Climate, streamflow, and legacy effects on growth of riparian *Populus angustifolia* in the arid San Luis Valley, Colorado

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Abstract

Knowledge of the factors affecting the vigor of desert riparian trees is important for their conservation and management. I used multiple regression to assess effects of streamflow and climate (12-14 years of data) or climate alone (up to 60 years of data) on radial growth of clonal narrowleaf cottonwood (*Populus angustifolia*), a foundation species in the arid, Closed Basin portion of the San Luis Valley, Colorado. I collected increment cores from trees (14-90 cm DBH) at four sites along each of Sand and Deadman creeks (total $N = 85$), including both perennial and ephemeral reaches. Analyses on trees < 110 m from the stream channel explained 33-64% of the variation in standardized growth index (SGI) over the period having discharge measurements. Only 3 of 7 models included a streamflow variable; inclusion of prior-year conditions was common. Models for trees farther from the channel or over a deep water table explained 23-71% of SGI variability, and 4 of 5 contained a streamflow variable. Analyses using solely climate variables over longer time periods explained 17-85% of SGI variability, and 10 of 12 included a variable indexing summer precipitation. Three large, abrupt shifts in recent decades from wet to dry conditions (indexed by a seasonal Palmer Drought Severity Index) coincided with dramatically reduced radial growth. Each shift was presumably associated with branch dieback that produced a legacy effect apparent in many SGI series: uncharacteristically low SGI in the year following the shift. My results suggest trees in locations distant from the active channel rely on the regional shallow unconfined aquifer, summer rainfall, or both to meet water demands. The landscape-level differences in the water supplies sustaining these trees

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implies variable effects from shifts in winter- versus monsoon-related precipitation, and from climate change versus streamflow or groundwater management.

KEYWORDS: climate variation; ephemeral stream; groundwater; narrowleaf cottonwood; Palmer Drought Severity Index; tree rings

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1. Introduction

Riparian plant communities are key contributors to local and regional biodiversity, particularly in arid and semiarid regions (drylands) where their physiognomic heterogeneity and high productivity support unique arrays of consumer, detritivore, and decomposer organisms (Levick et al., 2008; Soykan et al., 2012). The nature of dryland riparian plant communities, in turn, is strongly dependent on local streamflow and groundwater conditions (Stromberg and Merritt, 2015). This dependency makes these communities vulnerable to disruption by water resource management activities and has resulted in dramatic declines in desert riparian habitat extent and quality, both in the western United States (Andersen et al., 2007; Obedzinski et al., 2001) and globally (Tockner and Stanford, 2002). In the drylands of the western U.S., the precipitation decline predicted to accompany climate change (Perry et al., 2012) is likely to further alter riparian communities as local hydrologic regimes respond to shifts in catchment water budgets. These vulnerabilities have prompted research to acquire the knowledge and develop the tools for long-term management of remaining dryland riparian plant communities. These efforts rely on understanding how species respond to fluvial-geomorphic, hydrological, and other environmental conditions (Rood et al., 2005; Shafroth et al., 2010).

Dryland riparian woodlands in North America commonly contain tree species from the genus *Populus*, i.e., a cottonwood or poplar. These trees serve as foundation species, defining floodplain forest structure and controlling ecosystem dynamics (Ellison et al., 2005). Although much is known about the autecology of some *Populus* species, narrowleaf cottonwood (*P. angustifolia* James) has received relatively little attention despite its distribution in Rocky Mountain riparian habitats from southern Canada to northern Mexico (Argus et al., 2010). Dryland narrowleaf cottonwoods are obligate phreatophytes, with a root system generally confined to the soil's upper few meters (Pregitzer and Friend, 1996; Rood et al., 2011), making shallow groundwater during the growing season a necessary condition for population persistence. The species is dioecious and wind-pollinated, producing small, short-lived seeds dispersed by wind and water. However, individuals also readily expand clonally through production of root sprouts (Braatne et al., 1996; Gom and Rood, 1999). Plants are relatively tolerant of physical disturbance, including flooding. These traits contribute to narrowleaf cottonwood commonly serving as a pioneer species on floodplains.

Narrowleaf cottonwood is the only tree present in the northern portion of the San Luis Valley (SLV), a large (8300 km²), high altitude (2300 m) cold-desert basin in south-central Colorado. The trees form discontinuous bands along perennial and ephemeral stream channels that carry runoff from the adjacent Sangre de Cristo Mountains through federally owned and protected lands within Great Sand Dunes National Park and Preserve and neighboring Baca National Wildlife Refuge. In the early 2000s, biologists noted branch dieback in many of these trees, indicative of past or ongoing physiological stress from drought (Rood et al., 2000) or other factor. A regional drought had indeed begun in 1999 (Henz et al., 2004), but another potential source of stress was groundwater pumping near the park and refuge boundaries. The pumping had begun in the mid-1980s when the federal Closed Basin Project began extracting >10⁶ m³ of shallow groundwater annually from the SLV for delivery to the Rio Grande for downstream use (Reclamation, 2003).

Annual growth in mature dryland riparian *Populus* can be strongly correlated with factors affecting the water table and plant-available soil water (Andersen, 2016; Edmondson et al., 2014; Meko et al., 2015). Further, severe water stress can cause crown dieback (Rood et al., 2000) and is associated with greatly restricted radial growth (Scott et al., 2000; Scott et al., 1999). Thus, interannual variation in radial growth provides a means to assess a tree's history of exposure to water stress. Confounding the relationship, however, is the fact that dieback—a permanent loss of a portion of the tree's canopy—might produce at least a short-term legacy of restricted growth, even if environmental conditions are highly favorable, until lost primary production is replaced through canopy expansion and restoration of former leaf area.

Here I add to the autecological knowledge of narrowleaf cottonwood and assess the potential causes of dieback in the northern SLV by testing the hypothesis that interannual variation in radial growth of adult trees can be largely explained by interannual variability in climate and/or associated stream flow. I compare the factors affecting growth in spatial groups of trees near to and far from the stream channel at multiple sites along two streams in order to gain insight into whether summer precipitation associated with the North American monsoon is an important contributor to growth of SLV cottonwoods. By focusing on how growth is linked to streamflow, water table dynamics, and years having unusual climate conditions during the growing-season, I provide insight into the hydrological mechanisms sustaining these trees and the presence and magnitude of legacy effects. That focus also provides a means to assess the potential adverse

effects from the Closed Basin Project through a before-and-after comparison of growth patterns in trees closest to the project's extraction wells.

2. Materials and methods

2.1 Study Area

I worked along Sand and Deadman creeks in Great Sand Dunes National Park and Preserve and the Baca National Wildlife Refuge in south-central Colorado (Figure 1). Both creeks have their headwaters in the ~4,000-m high Sangre de Cristo Mountains and flow westward into the Closed Basin portion of the SLV, where their channels terminate in a playa complex (Mayo et al., 2007). Streamflow at the mountain front is probably perennial, whereas flow becomes ephemeral as one moves away from the alluvial fans of the mountain front and onto the “sand sheet” making up much of the valley floor. High infiltration rates in the channel beds (Hadlock et al., 1997; Harte et al., 2007) result in the streamflow-derived riparian water table declining with lateral distance from the channel (Wurster et al., 2003). Depth to the riparian water table also varies spatially due to topographic variation in the riparian zone produced through aeolian and fluvial geomorphic processes.

Both Deadman and Sand creeks feature a snowmelt-driven spring flood pulse. This pulse has been subject to human manipulation in reaches on the sand sheet. Sheep and cattle ranchers, present in the SLV since at least the mid-1800s, diverted flows to flood-irrigate valley floor areas for native grass (hay) production, but the location and frequency of diversions are unknown.

The valley floor climate is arid (mean annual precipitation < 250 mm), whereas the creek headwaters receive more than 1000 mm of precipitation annually, primarily as snow. Winter temperatures < -20 °C and summer temperatures > 30 °C are common; the warm season lasts ~90–110 days (Mix et al., 2011). Groundwater associated with the unconfined regional aquifer in the Closed Basin is generally shallow, with depth to the water table decreasing from >4 m at the Sangre de Cristo mountain front to <2 m in the center of the basin (Emery et al., 1971).

I worked at four sites on each of Sand (Sites S1-S4) and Deadman (Sites D1-D4) creek, at or downstream of the creek's exit point along the mountain front (Figure 1). Site elevations ranged from ~2480 to ~2300 m ASL, and the geomorphic setting and flow character varied along this elevation gradient (Table 1). To account for the streamflow-derived lateral gradient in depth to the water table, I sampled individual trees or tree clusters relatively near to and relatively far from the channel at sites where that was possible. To account for spatial variation in depth to the

water table due to local topography, I sampled trees on representative topographically-distinct landforms and over any elevation gradient present (Figure 2). I avoided obviously injured or unhealthy trees, but otherwise selected trees haphazardly, without regard to clone boundaries or local stem density. For analysis, trees were grouped as being close to or far from the active stream channel. For example, trees sampled near the channel at Sand Creek Site S2 were grouped as “S2-Near” trees, and trees sampled at Deadman Creek Site D3 but far from the channel were grouped as “D3-Far” trees. The Closed Basin Project’s eastern boundary, within which extraction wells were located, was ~3 km downstream of the lowest study site on each creek (D4 and S4; Figure 1), with the closest extraction wells in each case ~5 km away.

2.2 Methods

2.2.1 Surface water hydrology and climate

I examined two streamflow and nine climate variables for an effect on *P. angustifolia* radial growth (Table 2). Flow data for Sand and Deadman creeks have been collected since 1993 and 1999, respectively, at gauges located near each stream’s point of entry onto the valley floor (Figure 1). I obtained discharge records from the Colorado Division of Water Resources [e.g., recent daily mean and instantaneous discharge at 15-minute intervals (uncorrected) at <http://www.dwr.state.co.us/surfacewater/data/division.aspx?div=3>] or the National Park Service (pre-2006 Sand Creek daily mean discharge data; Andrew Valdez, *personal communication*). Gauge names are “Sand Creek near stream entrance into GRSA” (2005 and earlier), “Sand Creek at Great Sand Dunes National Park” (codename SANDUNCO), “Deadman Creek near Crestone” (codename DEDCRECO) and the latter’s replacement, “Deadman Creek at mouth of canyon near Crestone” (DEDMOUCO).

I generated values for 3- and 30-day maximums (Q_{M3} and Q_{M30}) for the spring run-off period (1 May through 15 July) from the daily discharge data using the Indicators of Hydrologic Alteration software package (The Nature Conservancy; Version 7.0.0 Beta 4.10). Discharge records were missing for 2003 in Sand Creek and 2000 in Deadman Creek. I estimated the missing summary statistics using regression equations relating flows in these streams to those in nearby streams (Supplementary Online Material Table A-1). Because prior-year environmental conditions can affect growth even in the absence of dieback (Rood et al., 2013), I assessed both current year and prior-year values of Q_{M3} as well as Q_{M30} .

