

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; Philipson 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

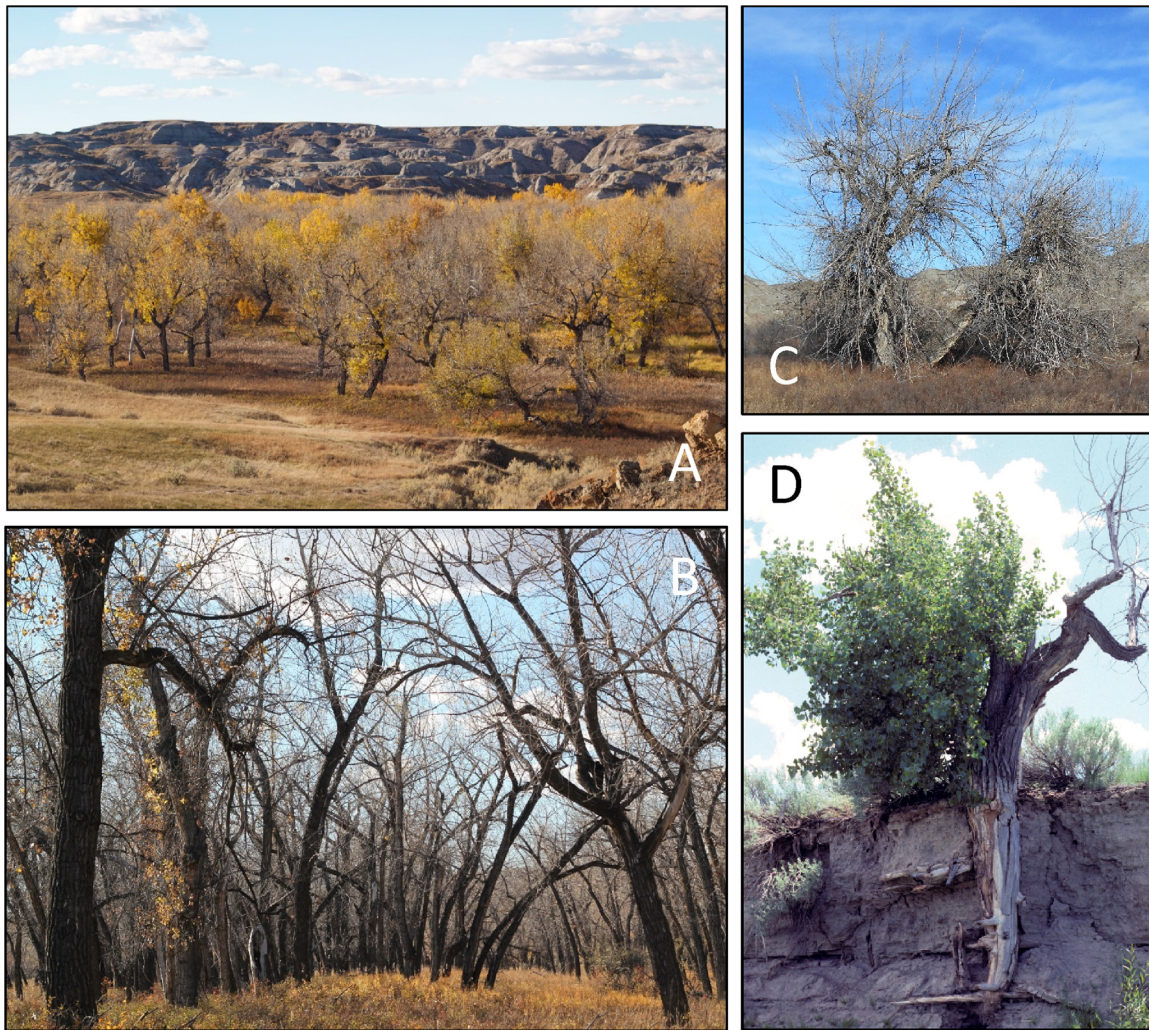


Fig. 1. Plains cottonwoods along the Red Deer River in Dinosaur Park, Canada: (A) woodland overview, autumn 2015; (B) view within the grove; (C) a solitary, very old tree with crown die-back and prolific epicormic branching; and (D) a trunk and root system exposed along a river cut-bank, with large, deep, horizontal roots indicating a phreatophytic form.

establishment years, the total ring counts were increased by six years to account for growth to the coring height and sediment accretion (Marken, 1993; Scott et al., 1997; Schook et al., 2017; Fig. 1D). We undertook skeleton plot cross-dating with comparisons across the ring series from different trees and especially those from common sites (Douglass, 1941). Increment sequences were plotted, and high- and low-growth years were identified.

