responses provide insight into how dryland vegetation communities have responded to climate over recent decades, as well as their likely response to different scenarios of climate change. Both upland forests and grasslands show a significant positive change in trend after the monsoon (figure 5(a)) which could be driven by the fact that these vegetation communities are more reliant on monsoon rain, and the shift to a monsoon-dominated precipitation regime (figure 6(c)). This positive influence of the increase of monsoon precipitation is also visible in figure 9(e). In the grasslands, an increase in monsoon rainfall paired with no change in PET brings an increase in soil moisture available to plants during the growing season. The riparian trees of both canyons and San Pedro River might not be as sensitive to the monsoon, thanks to the support of a shallow water table, and their NDVI trends pre- and post-monsoon show no significant change (figure 5(a)).

The partitioning of rainfall and associated seasonal water availability has changed in this region of the southwest USA (figure 6), which has impacted all vegetation communities. With the monsoon rains becoming the predominant water source after 2006, canyons, upland forests and grasslands have shown a shift from negative NDVI trends to positive trends (figure 9(c)), which suggests that the annual distribution of rainfall and the strength of the monsoon are important factors for the evolution of these communities. The San Pedro riparian forest shows the opposite pattern (figure 9(c)) and the flow permanence classes did not react in the same way to these changes in rainfall distribution. Both wet and intermediate reaches have seen an increase in NDVI values over time (figure 9(b)) but a shift from positive to negative trend (figure 9(d)), which might indicate a forest that has grown, has reached maturity and is now declining (high NDVI values but a slightly negative trend). Looking at NDVI trends of the last few years can be used as an early warning system by highlighting recent changes in a vegetation community. In the dry reaches, the median NDVI was high before 2006 and remained high afterwards (figure 9(b)), with no change in trends (figure 9(d)). This suggests that the scattered trees of the dry sites had reached maturity before 2006. Since 2006, the monsoon rains increased and overtook winter rains in terms of annual moisture contribution, apparently providing vegetation in the dry reaches a new source of moisture to exploit, providing a relative advantage compared to wet and intermediate reaches, and allowing them to maintain a trend close to zero (figure 9(d)).

The strength and trends of the North American monsoon is a subject of debate, probably because of near decadal cycles of strength and weakness based on ocean-atmosphere connections and opposing trends of annual precipitation and precipitation intensity (Luong *et al* 2017, Pascale *et al* 2017, Singer and Michaelides 2017). Regardless, our results suggest periods of stronger monsoons will maintain a more consistent source of moisture for riparian forests along all reaches of the San Pedro, overprinting the effects of subsurface geology, and maintaining a shallower water table and replenishing soil moisture every summer. However, a prolonged period of weaker monsoons may result in reduced water storage and moisture availability in intermediate and dry reaches, which might make them even less favorable for riparian vegetation, even for older trees with deeper roots. Thus, strengthened decadal cycles of strong and weak monsoons in the Southwest USA may result in prolonged periods of moisture stress followed by rapid greening for dryland riparian forests, especially for forests with no benefits from regional groundwater drainage and subsurface geology. When the currently mature trees of the San Pedro riparian forest start dying and leaving room for the establishment of younger trees, climate-controlled water distribution will affect the composition, density, and health of the successional riparian forest community. Future climate projections call for a weakened monsoon due to more stable air masses across the region under global warming (Pascale *et al* 2017). If this comes to pass, we suspect that this may ultimately lead to significant die back of dryland riparian forests across the region. Whereas, if there is a consistent intensification of the monsoon (Luong *et al* 2017), there is great potential to create a greener and more continuous riparian gallery forest. To complete this overview of water distribution and availability to vegetation in the landscape and through time, the snow from the Huachuca Mountains also needs to be taken into account, while dendrochronology and stable isotopes can help better understand the consequences of shifts in timing and amount of water available to trees.

5. Conclusion

In this paper, we analyzed long-term changes in water fluxes and vegetation greenness across a range of vegetation communities over a broad dryland region in Arizona. We show the importance of the driving climate in controlling water availability to dryland vegetation. We also illustrate the importance of subsurface geology, with its role in controlling water availability and vegetation distribution along the San Pedro River. Additionally, we identified distinct monsoonal cycles over a multi-decadal time series, which have affected subsurface water availability to a range of vegetation communities. This regional expression of the climate system is strong enough to overprint the effects of local geology in the strong monsoon phase, allowing trees in the dry reaches to maintain their leaf density, while trees of the wet and intermediate reaches show a decline in greenness trends, suggesting that they are reaching end of life. The renewal of water-limited riparian forest communities that have reached their maturity is strongly dependent on future shifts in water distribution and the availability of new surfaces for phreatophyte recruitment and establishment. Our results suggest that climate-controlled water availability is a first-order control on vegetation distribution and health in different vegetation communities within arid regions, subject to spatially varying constraints on water table support.

Data availability statement

No new data were created or analyzed in this study.

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