I obtained monthly mean air temperature and total monthly precipitation data for the period 1951-2012 for Station 53541 (Great Sand Dunes National Monument, Colorado) from the Western Regional Climate Center (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?cogrea>). A key missing datum (September 2006 precipitation) was estimated by regressing September values on those from the nearest station having data for that month (Station 050776, Blanca, Colorado; $n = 52$, $P < 0.001$, $r^2 = 0.60$). I based inclusion of the monthly temperature variables (Table 2) on the premise that a warm March or April reduces growth (because it reduces mountain snowpack development or initiates early runoff), whereas a warm May or June is beneficial (because it promotes a higher growth rate in the early portion of the growing season, given adequate moisture conditions). Daily meteorological data for the same station were obtained from the Colorado Climate Center (http://ccc.atmos.colostate.edu/dly_form.html). I quantified overall favorability of growing season moisture and temperature conditions using values of the Palmer Drought Severity Index for US Climate Division 5 in Colorado (Rio Grande Basin) obtained from the NOAA National Centers for Environmental Information (<http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp>). The Palmer Index (Palmer, 1965) uses temperature and precipitation data in a formula to determine region-specific relative dryness (or wetness) on a monthly basis. A value of 0.0 represents average or normal dryness. Negative values indicate drought, with -2, -3, and -4 indicating moderate, severe, and extreme drought, respectively. Comparable positive values indicate wet conditions, e.g., +3 indicates a severe wet period. I created a seasonal index (Table 2: PDSIs) by averaging monthly values for January through July. This 7-month period includes months when the mountain snowpack would be accumulating as well as the period of snowmelt and high stream discharge, and the early-through mid-growing season periods when local rainfall and air temperature would directly affect tree growth. Along with current-year values, I also assessed prior-year values for both PDSIs and total June through August precipitation (Ps).

2.2.2 Regional groundwater hydrology

Water table elevations in the regional unconfined aquifer have been monitored since the 1980s as part of the Closed Basin Project (CBP), which involved the installation of 170 groundwater extraction wells in five temporally- and spatially-distinct stages between the early 1980s and mid-1990s. Stages 1-3 began delivering water in 1986 and stages 4 and 5 began delivering water in 1992 and 1993, respectively (Reclamation, 2003). My lowest study reaches

on Sand and Deadman creeks are < 4 km outside (east and upstream) of the Stage 3 and Stage 4 project area boundaries, respectively. I examined records of annual stage-specific CBP pumping volumes as well as water table elevations in three CBP monitoring wells (available at <http://www.prinmath.com/rgwcd/loc/ewlist.htm>) located between those study reaches and the Stage 3 and Stage 4 project areas to gain insight into whether the pumping could have affected water table elevations at my study sites. A CBP monitoring well was located ~1 km from each of the Sand and Deadman creek channels (wells EW31 and EW54, respectively), and a third well (EW44) was located between Sand and Deadman creeks, ~3.5 km south of the Deadman Creek channel (Figure 1).

2.2.3 Study site water table depths and dynamics

I monitored streamside groundwater dynamics for ~2-yr on each creek using observation wells I installed at sites S4, D2 and D4 (Table 1; Figure 2). Shallow cobble stopped attempts to install wells at upstream sites S1, S2 and D1. I placed casings, either capped PVC pipe with hand-cut slots in the lowest meter or commercial slotted pipe, in hand-augered holes that I then back-filled with native sand. I added a layer of bentonite clay powder (≥ 1 cm thick) around the casing 15-20 cm below the ground surface. I placed continuously-recording water table sensors in five wells, and manually read water table position in nine others (Table 1).

I used a Total Station to survey the location of, and the local ground surface elevation at, each sampled tree at Sand Creek sites S1, S2, and S4. I also surveyed points in the stream channel bed and each well casing top and local ground surface. I mapped the active channel margin and well locations at S4, and trees at S3, using a hand-held GPS device (Garmin GPSMap 60CS). I determined the elevation of a single point (either well casing top or the ground surface) relative to mean sea level using real time kinematic GPS at Deadman Creek sites D2, D3, and D4. I mapped sampled tree locations at all four Deadman Creek sites using the GPS device, whereas a Total Station was used to survey well tops and ground surface elevation at trees in sites D2 and D4.

2.2.4 Dendrochronology

I used a 25-cm increment borer to obtain 5-mm cores from mature (≥ 14 cm diameter at breast height; DBH) trees (ramets) when leaf-drop was underway in 2007 (Sand Creek) and 2010 (Deadman Creek). A total of 71 trees were sampled along Sand Creek and 25 along Deadman Creek.

I typically collected a single core (Sand Creek) or two perpendicular cores (Deadman Creek) at breast height (~1.3 m) from each tree; a total of 136 cores were collected for processing. I air-dried and mounted each core and sanded its surface to a final 600 grit (26 μm). I delineated rings and measured their widths (0.01 mm precision) using a binocular microscope and measuring stage featuring a linear encoder and digital readout coupled to program MeasureJ2X. I visually cross-dated the raw ring-width series in each spatial group following the method of Yamaguchi (1991), generally using 1981, 1996 and 2002 as marker years because of their consistently narrow widths. In cases where simple adjustment (e.g., correction for a false or missing ring) did not result in relatively narrow rings for those years, I repeated the sanding, reading, and cross-dating process to confirm ring boundaries and widths before assignment of a ring's production year (PY). Program COFECHA ver. 6.06P (Grissino-Mayer, 2001) was used to provide further insight into possible cross-dating errors.

I detrended each series where regression indicated a significant ($P < 0.05$) negative exponential or linear age-trend was present. I assessed age trend using a modified 3-parameter single exponential decay model:

$$Y = a \cdot \exp[b/(t+c)] \quad (\text{Eq. 1})$$

where Y = ring width, t = calendar year, and a , b , and c are constants. This model is similar to the modified negative exponential model (Cook et al., 1990), but it produced higher r^2 values in test trials. Positive linear trends in ring width series were treated as real, and the associated series detrended, because of the possibility that conditions unrelated to hydrology, such as release from competition, were operating. I used SigmaPlot 2002 and SigmaPlot 11 for model fitting.

I standardized each series to account for differences in age trend and absolute growth rate among individual trees by dividing actual ring width by either the width predicted from the detrending model or the mean width in those series where no significant trend was detected (Cook et al. 1990). I generated final interseries correlation and sensitivity values for the standardized growth index (SGI) series for trees within each group using program COFECHA. The SGI series for selected trees identified in the COFECHA output as contributing to low interseries correlation values was examined for patterns that might provide insight into their contrary growth pattern, e.g., evidence of differential sensitivity to drought. For example, where annual growth in two trees within a group was divergent in a number of multi-year periods (i.e.,

periods in which one SGI $\gg 0$ and the other SGI $\ll 0$, intermixed with periods when the opposite pattern occurred), I used stepwise-forward logistic regression in an attempt to determine if any climate variable(s) could be used to predict when one or the other pattern would be evident.

I calculated the mean SGI series for each spatial group without regard to incongruities among the individual tree SGI series that remained after cross-dating. I assumed any incongruity present represented real differences in growth patterns and that the mean SGI series represented the population-level response of trees (ramets) at that locality to environmental conditions.

2.2.5 Statistical evaluation of climate and hydrologic effects on annual growth

I used a two-stage process to test for an effect from environmental variables on annual growth (mean SGI value) in each group (“Near” and “Far”) at each site. For the first stage, I used forward stepwise multiple linear regression analysis in an analysis limited to 1994–2007 (Sand Creek) or 1999–2010 (Deadman Creek), periods for which complete spring and summer stream discharge data were available. Thus, all streamflow and climate variables could be included in the analysis, although prior-year streamflow data were not available for 1994.

A time series of climate, streamflow, or SGI values will tend to show positive autocorrelation, because measurements close in time will tend to be similar—a result of climate being affected by multi-year phenomena like the Pacific Decadal Oscillation. Using an autocorrelated time series in a statistical procedure that assumes independent observations, e.g., linear regression, is temporal pseudoreplication, and although the model parameter estimates are unbiased, their estimated standard errors can be either too large or too small, depending on the nature of the autocorrelation. Because attempting to remove autocorrelation in short time series introduces other uncertainties (Bence, 1995), I elected to use “uncorrected” values in my multiple regression analyses. Thus, although the models I produce are accurate in terms of the incorporated variables, model significance and R^2 values require subjective interpretation. In particular, models with P values close to 0.05 may not, in fact, be statistically significant at the $\alpha = 0.05$ level.

Stage 2 involved a second round of forward stepwise multiple regression, performed as above but using only climate variables and over the longest time period possible (typically set the mean SGI series length). For both the Stage 1 and Stage 2 analyses, I compared and

contrasted variables and their manner of entry into models for the “near” and “far” spatial groups. All regression analyses were performed using SYSTAT 11.

To assess whether and when dieback legacy effects were present I first inspected the climate data for exceptionally dry years that might have been sufficiently stressful to result in branch dieback. The subsequent year was then considered a legacy-year candidate, i.e., a year in which growth would be much lower than expected based on climate or streamflow conditions. I assessed whether legacy effects were present by sequentially excluding the candidate years in each of the datasets used in the multiple regression analyses. I expected to see an increase in model R^2 values after reanalysis with the reduced dataset.

I tested for an effect from CBP groundwater pumping on the Sand Creek trees closest to the project boundary, i.e., the 16 trees in the S4-Far group farthest from the channel (Figure 2, cluster G). I independently tested for an effect in three subgroups that differed in depth to groundwater as a result of their positions along a sandhill topographic gradient (S4-LOW, -MID, and -HIGH, $n = 8, 2,$ and 6 trees, respectively). The surface elevation difference between the low and high subgroups was ~ 3 m. I used sequential ANOVAs to compare the relationship between SGI and PDSIs before and after pumping began, first testing for a difference in slope of the relationship, and then, given no difference in slope, testing for a difference in intercept.

3. Results

3.1 Valley floor climate

Precipitation on the valley floor is bimodal, with long-term data indicating a peak in May and an even larger peak in August (Supplementary Online Material Figure A-1). Total annual monsoon-related precipitation (July through October) during 1991-2012 (the period when stream discharge was being monitored) ranged from 86 to 239 mm (Supplementary Online Material Figure A-2). Summer (June through August) precipitation (P_s) ranged from 50 to 189 mm during the same period (Figure 3), reflecting the strong dependence of P_s on monsoon-related precipitation ($r = 0.79$, $P < 0.001$, $n = 22$). A regional drought that began in 1999 (Henz et al., 2004) was well documented in the very low January through May (P_w) and annual precipitation totals for 2002 (Figure 3).

The seasonal Palmer Drought Severity Index (PDSIs) values document regional drought reaching severe levels in the 1930s, 1950s, and 2000s (Figure 4, upper panel). PDSIs and P_w were only weakly correlated ($r = 0.26$, $P = 0.052$; $n = 57$). Three unusually large between-year

shifts in conditions from relatively moist to dry (difference between consecutive PDSIs values < -6) were concentrated in a 25-year period, and occurred in years that had been independently selected during core processing as marker years for cross-dating: 1981, 1996, and 2002. No other year in the 20th century was characterized by a shift of similar magnitude (Figure 4, lower panel). Further, in all three cases the shift to dry conditions followed ≥ 2 years that featured moist and relatively stable PDSIs values (Figure 4, lower panel). I focused on these three years to assess whether dieback, assuming it had occurred, produced a subsequent legacy effect.

