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Hydroclimatic drivers of the growth of riparian cottonwoods at the prairie margin: River flows, river regulation and the Pacific Decadal Oscillation

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ABSTRACT

Cottonwoods, riparian poplars, are facultative phreatophytes and can obtain water from shallow soil moisture originating from rainfall, or from the deeper capillary fringe above the alluvial water table that is recharged by river water infiltration. The correspondence between cottonwood growth and river flows should reveal the dependency upon alluvial groundwater and subsequently, the vulnerability to reduced river flows. To explore this association, we analyzed historic growth patterns of plains cottonwoods (*Populus deltoides*) along the Red Deer River (RDR), which is at the northwestern limit of the North American Great Plains. We developed chronologies of yearly radial increments (RI) and basal area increments (BAI) and explored correspondences with the environmental records from the past century. In this semi-arid region, the RI or BAI were not correlated with local precipitation while negative correlation with growth season temperature (T) ($r = -0.37, p < 0.01$) could reflect reduced growth with hot summers. There was correlation between growth and annual river discharge (*Q*, and particularly log *Q* that approximates river stage) and this increased with two year averaging ($r = 0.51, p < 0.01$), reflecting carry-over in the watershed hydrology and in the ecophysiological response. There was correspondence with the Pacific Decadal Oscillation index (PDO, $r = -0.45, p < 0.01$), which provides multi-decade transitions that influence Rocky Mountain headwater precipitation and other weather characteristics, and river flows. The combination of *Q*, PDO and T provided the strongest multiple regression model, accounting for 44% of the historic growth variation (52% correspondence for 1953–2013). The RDR was dammed in 1983, enabling winter flow augmentation, but summer flows were sustained and cottonwood growth and the streamflow correspondence persisted. This indicates that it is the pattern of dam operation and not damming *per se* that determines the fate of established riparian cottonwoods downstream. This study revealed that these cottonwoods are phreatophytic and dependent upon alluvial groundwater that is recharged from the river. This provides a research strategy to determine whether riparian woodlands along other regulated rivers are similarly groundwater-dependent and could be vulnerable to river flow reductions from excessive water withdrawal for irrigation or other uses, or with climate change.

1. Introduction

In the semi-arid prairies of western North America, limited precipitation excludes most tree species. The exception commonly exists in the riparian or streamside forests, which are dominated by cottonwoods, riparian *Populus* trees (Bradley and Smith, 1986; Cordes et al., 1997). Cottonwoods provide the foundation for woodland ecosystems in the otherwise treeless environment and these floodplain forests provide the highest levels of biodiversity and productivity in the prairie ecoregions, along with other valued ecosystem services (Knopf et al., 1988; Finch and Ruggiero, 1993; Sabo et al., 2005).

The capacity of cottonwoods to thrive in these dry ecoregions relies on their ability to tap into the abundant, shallow alluvial groundwater that is recharged by the adjacent river (Busch et al., 1992; Rood et al., 2013). This coupling between river flows and the alluvial aquifer makes cottonwoods highly sensitive to natural or anthropogenic changes in streamflow, or to interruptions in the groundwater linkage between the river and floodplain aquifer (Reily and Johnson, 1982; Stromberg and Patten, 1996 Shafroth et al., 2000; Horton et al., 2001; Amlin and Rood, 2003). These systems are also naturally dynamic with extensive seasonal and interannual variation, including multiple year low-flow and high-flow intervals (Stromberg et al., 2007).

Abbreviations: BAI, basal area increment; EPS, expressed population signal; PDO, Pacific Decadal Oscillation; *Q*, discharge (river flow); RDR, Red Deer River; RI, radial increment; SSS, subsample signal strength

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Challenging river and riparian ecosystems, river damming and water withdrawal are the primary human alterations. Demand for surface water provided by rivers is greater in semi-arid regions, and this enables irrigation agriculture and supports domestic and industrial uses. Human demands are increasing with population growth and agricultural and industrial expansion, and climate change is providing a further influence, with gradual river flow declines over the past century (Rood et al., 2005; Philipsen et al., 2018). Greater decline generally occurs in mid- to late summer flows, when instream flows are especially critical to sustain the fish and the aquatic ecosystems, as well as to avoid drought-induced mortality of the riparian cottonwoods (Tyree et al., 1994).

Due to their reliance on alluvial groundwater, it has been anticipated that cottonwood growth would be correlated with river flow variations but dendrochronological studies have produced variable outcomes. There have been positive correlations, which are more likely in dry regions (Reily and Johnson, 1982; Stromberg and Patten, 1990; Willms et al., 1998; Edmondson et al., 2014; Deng et al., 2015; Schook et al., 2016a, 2016b), although this correspondence is influenced by the hydrogeomorphic context relative to the river valley and channel form (Stromberg and Patten, 1996; Willms et al., 2006). In other studies, cottonwood growth has been complacent or relatively uniform, and not coordinated with river flows (Dudek et al., 1998; Disalvo and Hart, 2002). In these cases, the cottonwoods could be more dependent upon the higher local precipitation, which increases the shallow soil moisture. This would be reflected in shallow root systems, in contrast to the deeper roots of phreatophytic cottonwoods (Rood et al., 2011).