Several other recent years featured growing-season weather patterns that might have dramatically affected cottonwood growth. The 1987 PDSIs was the highest since 1942 (Figure 4 upper panel) and followed a series of very wet years. Record single-day and total monthly August precipitation (4.5 and 11.8 cm, respectively) were recorded at the Crestone climate station (Figure 1). A series of three wet years terminating in 1999, which featured a PDSIs = 3.96, resulted in the 1999 growing-season conditions being similar to those of 1987. The running 3-yr mean Pw for the period ending in 1999 was the 3rd largest in the 1951 to 2010 period. Finally, the spring and summer of 1995 was unusually cold. The monthly mean temperature for May (8 °C) was the lowest in the 1951-2007 period, and that followed the 9th coldest April, and preceded the fifth coldest June. Snow fell in April, May and June and three record low daily minimum temperatures occurred in July.

3.2 Stream hydrology

Discharge in Sand Creek typically exceeds that in Deadman Creek, and both creeks show large interannual variation during the spring and summer months. There was essentially no spring flood in 2002, and monsoon-related storms produced flash floods in several years (Figure 5). Sand Creek Q_{M3} and Q_{M30} values were at most only moderately correlated to PDSIs ($r = 0.15$ and 0.50 , respectively; Table 3), and neither flow variable was correlated to PDSIs in Deadman Creek ($r < 0.09$). Q_{M30} was strongly correlated to Pw at both Sand Creek ($r = 0.77$; Table 3) and Deadman Creek ($r = 0.71$, $P = 0.009$, $n = 12$).

Sand Creek discharge was comparatively low during spring and summer 2006 (Figure 5). A large flash flood (maximum mean daily flow $5.7 \text{ m}^3\text{s}^{-1}$) was recorded in mid-August, but the channel at Site S4 was dry when first visited three weeks later. In 2007, snowmelt produced a surface flow that filled the S4 channel by mid-May, but flow had ended by mid-July. The presence of surface flow at S4 in 2007, a year of moderate peak discharge and Q_{M3}

(Supplementary Online Material Figure A-3), suggests that a spring flow is present in the S4 reach most years.

Flow in the lowest Deadman Creek reach, D4, was subject to manipulation, and it is unclear whether surface water reached there during either the 2011 or 2012 spring flood. On 22 May 2012, I witnessed a diversion in operation between D3 and D4, and the channel at D4 was dry.

3.3 Water table depths and dynamics

3.3.1. Patterns in the study observation wells (sites S4, D2 and D4).— The absolute elevation of the water table in Sand Creek reach S4 declined with distance from the channel at least from early spring into autumn in both 2007 and 2008 (Figure 6A), indicating the presence of a lateral, channel-to-floodplain hydraulic gradient during the growing season. A longitudinal gradient was also present (e.g., from SW11 to SW6), reflecting the east-to-west hydraulic gradient from the Sangre de Cristo mountain front to the Closed Basin's central playa complex (Figure 6A). The water table at S4 showed a seasonal rise and fall in concert with the rise and fall in Sand Creek discharge, with the magnitude of the rise inversely related to distance from the active channel (Figure 7A). The water table appeared to be at or near its annual minimum by mid-October.

The autumn minimum groundwater elevation at S4 was higher in 2007 than in 2006, reflecting the higher summer flows of 2007 (Figure 5), but the interannual difference declined with distance from the channel, dropping from ~15 cm at the channel margin (Well SW6) to only 3 cm at a distance of 600 m (Well SW1; Figure 7B). During the 2007 growing season, daily water table fluctuations of 5- to ~15-cm were recorded under cottonwoods in Well SW2 (Figure 6B). Based on survey data and observed groundwater dynamics, the estimated mean depth to the water table at S4 ranged from ~1.0 to 2.5 m under the S4-Near trees, whereas it ranged from 1.6 to 5.0 m under the S4-Far trees (Table 4).

Groundwater dynamics in the Deadman Creek reaches differed markedly from those in Sand Creek's S4 reach. At D2, the water table beneath cottonwoods growing ~100 m from the incised channel rose slowly during autumn 2010, reached a winter high in February 2011—when creek discharge was low—and then began a very slow decline (Figure 6D). The water table was only a few centimeters below its February peak in mid-May, when it began to rise in concert with the 2011 spring flood pulse in Deadman Creek. That flood was relatively small and the response of the water table was a modest ~10 cm rise to the level reached the previous February (Figure 6D). The water table then tracked the receding limb of the flood pulse, falling by late summer to a

level ~36 cm below its previous mid-winter level. A similar autumn-through-late winter rise was observed in each of the following two years. Circadian water table fluctuations were noted under D2 trees during the growing season (Figure 6E). No comparable daily fluctuations were observed along either stream in the continuously-monitored wells located away from trees (wells SW1, SW3, and DW2). Mean water table depths at D2 were estimated to be ~1.7 m under the trees in the D2-Near group and ranged from ~1.7 to ~3.0 m under the trees in the D2-Far group (Table 4).

The water table in reach D4 (Well DW2) also slowly rose through the winter. In 2011, a high point was reached in early May (Figure 6D), ~2 weeks prior to a brief rise of ~18 cm that coincided with the spring flood pulse. As at D2, the water table then declined through the summer months (Figure 6D). The D4 water table dropped below the sensor position from August 2011 to February 2012, but a total decline of ~0.5 m from the previous peak appears reasonable based on the shapes of the declining and rising limbs of the associated curve (Figure 6D). In Spring 2012, there was a rapid rise in the D4 water table to a level ~70 cm higher than it had reached the previous year, but the rise abruptly ended and the water table dropped precipitously in mid-May.

The November 2010 survey data indicated a mean 0.43% slope for the water table between D2 and D4. This slope yields a depth to the water table under D3 trees of ~3.7 m at that time, assuming a planar water surface.

3.3.2. Patterns in the CBP observation wells.—Well EW31 was nearest CBP Stage 3, where pumping began in 1986 and production peaked in 1989 (Figure 8C). Records collected prior to initiation of pumping show the late autumn (November) water table dropping ~35 cm between 1982 and 1983 and rising ~50 cm between 1983 and 1984. This decline and rise contrasts with the prevailing climate conditions, which were dry in 1982 (PDSIs = -1.27), became wet in 1983 (PDSIs = 1.88) and even wetter in 1984 (PDSIs = 2.89).

Despite 1985, 1986, and 1987 being consecutively more wet than 1984 (Figure 4 upper panel), the November water table in EW31 dropped 69 cm between 1986 and 1987, coincident with initiation of the Stage 3 pumping (Figure 8C). (There are no Autumn 1985 data.) A 1986-1987 decline (44 cm) was also evident at Well EW54 (September records), near D4 (Figure 8B), although pumping had yet to start in the nearby Stage 4 area. Another large interannual decline (55 cm) was recorded in EW31 in the 1991-1992 November data, which coincided with initiation

of Stage 4 pumping. The decline contrasted with climate conditions, which were wet in 1990 and became very wet in both 1991 and 1992 (Figure 4 upper panel). No interannual fluctuation in a monthly record comparable to those at wells EW31 or EW54 was apparent at Well EW44 (Figure 8A).

The monthly water table elevations collected in the three CBP wells since the mid-1990s indicate the water table associated with the regional unconfined aquifer is consistently lowest in late-summer or autumn and highest in late-winter to early-spring (March-April; Figure 8). The 2007-2008 water table fluctuations in well EW31, near Sand Creek, show little similarity to those noted at S4 (Figure 6A and C), other than having an autumn minimum. In contrast, the 2011-2013 fluctuations in Well EW54, near Deadman Creek, clearly show the winter rise and summer decline observed at D2 and D4 (Figure 6D and F). There is no evidence in the EW31 record of the Sand Creek flood pulse affecting the spring-to-autumn water table decline there (Figure 6C), nor is there evidence of the Deadman Creek flood pulse affecting water table dynamics at EW54 (Figure 6F).

3.4 Streamflow and climate effects on narrowleaf cottonwood growth

Cores from 85 of the 96 sampled trees produced ring series with reliable PY assignments that extended to at least the beginning of the streamflow record. The longest series extended to the 1920s. Most trees showed distinctively narrow rings in 1981, 1996, and/or 2002 (Table 5). Trees also tended to show above-average growth in unusually-wet 1987 and below-average growth in unusually-cold 1995 (Table 5).

Interseries correlations of the mean SGI series varied from near zero to 0.46 (Table 5). Low values were generated where neighboring trees showed very different growth patterns. For example, the very low value for the D2-Near group of four trees was due in part to two trees that showed contrasting positive and negative SGI values during multiple, often lengthy periods ($r = -0.33$, $P = 0.014$). Which tree grew best varied among the periods (Figure 9). Logistic regression using years when one pattern ($n = 14$) or its opposite ($n = 14$) was evident suggested that T_{MAR} was a determining factor (odds ratio = 0.73; 95% confidence interval < 1.0), although model fit was poor (McFadden's $\rho^2 = 0.16$). The model suggested that when T_{MAR} was low (e.g., 30°F), the probability of one tree having an above-average SGI while the other had a below-average SGI was relatively high (0.78), whereas that probability fell to a relatively low value (0.28) when T_{MAR} was high (e.g., 37°F). An even more complex pattern was observed at

S1-Near, where all four trees appeared to be competing or otherwise responding independently to environmental conditions, leading to essentially no interseries correlation (Table 5).

3.4.1. Trees near the channel—Seven of the eight sites had trees growing quite close to the channel. The exception was D3, where the closest trees were >160 m away. For most “near” trees, the distance to the channel was < 30 m, but trees up to ~100 m away were included in the S4 “near” group (Table 4; Figure 2). A single SGI series was available to represent streamside trees at D1. I used the series in a Stage 1 analysis, but pooled the series with those from streamside trees at S2, which featured a similar physical environment (Table 1), for the Stage 2 analysis.

The Stage 1 “recent-years only” analyses using the full datasets produced models for only two of the six “near” groups (S1- and S2-Near) and the single D1-Near tree. No model was produced for the D2-, D4-, S3- or S4-Near trees. However, exclusion of 1996 and legacy-candidate year 1997 from the S4-Near dataset resulted in a model, as did the exclusion of legacy-candidate years 1997 and 2003 from the D4-Near data set (Table 6). Exclusion of both 1997 and 2003 failed to produce a model for either S3- or S4-Near trees (Table 6). Scatterplots identified 1996 (and 1972) as well as 1997 as outliers, with the 1996 SGI for S3-Near trees the lowest in the 50-yr series. Exclusion of 2003 failed to produce a model for D2-Near trees, but a model resulted from the exclusion of 1999, identified as a year of unusual weather. The seven models nominally explained from 33 to 64% of the variation in the SGI series during recent years (Table 4).

The mix of independent variables included in these seven Stage 1 models varied widely (Table 4); only two variables, Pw and P_{SMAX}, were not included in a model. A variable indexing summer precipitation was included in five models, in all cases through an inverse relationship between precipitation and growth. Streamflow variables were included in three of the four models for trees along Sand Creek; no streamflow variable was included in the model for S3, where the stream had incised and trees were over a very deep (≥ 3 m) water table. No model developed for Deadman Creek streamside trees included a streamflow variable. The water table was deep at D2, and moderately deep at D4. Water table depth at D1 was judged to be relatively shallow, but true depth and its dynamics were unknown. Four of the seven Stage 1 models included prior-year variables.

Inspection of the ring-width series for streamside trees at Site S2 indicated dramatically different growth patterns before and after 1987 (Supplementary Online Material Figure B-1). Because a major change in local environmental conditions was likely responsible for the shift, I performed separate Stage 2 analyses over the pre- and post-1987 periods for the S2-Near trees.

The Stage 2 “longest-period possible” analyses for the streamside groups produced models in five of the six possible cases. No model was produced for D4-Near trees even with the exclusion of legacy-candidate years 1997 and 2003, but scatterplots indicated 2002 also to be an outlier and its additional exclusion led to a significant model. Most variation in SGI at D4 was explained by an inverse relationship with prior-year Ps (Table 4). Overall, the Stage 2 models explained less of the variation in the SGI series (15 to 48%) than did the Stage 1 models. The variables included in the Stage 2 models often mirrored to some degree those in the Stage 1 model for the same trees. For example, the annual variation in SGI of S1-Near trees during 1994-2007 (Stage 1 analysis) was explained to a large extent by a model that contained current year Ps, prior-year Ps, and Q_{M30} , whereas annual variation over the full 52-yr long SGI series (1955-2007) was explained (to a much smaller extent) by a combination of current-year Ps and T_{MAY} (Table 4). Sand Creek Q_{M30} was negatively correlated to T_{MAY} ($r = -0.77$) during the discharge measurement period (Table 3), and thus Q_{M30} in the Stage 1 model might have been replaced by T_{MAY} in the Stage 2 model, assuming their association remained strong over the entire 1955-2007 period. Five of the Stage 2 models for streamside trees contained a variable indexing summer precipitation, and in four of those models that variable explained most of the variation.

3.4.2. Trees far from the active channel—Five of the eight sites had tree groups classified as far from the channel. Actual distances separating the sampled trees from the channel varied among both trees and sites (Table 4). S1-Far trees were relatively close to the channel but growing on a surface well above the stream channel. I include them in the “far” group because of their relative isolation from the stream through the presumably deep water table present. The largest distances (> 500 m) were for the majority of S4-Far trees (Figure 2: Group G). The SGI series for individual S2-Far trees showed a growth pattern shift ca. 1987 similar to that noted in the S2-Near trees, and I again split the SGI series into pre- and post-1987 periods for the Stage 2 analysis (Table 4). Site S2 was the only location where such an abrupt shift in growth pattern was observed.

The Stage 1 analysis produced a model for four of the five tree groups; no variable was entered into a model for S4-Far trees. Exclusion of legacy-candidate year 1997, however, resulted in a model for S4-Far trees that explained 71% of the variation in the recent SGI series (Table 4). A scatterplot of each year's SGI and P_{SMIN} values (Figure 10) confirmed the 1997 SGI as being an extremely low-value outlier. Overall, the five models explained from 23 to 71% of the variation in the recent SGI series.

Four of the five models included a streamflow variable, and in all cases it was the prior-year value. An index of summer precipitation was included in three models, and in all cases it was the current-year value (Table 4).

The Stage 2 analyses produced six models, including the two pre- and post-1987 models for S2-Far trees. Those two models were quite different, both in terms of the variables included and the amount of variation explained (Table 4). Overall, the six models explained from 22 to 85% of the variation in SGI values for trees growing far from the channel (Table 4).

Variables indexing summer precipitation were included in five of the six models. P_{SMIN} was the leading explanatory variable in two models (post-1987 S2-Far and D2-Far) and included in two others. Current-year PDSIs was the leading explanatory variable in two models (S1-Far and S4-Far). No variable indexing summer precipitation was included in the Stage 2 model for D3-Far trees. However, a scatterplot of the D3-Far trees' mean SGI values and P_{SMIN} values for the same year (Figure 10) revealed several outlier years, including legacy-candidate 1997, and suggested SGI was non-linearly related to P_{SMIN} . A statistically significant relationship ($P = 0.03$) became evident when four outlier years (1987 and 1995-97) were removed. The uncharacteristic growth in each of 1987, 1995, and 1996 coincided with unusual weather conditions.

Inspection of scatterplots comparing SGI values for "near" and "far" groups across years identified years when conditions were more-or-less equally favorable or equally unfavorable to the two groups. For example, the SGI was extraordinarily high in all Site S1 trees in 1987 (Supplementary Online Material Figure B-2), suggesting conditions for growth at that site were exceptionally favorable that year. The SGI values for trees in groups D3-Far and S4-Far were also very high that year (Figure 10). An analysis using logistic regression to elucidate a relationship between climate condition and the years in which the growth pattern dramatically differed between "near" and "far" trees was unfruitful.

3.5 Evidence for a legacy effect on cottonwood growth

I tested for the presence of dieback legacy effects in 10 tree groups (Table 6) distributed over six sites. Exclusion of a legacy-candidate year increased R^2 values in six of 17 Stage 1 models and 7 of 28 Stage 2 models (Table 6). Five of the six Stage 1 confirmations involved 1997, whereas five of the seven Stage 2 confirmations involved 2003. The presence of a legacy effect in 1982 was supported solely in the D2-Near trees.

3.6 Evidence for an effect from CBP groundwater pumping

The test for an effect from CBP groundwater extraction on the S4-LOW, -MID, and -HIGH trees detected an effect only in the S4-HIGH trees, which were growing on the highest landform and thus over the deepest groundwater (Table 7). All three groups showed similar fluctuations in SGI from 1985 through 1989—the period that spanned both the start and peak level of CBP pumping—and those fluctuations generally matched the expected responses to changes in PDSIs. However, the ANOVA for the S4-HIGH group indicated a shift in the relationship of SGI to PDSIs after CBP pumping began. Despite mean PDSIs values for 1966-1986 and 1987-2007 being nearly identical (1.327 and 1.331, respectively), growth in the S4-HIGH trees was depressed after pumping began ($P = 0.050$).

4. Discussion

4.1. Climate and streamflow effects on growth.

The very low interseries correlations for some groups (Table 5) could reflect inaccurate ring chronologies, a possibility that cannot be completely dismissed. However, a large effort was made to ensure ring-series accuracy and trees, even close neighbors, could clearly differ in their growth pattern (Figure 9). Moreover, the presence of such differences is not unexpected, given the potential for large between-tree variability in physiological condition in some years (e.g., variation in legacy effects associated with differential presence/absence or extent of dieback) coupled with more general differences in sensitivity to environmental conditions (e.g., due to variation in root architecture, clonal integration level, intraspecific competition, browsing injury, or other factor). Assuming accurate chronologies, the mean SGI series used in the analyses approximate a tree group's "average" response to environmental conditions.

The results of the Stage 1 regression analyses over the 12 to 14 years for which hydrologic data were available support the hypothesis that variation in weather and/or streamflow can explain major proportions of the variation in narrowleaf cottonwood growth along Sand and

Deadman creeks. However, the paucity of positive relationships between growth and a current-year streamflow variable was unexpected. This may reflect a relatively low probability of insufficient soil water and very shallow depth to ground water commonly found under these trees. The models indicated streamside trees had growth reduced by current-year factors contributing to soil saturation at rooting depth during the growing season, particularly high levels of summer precipitation. An inverse relationship to summer precipitation (as either P_s or P_{SMIN}) was included in four of the seven models developed for such trees (Table 4), and in two cases (S1- and S2-Near) the same relationship appeared in the Stage 2 model. Once saturated, a warm soil can quickly become anoxic through O_2 uptake by microbes, and roots in such soils may cease to function or die (Cao and Conner, 1999; Pregitzer and Friend, 1996), either of which would reduce growth in aboveground plant parts. The overriding importance of this constraining influence on growth of streamside cottonwoods is further underscored by the common occurrence of an inverse relationship to a prior-year streamflow or climate variable in the Stage 1 models. Late-growing season soil saturation the prior year would hinder production and storage of carbon and other resources critical for early-season flower and foliage production.

Positive relationships between growth and environmental variables were more common in the models for trees growing far from the channel. Although no Stage 1 model included a current-year flow variable, inverse relationships to a prior-year flow variable appeared in several (S4-, D2-, and D3-Far), suggesting these trees were not fully independent of the stream's influence on the water table beneath them. Positive relationships to PDSIs, dominant in two Stage 2 models (S1- and S4-Far) and contributors in three others (pre-1987 S2-, D2-, and D3-Far) point to the importance of overall growing season moisture availability for these trees. The prominence of a positive relationship to a monthly temperature in two groups (pre-1987 S2- and D3-Far) could be interpreted to mean a warm spring is beneficial, but the particular variables involved (T_{APR} and T_{MAY}) were inversely correlated to P_w and P_s , as well as Sand Creek Q_{M30} (Table 3) during the period when streamflow data were being collected. Thus, the effects of temperature and moisture excess may be confounded, and remain to be resolved. Taken together, the variability in the Stage 1 and Stage 2 models for the “near” and “far” tree groups suggest a complex relationship exists among streamflow, the regional aquifer, and summer precipitation in determining annual growth in these trees. The appearance of P_{SMIN} or P_s in the

majority of models points to the large effect from summer and monsoon precipitation on growth in these trees.

4.2 Evidence that Closed Basin cottonwoods are phreatophytic.

All of the narrowleaf cottonwoods examined in this study must rely on groundwater to some extent for their survival. Given the small amount of precipitation directly deposited on valley floor landforms, soil moisture at mature cottonwood rooting depths is supplied primarily by either infiltrating stream water or by water in the regional unconfined aquifer. The phreatophytic nature of the trees in this study was demonstrated by the presence of circadian water table fluctuations under trees during the growing season (Figure 6B and 6E) (Gribovszki et al., 2010).

Narrowleaf cottonwood rooting depth varies with local soil moisture conditions, and can be relatively deep compared to other *Populus* species (Rood et al., 2011). Nevertheless, not all of the cored trees may be independently phreatophytic. Wiehle et al. (2009) examined clonal stands of Euphrates poplar (*P. euphratica*) and found that ramets originating as root suckers did not develop a deep tap root and maintained a connection to the parental tree for some years. How long the parent-sucker connection remains functional in narrowleaf cottonwood is unclear, but in trembling aspen (*P. tremuloides*) the connection can remain functional for many decades, even after the death of the aboveground part of the parent tree (DesRochers and Lieffers, 2001). The irregular topography in the riparian corridor produced strong differences in depth-to-the-water table under trees only 10-20 m apart. Thus, specific locations of ramets as well as the clone itself may have influenced growth patterns. For example, water transfers between interconnected ramets growing in low and high topographic positions may have reduced adverse effects from drought-induced water table decline or other environmental factor that stressed nearby but unconnected trees on the same high surface (Peltzer, 2002). Such differences could help explain the low interseries correlation observed in some tree groups.

4.3 Closed Basin shallow groundwater sources.

Both Sand and Deadman creeks continuously lose water as they move away from the mountain front (Wurster et al., 2003), thereby contributing to annual recharge of the regional shallow unconfined aquifer. Their water adds to that from the multitude of small channels along the mountain front that contain surface flow only during spring snowmelt or other large runoff events. Recharge by direct precipitation on the valley floor is probably minor, with the result that the groundwater flow system recharges primarily along the entire Sangre de Cristo mountain

front and flows toward the Closed Basin center (Emery et al., 1971; Mayo et al., 2007). A groundwater wave is presumably generated each year by mountain snowmelt and rainfall runoff that produces both diffuse and focused surface and subsurface contributions to the unconfined aquifer (mountain-front recharge).