Supporting the dependency of phreatophytic cottonwoods on sufficient instream flows, declines in riparian woodlands in western North America and elsewhere have been found to be due in part to river damming and water withdrawal (Rood and Mahoney, 1990; Stromberg, 1993; Deng et al., 2015). Instream flows are reduced, and prolonged drought stress can reduce tree growth and cause canopy dieback and eventual mortality (Reily and Johnson, 1982; Tyree et al., 1994; Stromberg and Patten, 1996; Scott et al., 1999; Rood et al., 2000), with older trees being particularly susceptible (Albertson and Weaver, 1945). Reversals of woodland decline following the recovery of alluvial groundwater either with increasing river flows (Foster et al., 2018) or by reconnection of the hydrological linkage between the stream and the alluvial aquifer (Amlin and Rood, 2003; Cooper et al., 2003), support the causal association between instream flow sufficiency and cottonwood health.

In this study, we applied a dendrochronological approach to (1) analyze the hydroclimatic factors that influence cottonwood growth, and (2) investigate the prospective impacts following the implementation of Dickson Dam in 1983. The Red Deer River (RDR) provided the study system and is the only tributary of the South Saskatchewan River Basin in Alberta that is not fully allocated and remains open for additional licensing of water withdrawal (Pentney and Ohrn, 2008). Unlike other regional dams that are operated for hydroelectric power generation or agricultural irrigation, the Dickson Dam captures and stores water during the spring and summer, for release during the winter to avoid dissolved oxygen depletion due to the organic loading during ice cover (Baker and Telang, 1985; Clipperton et al., 2003). Consequently, downstream flows are slightly reduced during the growth season but the impact on riparian cottonwoods is unknown since dendrochronological studies along the RDR have been limited. Marken (1993) and Cordes et al. (1993; 1997) assessed tree rings to age cottonwoods and identify historic cottonwood recruitment events, and Smith and Reynolds (1983) used tree cores, wedges, and cross sections to assess the stage and frequency of prior ice drives. These studies did not investigate the interannual growth of cottonwoods or possible associations with climate or streamflow.

Following from the prior studies, we anticipated that the growth of the RDR cottonwoods would be positively correlated with river flows. Those studies revealed correspondence between the regionally-relevant climate cycle, the Pacific Decadal Oscillation (PDO), and river flow patterns (Gobena and Gan, 2009; Whited et al., 2007; Whitfield et al., 2010; Rood et al., 2013) and we consequently explored correspondences between the PDO, river hydrology and cottonwood growth. We predicted that:

(1) river flows would be correlated with the PDO,
(2) cottonwood growth would be positively correlated with river flows, indicating groundwater dependency, and
(3) dependent upon the operational pattern, cottonwood growth could decline following river regulation by Dickson Dam.

1.1. The study system

The lower RDR flows through the semiarid shortgrass prairie ecoregion of southeastern Alberta. The region receives limited precipitation, annually averaging 279 mm. About one-quarter of this (77 mm) falls as winter snow and much of this sublimates, providing limited contribution to soil moisture. Rain is maximal in June (58 mm), and lower in July and August (32 and 34 mm), generally from brief and moderately intense, convective rainstorms (Bryan and Campbell, 1980). Summer temperatures are warm with average daily maxima of 26.8 and 26.7 °C in July and August (http://climate.weather.gc.ca/climate_normals/, Brooks North weather station).

Along the lower RDR, floodplains within Dinosaur Provincial Park contain some of the largest and least disturbed plains cottonwood (*Populus deltoides* Bartr. ex Marsh subsp. *monilifera* (Ait.) Eckenw.) groves in Canada, and this was a major factor in the park's designation as a UNESCO World Heritage Site (Bradley et al., 1991). Along other rivers in western North America, *P. deltoides* and the closely related *P. fremontii* were highly vulnerable to groundwater recession (Cooper et al., 2003; Cleverly et al., 2006; Stromberg and Patten, 1996) and the RDR cottonwoods could also be sensitive to streamflow alterations (Cordes et al., 1993, 1997). Additionally, the lower Red Deer River valley is at the northern and western limit of plains cottonwoods in North America (Cooke and Rood, 2007) and floodplain trees at the edge of their native distribution could be particularly sensitive to streamflow alterations (Johnson et al., 1976).

The RDR was dammed in 1983 with the 36 m high Dickson Dam that created the reservoir, 'Gleniffer Lake'. The majority of streamflow in the RDR originates from the Rocky Mountains and more than 80% of the annual average discharge (*Q*) at Dinosaur Provincial Park originates from upstream of the Dam. Consequently, dam operation could have substantial influence on streamflow and prospectively on the cottonwoods of the park (Cordes et al., 1997)

2. Materials and methods

2.1. Dendrochronology

During the summers of 2014 and 2015, trees were cored throughout floodplains in Dinosaur Provincial Park (around 50°45′N; 111°31′W). Trees with single main trunks that appeared to be representative of those within the woodland arcuate bands along the broad meander lobes were selected for coring. An increment core was extracted from the south side of each tree using a 5.15 mm diameter Haglöf borer at approximately 30 cm above the ground surface, the lowest height allowing auger rotation. A few trees with extensive heart rot were rejected.

The cores from 62 trees were cut lengthwise with a razor blade and the annual radial growth increments (RI) were measured using a dissecting microscope (10-40x) with a Velmex stage, an Acu-Rite encoder (0.002 mm precision) and MeasureJ2X version 5.0 software (VoorTech Consulting, Holderness, NH, USA). If the pith was missed, a transparent concentric circle ruler was used to estimate the missing distance and number of rings, for age estimation (Applequist, 1958). To estimate