At both wells SW1 and DW1, most distant from the channel, the decline in the water table that coincided with the recession of the spring flood flows (Figure 6A and 6D) indicates that hydraulic conductivity is high and any rise in the riparian water table produced by stream flooding lasts only as long as the flood. This implies that the water table's annual autumn minimum, subsequent rise and winter peak at Deadman site D2 is determined by conditions in the regional unconfined aquifer. The 2011 wave peak reached site D2 in about mid-February and site D4 in mid-May (Figure 6C), suggesting 3 months were required for the wave to travel the 4.5 km between the two sites. Given that D2 is ~7 km from the mountain front and assuming a similar propagation speed, the wave can be estimated to have originated near the mountain front east of D2 during the spring-to-autumn runoff period of the previous year.

If this scenario is correct, the peak height of the water table at site D2 in February 2011 was determined primarily by the moderately-sized 2010 spring runoff, because monsoon-related runoff was slight. The 2012 groundwater pulse was in turn determined by 2011 spring snowmelt and monsoon-related runoff. Such a lag would explain the contrasting patterns in annual PDSIs values and water table dynamics noted in CBP observation well EW31 prior to the start of project pumping. The lag may also be responsible for D2 trees far from the channel showing a negative effect from prior-year P_{SMIN} (Table 4). Whereas total summer rainfall tends to vary somewhat slowly over multiyear periods, P_{SMIN} reflects the nature of the driest summer month and varies sharply from near zero to high values almost annually (Supplementary Online Material Figure A-4). An above-average P_{SMIN} immediately followed a well-below average P_{SMIN} in 13 of the 57 years from 1951 to 2007, including 1995, 1999, 2003, and 2006.

4.4 *Narrowleaf cottonwood tree locations.*

The sampled trees growing far from the present channel presumably established in a different hydrologic environment, or the clonal parent tree did. Seed germination requires a moist surface and seedling establishment requires rooting zone moisture and a landscape position safe from desiccation and scour until the plant becomes phreatophytic. These conditions are typically provided by a streamside location (Baker, 1990). The sampled trees' current locations

far from the channel could be due to a shift in the active channel's position (e.g., avulsion during a flood event) or channel abandonment (e.g., through a meander-neck breach). Such an event at Site S2 might explain the 1987 shift in growth pattern observed in both the "near" and "far" tree groups there. Alternatively, current "far" tree location could reflect seedling establishment outside of the normal floodplain, incidental to flow diversions made as part of historic water management operations.

4.5 Groundwater sources, groundwater dynamics, and cottonwood dependencies.

Taken together, the models for tree growth and the information on regional and streamside water table dynamics suggest trees near the channel are dependent on local streamflow whereas trees far from the channel rely on the regional unconfined aquifer to supply soil moisture. Interannual dynamics in the regional aquifer are less variable than those in the streamside water table, suggesting environmental factors other than streamflow, e.g., growing season length, growing season temperature, or seasonal precipitation, contribute more to variation in the SGI of trees far from the channel. Early growing season temperature was variable in its role among individual models, perhaps reflecting microclimatic differences among the tree group locations. Warm early spring months may promote early foliage development and a longer growing season, but they also increase the risk of foliage-killing spring frost in areas of cold-air drainage. Such frosts would result in a shift in carbon allocation from wood production to development of replacement foliage. A warm spring can also be detrimental when or where extensive foliage development (high leaf area) combines with temperature-sensitive evaporative demand to produce transpiration rates that exceed water uptake rates.

The poor model fit for some tree groups (e.g., S1-Far) might also reflect genetically-based variability among neighboring trees in vulnerability to environmental stressors. Male narrowleaf cottonwoods are less tolerant of flooding and may be more tolerant to drought than female trees (Nielsen et al., 2010; Rood et al., 2010). Also, the initiation and ultimate extent of canopy dieback is dependent on moisture stress history (Anderegg et al., 2013), as well as the presence or absence of physical connections among ramet root systems (Gom and Rood, 1999). Finally, relationships between SGI and climate or streamflow may have in some cases been masked by effects from browsing. Elk (*Cervus elaphus*) were present at all eight study sites, and bison (*Bison bison*) were present at Sand Creek site S4. Both species will browse cottonwoods. In a 4-yr study overlapping this one, Schoenecker (2012) estimated that 47% of cottonwood sprouts and

twigs in the Closed Basin were browsed each year. The SLV elk population expanded from ~1000 to ~5000 individuals during 1983-2000 (B. C. Lubow and K. Schoenecker, unpublished data) and sampled trees that were young in the 1980s would have been directly vulnerable to browsing. Older, larger trees, even if not browsed themselves, may be vulnerable to reductions in SGI if they reallocate photosynthate from supporting radial growth to subsidizing regrowth in browsed sprouts (Ishihama et al., 2014).

The uncharacteristically poor growth documented in the outlier years 1982, 1997, and 2003 strongly supports the notion that canopy dieback occurred in the drought years of 1981, 1996, and 2002. The results from sequentially excluding the legacy-candidate years in the regression analyses (Table 6) suggest dieback varied in intensity both spatially and temporally. Although the 2002 dieback may have attracted the attention of the field biologists, it likely only added to the number of dead branches already in the canopy.

Closed Basin Project pumping appeared to have reduced growth in trees closest to the project boundary, but only those over the deepest groundwater (S4-HIGH). Detection of an effect in neighboring but lower trees may have been hindered by the shorter pre-pumping SGI series available for those trees (Table 7). The large 1986-1987 reduction in the water table at wells EW31 and EW44 was almost certainly attributable to initiation of CBP Stage 3 pumping, and the depression documented in those wells presumably reached site S4. The S4-LOW trees showed growth patterns from 1985 through 1989 that could reasonably be explained as responses to changes in PDSIs or associated climate variables. However, the greater depth to groundwater under the S4-HIGH trees may have made them particularly sensitive to even a small drop in the regional water table (Shafroth et al., 2000).

Although a small number of studies have examined environmental influences on growth in naturally established narrowleaf cottonwood (e.g., Gom and Rood, 1999; Rood et al., 2013; Willms et al., 2006), this is the first study to examine a population in the southern portion of its range. My results are generally consistent with those of Rood et al. (2013), who found a strong association between annual basal area increment and streamflow in mature narrowleaf cottonwood on the regulated Oldman River in southern Alberta, Canada. They found a combination of current- and prior-year mean growing season discharges could explain 36% of the variation in annual growth over their 17-yr long study period. In contrast to my study,

however, growth in their trees was unrelated to local growing season precipitation or mean temperature.

Studies of other riparian *Populus* species support the idea that these trees, through plasticity of root and crown architecture, can adapt to changes in the water supply within certain limits. Most notably, Scott et al. (1999) assessed effects of in-channel mining on growth in Plains cottonwoods (*P. deltoides*). They reported that a 0.5-m gradual and permanent drop in the water table caused only a small reduction in annual branch growth, and no branch dieback or change in radial growth, whereas a 1-m permanent drop resulted in leaf desiccation, branch dieback, and eventually the death of most sampled trees. Similarly, Scott et al. (2000) documented a greater proportion of dead trees and reduced radial growth in stands of riparian Fremont cottonwood that had been exposed to abrupt, sustained water table declines brought about by channel incision and/or avulsion.

4.6 Conclusions

The narrowleaf cottonwoods fringing Sand and Deadman creeks depend on groundwater supplied by the stream, by the regional aquifer, or both. With the caveat that the period of record is short for both the stream discharge and water table elevation data (Kennard et al., 2010), I conclude that stream discharge has little or no direct effect on the growth of cottonwoods growing far from the channel. Instead, those trees now depend on the regional unconfined aquifer, direct infiltration of growing-season precipitation, or both to meet their water demands. Together, the Stage 1 and Stage 2 models indicate that local climate is an important determinant of annual tree growth for most of the trees along Sand and Deadman creeks, and that prior-year conditions play a significant role. The difference in environmental conditions under which seedlings establish and those under which many adult trees are currently living indicate the species is adaptable to a changing hydrologic environment. Nevertheless, because of the reliance of the trees on either streamflow or the regional shallow aquifer, factors affecting those sources of water will influence tree radial growth and, presumably, overall tree vigor. Even within a site, effects can be expected to differ among individual ramets based on their landscape position (depth to groundwater) and the physical connections among root systems. Globally, populations of dryland riparian trees in similar hydrologic settings can be expected to show similar variability in water-source dependency. The full nature and extent of effects from groundwater declines produced by the Closed Basin Project on nearby narrowleaf cottonwoods remain unclear. It is

clear, however, that streamflow diversion—or its elimination—has the potential to strongly affect these trees' productivity, as will any shift in winter or monsoon precipitation associated with global climate change.

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References

- Anderegg, W.R.L., Plavcova, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A., Field, C.B., 2013. Drought's legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology* 19, 1188-1196. DOI: 10.1111/gcb.12100.
- Andersen, D.C., 2016. Flow regime effects on mature *Populus fremontii* (Fremont cottonwood) productivity on two contrasting dryland river floodplains. *The Southwestern Naturalist* 61, 8-17. DOI: 10.1894/0038-4909-61.1.8
- Andersen, D.C., Cooper, D.J., Northcott, K., 2007. Dams, floodplain land use, and riparian forest conservation in the semiarid Upper Colorado River Basin, USA. *Environmental Management* 40, 453-475. DOI: 10.1007/s00267-006-0294-7.

- 737 Argus, G.W., Eckenwalder, J.E., Kiger, R.W., 2010. Salicaceae Mirbel, willow family, in: Flora
738 of North America Editorial Committee (Eds.), Flora of North America North of Mexico,
739 Vol. 7. Oxford University Press, New York.
- 740 Baker, W.L., 1990. Climatic and hydrologic effects on the regeneration of *Populus angustifolia*
741 James along the Animas River, Colorado. Journal of Biogeography 17, 59-73.
- 742 Bence, J.R., 1995. Analysis of short time series: correcting for autocorrelation. Ecology 76, 628-
743 639. DOI: 10.2307/1941218.
- 744 Braatne, J.H., Rood, S.B., Heilman, P.E., 1996. Life history, ecology, and conservation of
745 riparian cottonwoods in North America, in: Stettler, R.F., Bradshaw, H.D., Jr., Heilman,
746 P.E., Hinckley, T.M. (Eds.), Biology of *Populus* and its implications for management and
747 conservation. NRC Research Press, Ottawa, Canada, pp. 57-85.
- 748 Cao, F.L., Conner, W.H., 1999. Selection of flood-tolerant *Populus deltoides* clones for
749 reforestation projects in China. Forest Ecology and Management 117, 211-220.
- 750 Cook, E.R., Briffa, K.R., Shiyatov, S.G., Mazepa, V.S., 1990. Tree-ring standardization and
751 growth-trend estimation, in: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of
752 Dendrochronology. Kluwer, Dordrecht, Netherlands, pp. 104-123.
- 753 DesRochers, A., Lieffers, V.J., 2001. The coarse-root system of mature *Populus tremuloides* in
754 declining stands in Alberta, Canada. Journal of Vegetation Science 12, 355-360. DOI:
755 10.2307/3236849.
- 756 Edmondson, J., Friedman, J., Meko, D., Touchan, R., Scott, J., Edmondson, A., 2014.
757 Dendroclimatic potential of plains cottonwood (*Populus deltoides* ssp. *monilifera*) from
758 the northern Great Plains, USA. Tree-Ring Research 70, 21-30. DOI: 10.3959/1536-
759 1098-70.1.21.
- 760 Ellison, A.M., Bank, M.S., Clinton, B.D., Colburn, E.A., Elliott, K., Ford, C.R., Foster, D.R.,
761 Kloeppe, B.D., Knoepp, J.D., Lovett, G.M., Mohan, J., Orwig, D.A., Rodenhouse, N.L.,
762 Sobczak, W.V., Stinson, K.A., Stone, J.K., Swan, C.M., Thompson, J., Von Holle, B.,
763 Webster, J.R., 2005. Loss of foundation species: consequences for the structure and
764 dynamics of forested ecosystems. Frontiers in Ecology and the Environment 3, 479-486.
765 DOI: 10.2307/3868635.

- Emery, P.A., Boettcher, A.J., Snipes, R.J., McIntyre, H.J., 1971. Hydrology of the San Luis Valley, south-central Colorado. U.S. Geological Survey Hydrologic Investigations Atlas HA-381. U. S. Geological Survey, Washington, D. C.
- Gom, L.A., Rood, S.B., 1999. Patterns of clonal occurrence in a mature cottonwood grove along the Oldman River, Alberta. Canadian Journal of Botany 77, 1095-1105.
- Gribovszki, Z., Szilagyi, J., Kalicz, P., 2010. Diurnal fluctuations in shallow groundwater levels and streamflow rates and their interpretation - a review. Journal of Hydrology 385, 371-383. DOI:10.1016/j.jhydrol.2010.02.001
- Grissino-Mayer, H.D., 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57, 205-221.
- Hadlock, G.L., Lachmar, T.E., McCalpin, J.P., 1997. The relationship between the water table and the surface flow of a losing stream, lower Medano Creek, Great Sand Dunes National Monument, Colorado. Environmental Geology 30, 10-16.
- Harte, J.J., Valdez, A.D., Stevenson, S.A., 2007. Seepage investigation of Deadman Creek, Sand Creek, Big Spring Creek, and Little Spring Creek, September 22, 23, and 24, 2004, Great Sand Dunes National Park and Preserve Colorado. Natural Resource Technical Report NPS/NRPC/WRD/NRTR-2007/071. National Park Service, Fort Collins, Colorado.
- Henz, J., Turner, S., Badini, W., Kenny, J., 2004. Historical perspectives on Colorado drought. Colorado Water Conservation Board. Available online: http://cwcb.state.co.us/apps/drought_water/html/chapter01.html (accessed 29 April 2013).
- Board, C.W.C.
- Ishihama, F., Fujii, S., Yamamoto, K., Takada, T., 2014. Estimation of dieback process caused by herbivory in an endangered root-sprouting shrub species, *Paliurus ramosissimus* (Lour.) Poir., using a shoot-dynamics matrix model. Population Ecology 56, 275-288. DOI: 10.1007/s10144-013-0414-1.
- Johnson, R.B., 1967. The Great Sand Dunes of southern Colorado. U.S. Geological Survey Professional Paper 575-C, C177-C183. U. S. Geological Survey, Washington, D. C.
- Kennard, M.J., Mackay, S.J., Pusey, B.J., Olden, J.D., Marsh, N., 2010. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. River Research and Applications 26, 137-156. DOI: 10.1002/rra.1249

- 796 Levick, L., Fonseca, J., Goodrich, D., Hernandez, M., Semmens, D., Stromberg, J., Leidy, R.,
797 Scianni, M., Guertin, D.P., Tluczek, M., Kepner, W., 2008. The ecological and hydrological
798 significance of ephemeral and intermittent streams in the arid and semi-arid American
799 Southwest. U.S. Environmental Protection Agency and USDA/ARS Southwest Watershed
800 Research Center. EPA/600/R-08/134, ARS/233046. Environmental Protection Agency,
801 Washington, D. C.
- 802 Mayo, A.L., Davey, A., Christiansen, D., 2007. Groundwater flow patterns in the San Luis
803 Valley, Colorado, USA revisited: an evaluation of solute and isotopic data. Hydrogeology
804 Journal 15, 383-408. DOI: 10.1007/s10040-006-0079-3
- 805 Meko, D.M., Friedman, J.M., Touchan, R., Edmondson, J.R., Griffin, E.R., Scott, J.A., 2015.
806 Alternative standardization approaches to improving streamflow reconstructions with
807 ring-width indices of riparian trees. The Holocene 25, 1093-1101. DOI:
808 10.1177/0959683615580181.
- 809 Mix, K., Lopes, V.L., Rast, W., 2011. Annual and growing season temperature changes in the
810 San Luis Valley, Colorado. Water Air and Soil Pollution 220, 189-203. DOI:
811 10.1007/s11270-011-0746-4.
- 812 Nielsen, J.L., Rood, S.B., Pearce, D.W., Letts, M.G., Jiskoot, H., 2010. Streamside trees:
813 responses of male, female and hybrid cottonwoods to flooding. Tree Physiology 30, 1479-
814 1488. DOI: 10.1093/treephys/tpq089.
- 815 Obedzinski, R.A., Shaw, C.G., III, Neary, D.G., 2001. Declining woody vegetation in riparian
816 ecosystems of the western United States. Western Journal of Applied Forestry 16, 169-181.
- 817 Palmer, W.C., 1965. Meteorological drought. U. S. Weather Bureau, Office of Climatology
818 Research Paper 45. Washington, D. C.
- 819 Peltzer, D.A., 2002. Does clonal integration improve competitive ability? A test using aspen
820 (*Populus tremuloides* Salicaceae) invasion into prairie. American Journal of Botany 89,
821 494-499. DOI: 10.3732/ajb.89.3.494.
- 822 Perry, L.G., Andersen, D.C., Reynolds, L.V., Nelson, S.M., Shafroth, P.B., 2012. Vulnerability
823 of riparian ecosystems to elevated CO₂ and climate change in arid and semiarid western
824 North America. Global Change Biology 18, 821-842. DOI: 10.1111/j.1365-
825 2486.2011.02588.x.

- 826 Pregitzer, K.S., Friend, A.L., 1996. The structure and function of *Populus* root systems, in:
827 Stettler, R.F., Bradshaw, H.D., Jr., Heilman, P.E., Hinckley, T.M. (Eds.), Biology of
828 *Populus* and its implications for management and conservation. NRC Research Press,
829 Ottawa, Canada, pp. 331-354.
- 830 Reclamation, Bureau of, 2003. Relocation of Salvage Wells, Closed Basin Division, San Luis
831 Basin Project, Colorado. Finding of no significant impact and environmental assessment.
832 Biological Assessment. Final. Albuquerque Area Office, Upper Colorado Region.
833 Albuquerque, New Mexico.
- 834 Rood, S., Bigelow, S., Hall, A., 2011. Root architecture of riparian trees: river cut-banks provide
835 natural hydraulic excavation, revealing that cottonwoods are facultative phreatophytes.
836 Trees-Structure and Function 25, 907-917. DOI: 10.1007/s00468-011-0565-7.
- 837 Rood, S.B., Ball, D.J., Gill, K.M., Kaluthota, S., Letts, M.G., Pearce, D.W., 2013. Hydrologic
838 linkages between a climate oscillation, river flows, growth, and wood $\Delta^{13}\text{C}$ of male and
839 female cottonwood trees. Plant, Cell & Environment 36, 984-993. DOI: 10.1111/pce.12031.
- 840 Rood, S.B., Nielsen, J.L., Shenton, L., Gill, K.M., Letts, M.G., 2010. Effects of flooding on leaf
841 development, transpiration, and photosynthesis in narrowleaf cottonwood, a willow-like
842 poplar. Photosynthesis Research 104, 31-39. DOI: 10.1007/s11120-009-9511-6.
- 843 Rood, S.B., Patiño, S., Coombs, K., Tyree, M.T., 2000. Branch sacrifice: Cavitation-associated
844 drought adaptation of riparian cottonwoods. Trees-Structure and Function 14, 248-257.
- 845 Rood, S.B., Samuelson, G.M., Braatne, J.H., Gourley, C.R., Hughes, F.M.R., Mahoney, J.M.,
846 2005. Managing river flows to restore floodplain forests. Frontiers in Ecology and the
847 Environment 3, 193-201. DOI: 10.1890/1540-9295(2005)003[0193:MRFTRF]2.0.CO;2.
- 848 Schoenecker, K.A., 2012. Ecology of bison, elk, and vegetation in an arid ecosystem, PhD.
849 Dissertation. Colorado State University, Fort Collins, Colorado.
- 850 Scott, M.L., Lines, G.C., Auble, G.T., 2000. Channel incision and patterns of cottonwood stress
851 and mortality along the Mojave River, California. Journal of Arid Environments 44, 399-
852 414.
- 853 Scott, M.L., Shafroth, P.B., Auble, G.T., 1999. Responses of riparian cottonwoods to alluvial
854 water table declines. Environmental Management 23, 347-358.
- 855 Shafroth, P.B., Stromberg, J.C., Patten, D.T., 2000. Woody riparian vegetation response to
856 different alluvial water table regimes. Western North American Naturalist 60, 66-76.

- 857 Shafroth, P.B., Wilcox, A.C., Lytle, D.A., Hickey, J.T., Andersen, D.C., Beauchamp, V.B.,
858 Hautzinger, A., McMullen, L.E., Warner, A., 2010. Ecosystem effects of environmental
859 flows: modelling and experimental floods in a dryland river. *Freshwater Biology* 55, 68-85.
860 DOI: 10.1111/j.1365-2427.2009.02271.x
- 861 Soykan, C.U., Brand, L.A., Ries, L., Stromberg, J.C., Hass, C., Simmons, D.A., Jr., Patterson,
862 W.J.D., Sabo, J.L., 2012. Multitaxonomic diversity patterns along a desert riparian–upland
863 gradient. *PLoS ONE* 7, e28235. DOI: 10.1371/journal.pone.0028235.
- 864 Stromberg, J.C., Merritt, D.M., 2015. Riparian plant guilds of ephemeral, intermittent and
865 perennial rivers. *Freshwater Biology*, n/a-n/a. DOI: 10.1111/fw.12686.
- 866 Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends.
867 *Environmental Conservation* 29, 308-330. DOI: 10.1017/S037689290200022X.
- 868 Wiehle, M., Eusemann, P., Thevs, N., Schnittler, M., 2009. Root suckering patterns in *Populus*
869 *euphratica* (Euphrates poplar, Salicaceae). *Trees-Structure and Function* 23, 991-1001.
870 DOI: 10.1007/s00468-009-0341-0.
- 871 Willms, C.R., Pearce, D.W., Rood, S.B., 2006. Growth of riparian cottonwoods: a developmental
872 pattern and the influence of geomorphic context. *Trees-Structure and Function* 20, 210-218.
873 DOI: 10.1007/s00468-005-0027-1.
- 874 Wurster, F.C., Cooper, D.J., Sanford, W.E., 2003. Stream/aquifer interactions at Great Sand
875 Dunes National Monument, Colorado: influences on interdunal wetland disappearance.
876 *Journal of Hydrology* 271, 77-100. DOI: 10.1016/S0022-1694(02)00317-7.
- 877 Yamaguchi, D.K., 1991. A simple method for cross-dating increment cores from living trees.
878 *Canadian Journal of Forest Research* 21, 414-416. DOI: 10.1139/x91-053.

Table 1. Sites along Sand and Deadman creeks where relationships between Fremont cottonwood radial growth and local hydrologic conditions were investigated.

Site (altitude, m)	Stream			Floodplain soil texture‡	Observation wells		
	Geomorphic setting	Flow character	Channel condition		Number	ID	Monitoring period
S1 (~2484)	Semi- confined†	Perennial?	Incised?	Variably thin (<1 m to ~2.5 m) sands over cobble	None		---
S2 (~2414)	Unconfined	Perennial?	Unincised	Variably thin (<1 m to ~2.5 m) sands over cobble	None		---
S3 (~2399)	Semi- confined	Perennial?	Incised	Variably thin (1 to ~2.5 m) sands over cobble	None		---
S4 (~2316)	Unconfined	Ephemeral	Unincised	Thick sands	12	SW-1 to SW12	October 2006 to September 2008#
D1 (~2377)	Unconfined	Perennial?	Unincised	Sand and silt (<1 m) over cobble	None		---
D2 (~2327)	Unconfined	Ephemeral?	Incised	Thick sands with a 5-cm thick clay lens at 1.5-m depth	1	DW1	1 Dec 2010 through May 2012**
D3 (~2319)	Unconfined	Ephemeral	Slightly incised	Fine sands with clay lenses	None		---
D4 (~2307)	Unconfined	Ephemeral	Unincised	Fine sands with clay lenses	1	DW2	1 Dec 2010 through May 2012

†The segment of Sand Creek containing S1, S2 and S3 transects the major transverse dune field of Great Sand Dunes National Park and passes through an area featuring fixed parabolic and active parabolic dunes of accumulation (Johnson, 1967).

‡Observed during installation of hand-augered observation wells; shallow cobble precluded well installation at sites S1, S2, S3, and D1.

S4 groundwater levels during the 2007 growing season were monitored manually every few weeks (9 wells) or at 3-hr intervals using vented water-level loggers (GlobalWater Model WL15; wells SW1, SW2 and SW3). Wells were monitored manually on a sporadic basis during the 2008 growing season.

**Groundwater level at sites D2 and D4 were monitored continuously using unvented Onset® Hobo U20-001-04 pressure sensor/loggers and an associated non-submerged sensor recording local barometric pressures for compensation calculations.

Table 2. Hydrologic and meteorological variables assessed for their effect on radial growth of Fremont cottonwood present on the floodplains of Sand and Deadman creeks in Great Sand Dunes National Park. Both current and previous year values were assessed for the two discharge variables, PDSIs, and Ps, thus producing a total of 15 variables.

Symbol	Environmental variable	Definition	Data period	
			Sand Creek	Deadman Cr.
Q _{M3}	Maximum 3-day discharge	During 1 May to 15 July	1994-2007	1999-2010
Q _{M30}	Maximum 30-day discharge	During 1 May to 15 July	1994-2007	1999-2010
P _W	Late winter & spring precipitation	Total precipitation January through May	1951-2007	1951-2007
P _S	Summer precipitation	Total precipitation June through August	1951-2007	1951-2007
P _{SMAX}	Maximum total monthly summer precipitation	Maximum monthly precipitation among June, July and August	1951-2007	1951-2007
P _{SMIN}	Minimum total monthly precipitation	Minimum monthly precipitation among June, July, August and September	1951-2007	1951-2007
T _{MAR}	Mean March air temperature		1951-2007	1951-2007
T _{APR}	Mean April air temperature		1951-2007	1951-2007
T _{MAY}	Mean May air temperature		1951-2007	1951-2007
T _{JUN}	Mean June air temperature		1951-2007	1951-2007
PDSIs	Seasonal Palmer Drought Severity Index	Mean of January through July monthly PDSI values	1900-2007	1900-2010

Table 3. Pearson correlation matrix for 15 environmental variables considered in assessment of hydrologic factors affecting growth of floodplain narrowleaf cottonwood along Sand Creek ($n = 14$ years, 1994-2007). Variable abbreviations are defined in Table 2. Values in bold text are ≥ 0.70 .

	PDSI _S	PYPDSI _S	P _W	P _S	PYP _S	P _S MAX	P _S MIN	Q _{M3}	PYQ _{M3}	Q _{M30}	PYQ _{M30}	T _{MAR}	T _{APR}	T _{MAY}	T _{JUN}
PDSI _S	1.00														
PYPDSI _S	0.69	1.00													
P _W	0.45	-0.05	1.00												
P _S	0.35	-0.12	0.38	1.00											
PYP _S	0.48	0.44	-0.17	0.20	1.00										
P _S MAX	0.32	-0.14	0.42	0.82	0.40	1.00									
P _S MIN	0.18	-0.003	0.22	0.47	-0.17	-0.02	1.00								
Q _{M3}	0.15	-0.34	0.46	0.46	-0.32	0.25	0.38	1.00							
PYQ _{M3}	0.02	0.11	-0.40	0.29	0.54	0.46	-0.22	-0.23	1.00						
Q _{M30}	0.50	-0.05	0.77	0.47	-0.11	0.42	0.20	0.78	-0.21	1.00					
PYQ _{M30}	0.22	0.54	-0.28	-0.03	0.49	0.10	-0.13	-0.35	0.76	-0.26	1.00				
T _{MAR}	0.17	-0.16	0.52	0.41	0.01	0.36	0.39	-0.09	0.02	0.08	0.03	1.00			
T _{APR}	-0.46	0.04	-0.67	-0.57	-0.24	-0.61	-0.38	-0.49	-0.15	-0.70	-0.10	-0.36	1.00		
T _{MAY}	-0.49	-0.04	-0.64	-0.47	0.03	-0.32	-0.35	-0.46	0.16	-0.77	0.19	-0.36	0.56	1.00	
T _{JUN}	-0.28	0.17	-0.59	-0.26	0.10	-0.19	-0.33	-0.43	0.21	-0.63	0.22	-0.24	0.72	0.54	1.00

Table 4. Qualitative results of stepwise-forward multiple regression analysis relating narrowleaf cottonwood annual standardized growth index (SGI) values to recent streamflow and climate variables over the length of the streamflow record, and to solely climate variables over the longest period possible (determined by SGI series length). Analyses are for Sand Creek (S) and Deadman Creek (D) tree groups classified as “near to” or “far from” the stream channel (see text for full details). Mean depth to the water table under the analyzed trees is an estimate for October 2007. N = number of trees contributing to the SGI series used in the recent-years analysis; the number of contributing trees in the longest-period analysis declined as the SGI series lengthened, but was never less than three. $P(\text{entry}) = P(\text{remove}) = 0.15$ unless otherwise noted. Final model probability: $*$ = <0.05 , $**$ = ≤ 0.01 , $***$ = ≤ 0.001 . The number of years of data in the analysis (n) was 13-14 for all Sand Creek and 11-12 for all Deadman Creek recent-year analyses. The first variable entered into the model is indicated with **bold** font; the sign (positive or negative) indicates the direct or inverse nature of the relationship.

Tree Grp	Dist. to chan. (m)	Mean water table depth (m)	Time period in the SGI series examined													
			Recent years only (both climate and streamflow variables)						Longest period possible (climate variables only)							
			N	Environmental variables in the final model				Model statistics		Environmental variables in the final model				Model statistics		
				Current year		Prior year		P	Adj. R ²	Current year		Prior year		P	n	Adj. R ²
				+	-	+	-			+	-	+	-			
Site S1																
S1-Near	≤ 20	< 2.5	4		P_S	Q_{M30}	P_S	**	0.63		P_S, T_{MAY}		**	52	0.17	
S1-Far	> 50	> 4	5			Q_{M30}		0.07 ^a	0.23	PDSI_S, P_W, T_{MAY}	P_SMIN		**	52	0.24	
Site S2																
S2-Near ^b (post-1987)	≤ 30	< 1.5	6	Q_{M3}, T_{MAR}, T_{MAY}	P_SMIN			*	0.62	P_S	P_SMIN		P_S	**	20	0.48
S2-Far (post-1987)	≥ 90	1-2.5	5		T_{JUN}, P_SMIN		PDSI_S	*	0.40		P_SMIN, T_{JUN}		P_S	*^c	20	0.39
S2-Far (pre-1987)										T_{MAY}, PDSI_S, P_SMAX, T_{APR}	P_S		***^d	15	0.85	
Site S3																
S3-Near	~20	~3	6	T_{MAR}		PDSI_S	Q_{M3}	*^e	0.64	PDSI_S	P_SMIN			**	47	0.25
Site S4																
S4-Near	<110	<2.5	16				Q_{M30}	*^f	0.32		T_{JUN}, P_S			*	42	0.15
S4-Far	220-530	1.6-5	22	P_S			Q_{M3}	**^f	0.71	PDSI_S, P_W	P_SMIN			***	54	0.24

Site D1															
D1-Near	~20	<2	1		P _{SMIN}		PDSI _S	*	0.40						
Site D2															
D2-Near	<20	~1.75	4	T _{MAY}				*g	0.33	T _{MAR} , T _{MAY}		PDSI _S	**	36	0.29
D2-Far	>120	≥2.75	6		Q _{M3}	Q _{M30}	0.052	0.40		PDSI _S , T _{APR}	P _{SMIN} , T _{JUN}		*	32	0.23
Site D3															
D3-Far	>160	≥3	9		P _{SMIN} , T _{MAY}	Q _{M30}	**	0.69		T _{APR} , PDSI _S		PDSI _S	*	37	0.22
Site D4															
D4-Near	<20	>1.5	3	P _S		P _S	*h	0.42		P _S MAX	P _W , P _{SMIN}	PDSI _S	P _S	*i	21 0.41

^aModel is for dataset excluding 1996; no model resulted using the full dataset.

^b $P(\text{enter}) = P(\text{Remove}) = 0.10$ for Stage 1 analysis; single D1-Near tree and six S2-Near trees pooled for Stage 2 analysis.

^cS2-Far “longest period” data are limited to years post-1987.

^dS2-Far “longest period” data are limited to years pre-1988.

^eModel is for dataset excluding 1996 and 1997; no model was produced using the full dataset, exclusion of solely 1997, or exclusion of 1997 and 2003.

^fModel is for dataset excluding 1997; no model resulted using the full dataset.

^gModel is for dataset excluding 1999; no model resulted using the full dataset.

^hModel is for dataset excluding 1997 and 2003; no model resulted using the full dataset or excluding solely 1997.

ⁱModel is for dataset excluding 1997, 2002, and 2003; no model resulted using the full data set or excluding only 1997 and 2003.

Table 5. Group statistics for the standardized growth index (SGI) series for tree groups output from the tree-ring analysis program COFECHA and mean SGI values for five years with unusually dry (1981, 1996, and 2002), wet (1987), or cold (1995) conditions during the growing season.

Creek	Site	Tree group	Number of trees	Longest series (yr)	Mean series length (yr)	Interseries correlation	Average mean sensitivity	Mean SGI				
								1981	1987	1995	1996	2002
Sand	S1	Near	4	53	53	0.01	0.32	1.34	1.26	0.95	1.01	1.19
		Far	5	53	53	0.20	0.27	0.62	1.67	1.02	0.84	0.74
	S2	Near ^a	7	56	31	0.38 ^b	0.32	0.99	0.85	0.73	0.62	0.63
		Far	6	56	42	0.13	0.34	0.84	1.26	0.87	0.82	0.61
	S3	Near	6	70	54	0.25	0.25	0.77	1.17	1.00	0.55	1.00
	S4	Near	16	85	33	0.46	0.27	0.54	1.08	0.88	0.58	0.91
		Far	22	86	45	0.36 ^c	0.24	0.82	1.19	1.01	0.80	0.87
	Deadman	D2	Near	4	67	50	0.02	0.21	0.89	0.74	0.80	0.88
Far			6	39	31	0.41	0.19	---	1.11	0.85	0.63	1.07
D3		Far	9	73	48	0.36	0.22	0.95	1.21	0.66	0.74	1.05
D4		Near	3	32	29	0.32	0.30	---	1.28	0.92	1.05	0.53

^aIncludes single SGI series from D1-Near.

^bInterseries correlation = 0.50 for post-1987.

^cExclusion of two “contrary” trees raises the interseries correlation to 0.43

Table 6. Results of sequential comparisons of multiple regression analyses to link narrowleaf cottonwood growth to environmental variables with and without candidate legacy years 1982, 1997, and 2003 in the analyzed dataset.

Site	Tree group	Stage 1 analyses			Stage 2 analyses			
		Was a model produced?	Was model produced or R ² increased by exclusion of...		Was a model produced?	Was model produced or R ² increased by exclusion of...		
			1997	2003		1982	1997	2003
D2	D2-Near	No	---	No	Yes	Yes	No	No
	D2-Far	Yes	---	No	Yes	No	No	Yes
D3	D3-Far	Yes	---	No	Yes	No	No	No
S1	S1-Near	Yes	Yes	Yes	Yes	No	No	No
	S1-Far	No	No	No	Yes	No	No	No
S2	S2-Near post-1987 ^a	Yes	Yes	No	Yes	---	No	No
	S2-Far post-1987	Yes	Yes	No	Yes	---	No	Yes
S3	S3-Near	No	No	No	Yes	No	No	Yes
S4	S4-Near	No	Yes	No	Yes	No	No	Yes
	S4-Far	No	Yes	No	Yes	No	Yes	Yes

^aMean SGI for Stage 2 analysis based on pooled S2-Near trees and single D1-Near tree.

Table 7. Results of sequential ANOVAs testing for an effect from Closed Basin Project groundwater pumping on annual growth (mean SGI) in tree groups far from the Sand Creek channel, with annual climate index PDSIs as a covariate. Groups S4-LOW, -MID and -HIGH were separately tested. “Pumping” is a categorical variable with value “No” for years before 1986, when Stage 3 pumping began, and “Yes” for years 1986 and after. The number of years of pre-pumping SGI values varied among the groups, hence the differences in error degrees of freedom. **(A)** The first ANOVA tests for differences in slope. The interaction term “Pumping*PDSIs” tests the null hypothesis that slopes of the regressions of SGI on PDSIs before and after pumping began are equal. **(B)** Given the result of no statistical difference in the two slopes for any group, the second ANOVA tests the null hypothesis, via the term Pumping, that the intercepts of the parallel regression lines are equal.

Analysis	Tree group	Source	Sum of squares	df	Mean-square	F-ratio	P
A	LOW	PDSIs	0.373	1	0.373	16.495	<0.001
		Pumping	0.005	1	0.005	0.228	0.636
		Pumping*PDSIs	0.032	1	0.032	1.418	0.243
		Error	0.679	30	0.023		
	MED	PDSIs	0.315	1	0.315	12.627	0.001
		Pumping	0.001	1	0.001	0.020	0.887
		Pumping*PDSIs	0.065	1	0.065	2.622	0.117
		Error	0.648	26	0.025		
	HIGH	PDSIs	0.066	1	0.066	3.282	0.078
		Pumping	0.051	1	0.051	2.554	0.118
		Pumping*PDSIs	0.006	1	0.006	0.311	0.580
		Error	0.762	38	0.020		
B	LOW	PDSIs	0.364	1	0.364	15.876	0.000
		Pumping	0.000	1	0.000	0.002	0.963
		Error	0.711	31	0.023		
	MED	PDSIs	0.257	1	0.257	9.720	0.004
		Pumping	0.026	1	0.026	0.970	0.333
		Error	0.714	27	0.026		
	HIGH	PDSIs	0.061	1	0.061	3.086	0.087
		Pumping	0.081	1	0.081	4.108	0.050
		Error	0.768	39	0.020

Figure 1. Map of the study area within the Baca National Wildlife Refuge (BNWR) and Great Sand Dunes National Park (GRSA) and adjacent Preserve, near Crestone, Colorado, showing drainage channels on the west slope of the Sangre de Cristo Mountains and the location of the four study sites along each of Sand and Deadman creeks (S1-S4 and D1-D4, respectively). Stream gauge locations are shown with the quarter-filled circles. The locations of the Closed Basin Project (CBP) monitoring wells (EW31, EW44, and EW54) closest to the study sites are also shown. The closest CBP groundwater extraction wells are located ~4 km west of the map boundary.

Figure 2. Lower Sand Creek study site S4 showing the approximate locations of the 2007 active channel margins (dashed lines) and the locations of observation wells SW1 to SW12 (numbered circles) and the narrowleaf cottonwood trees cored for radial growth analysis (triangles). Letters (A-G) identify separate landforms and tree clusters sampled; not all individual trees are shown. Group S4-Far was made up of trees in clusters E, F, and G; all other trees were in Group S4-Near. North is to the top of the image. Anecdotal evidence suggests that ranch management activities prior to 2006 included periodic diversion of Sand Creek flows at a point in the channel near or above tree group A. Imagery is from ArcGIS World Imagery (acquisition date is probably October 2011). World Imagery sources: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 3. Stacked bar graph depicting seasonal precipitation values calculated from monthly totals at National Weather Service station Great Sand Dunes National Monument (053541). The height of each column is the total annual precipitation. The horizontal dashed line is the mean annual precipitation for 1951-2012, excluding years with incomplete seasonal data (columns with an asterisk and one or more missing seasonal totals). Mean total January through May precipitation (P_w) is 90 mm ($SE = 5.2$, $n = 61$; 1951-2012 data).

Figure 4. (Upper panel) Seasonal Palmer Drought Severity Index (PDSIs) for Colorado Climate Division 5, which includes the San Luis Valley and the study area. **(Lower panel)** Change in the value of PDSIs from the prior year's value. An extreme shift to much drier conditions occurred in 1981, 1996, and 2002, and each of those years was preceded by two years with similar, relatively wet PDSIs values.

Figure 5. Measured daily mean discharge in Sand Creek (thick/red line) and Deadman Creek (thin/blue line) during April through September in years 1993 to 2008. There are no Sand Creek data for 2003 nor Deadman Creek data for 2000, and missing data in other years. The limited Sand Creek data for 1993 were not used in analyses. Late summer spikes in Sand Creek discharge represent runoff generated during monsoon-related storm events; gauge malfunction may affect subsequent data collected that year. See text for gauge information.

Figure 6. (A) Comparative water table dynamics recorded during the 2007 and 2008 growing seasons at seven of the 12 observation wells established at Sand Creek Site S4. Measurements have been adjusted to a common arbitrary datum. Well locations are shown in Figure 2. Wells SW1, SW2 and SW3 were monitored continuously in 2007, whereas the remaining wells were read manually. The low water table at SW6 in May 2007 is probably a measurement error. June is shaded for clarity. (B) Circadian water table fluctuations in Well SW2 during August 2007. (C) Water table dynamics recorded in Closed Basin Project monitoring well EW31 during the same period shown in Panel A. (D) Water table dynamics measured with respect to the local ground surface in Deadman Creek wells DW1 and DW2 during 2011 to 2013. June is shaded for clarity. (E) Circadian water table fluctuations in Well DW1 during August 2011. (F) Water table dynamics recorded in Closed Basin Project monitoring well EW54 during the same period shown in Panel D.

Figure 7. (A) The total rise in the floodplain water table from an annual minimum (autumn 2006) to the following annual maximum (summer 2007) versus distance to the active channel margin at Sand Creek Site S4. Well numbers are indicated next to symbols. Dashed line is modified 3-parameter exponential decay fit to the points ($P = 0.001$; $r^2 = 0.87$). **(B)** Scatterplot showing the difference between the water table elevation in October 2007 and October 2006 plotted against the distance to the active channel for S4 wells. October 2007 water table elevations were universally higher, but the difference declined with distance from the active channel margin. Well numbers are indicated next to symbols.

Figure 8. Water table elevation (circles) in Closed Basin Project monitoring wells EW44, EW54, and EW31 plotted over annual pumping volumes (vertical bars) from Stage 3 (light gray) and Stage 4 (dark gray) project areas. Lines connect elevations recorded < 7 months apart. Elevations with black fill are summer month measurements (June through August). Gray (or colored) circles are September (EW54), October (EW44), or November (EW31) measurements. (A) Well EW44 plotted with stacked bar graph showing total volume extracted from both project areas. (B) EW54 (~1 km from the lower Deadman Creek channel) with nearby Stage 4 volume data. (C) Well EW31 (~1 km from the Sand Creek channel) with nearby Stage 3 volume data. Elevations are relative to 2300 m datum (NAVD88); all panels have the same elevation scale; B and C also have the same volume scale.

Figure 9. An example of contrary patterns of annual standardized growth index (SGI) values in two neighboring narrowleaf cottonwood trees. Data are from Tree 1 and Tree 3 growing near the channel at Deadman Creek Site D2 and cover years 1958-2010. **(A)** Upward bars indicate the individual years in which Tree 3 showed above-average growth (SGI > 1) while Tree 1 showed below-average growth (SGI < 1). Downward bars indicate years in which the opposite pattern appeared. **(B)** A scatterplot of the actual SGI values for each year, with some of the years with greatest growth differences labelled. The points in the upper left and lower right quadrants are represented in (A).

Figure 10. The relationships between mean annual radial growth in narrowleaf cottonwood growing far from the stream channel and minimum total monthly precipitation during June-September (P_{SMIN}) for Deadman Creek Site D3 (D3-Far trees) and Sand Creek Site S4 (S4-Far trees). Both sites are distant from the Sangre de Cristo mountain front (see Figure 1). The fitted 3-parameter power function for Deadman Creek data (solid line; $P = 0.026$) is based on 1982-2010 data with four outlier years (filled circles) removed (see text for details). No relationship was found for the Sand Creek data with outlier 1997, a legacy-candidate year, excluded.