Based on the expanding wood diameters as determined from the RI, annual basal area increments (BAI) were calculated (West, 1980; Biondi and Qeadan, 2008). For mature cottonwoods in floodplain forests, RI commonly decline as the trunk area increases (Meko et al., 2015), while BAI can be more uniform, benefitting environmental investigation (Willms et al., 2006; Berg et al., 2007; Schook et al., 2016a), and provided the study focus.

The BAI chronology from the 62 tree series revealed substantial variation, and the average inter-series correlation coefficient (\bar{r}) was 0.205. This partly reflected the variation with the juvenile phase, and in a subset of the 39 trees that exceeded 40 years in age (BAI_{40}) \bar{r} increased to 0.301, providing an expressed population signal (EPS; Wigley et al., 1984; Buras, 2017) of 0.94, with the subsample signal strength (SSS; Wigley et al., 1984; Buras, 2017) exceeding 0.85 from 1909 (ten or more trees), indicating that the chronology was reliable from that year. For a chronology of the older trees, the ten oldest series provided a record extending back to 1842 ($\bar{r} = 0.503$, $\text{EPS} = 0.901$), with the SSS exceeding 0.85 from 1858 (four or more trees).

To remove the effect of the apparent gradual increase in BAI displayed over the past century, the averaged BAI_{40} chronology was detrended using linear regression with the mean BAI ('dBAI'). In order to correct for carryover effects across sequential years, the detrended chronology was then fitted with a first order autoregressive model (AR (1); Riitters, 1990), selected after different models were explored (Box and Jenkins, 1970). The values forecast by the AR(1) model were then subtracted from the detrended chronology to produce a residual chronology which was also analyzed ('rBAI'). The strongest correspondences with environmental factors were generally observed with the dBAI series, which provides the focus of the presentation; additional analyses are provided in Philipson (2017).

2.2. Hydrology, weather and climate

Streamflow, weather and climate data were analyzed from 1912 to 2013, prior to the tree core sampling. Yearly and monthly average river discharges (Q) for the RDR at Red Deer (WCS#05CC002) were obtained from the Water Survey of Canada's HYDAT database (<http://wateroffice.ec.gc.ca/>). The logQ was also included, since this approximates river stage (elevation). Average monthly minimum and maximum temperatures (T) for April to October were from the weather station at Brooks, Alberta, and June, July and August precipitation (P) were from Vauxhall, Alberta (<http://climate.weather.gc.ca/>), in the prairie upland, 35 km and 85 km, respectively, from Dinosaur Park.

Evapotranspiration (ET) during the summer (June, July, August) was estimated using the Hargreaves equation (Hargreaves and Samani, 1985). Monthly Pacific Decadal Oscillation (PDO; Mantua and Hare, 2002) indices were obtained from the Mantua (2000) directory (<http://research.jisao.washington.edu/pdo/>) and averaged to provide calendar year means.

The correspondences between tree growth, as displayed with the interannual patterns of RI, BAI, BAI₄₀, and dBAI, and the environmental factors P, T, ET, Q (annual; monthly; seasonal (3 months); and growth season, May - October) and the PDO were investigated. In addition to annual values, averages of the environmental factors across the growth year and prior year were also assessed, including logQ2 and PDO2. These would consider environmental influences that carry-over across years such as with gradual groundwater outflows. We used Pearson Product correlations (r), and Kendall τ and Spearman ρ non-parametric, rank-order tests. ‘Association’ refers to the % coefficient of determination ($r^2 \times 100$). Multiple linear regression was also applied to investigate combinations of environmental factors that were individually correlated with growth.

Our study also investigated the patterns in association with the Dickson Dam and the correlations were also assessed for the interval from 1953 to 2013, to include the pre-dam (1953–1982) versus post-dam (1984 to 2013) intervals. To compare patterns between those two intervals, P, T, ET, Q, dBAI and the PDO indices were compared using the Wilcoxon signed-rank test. All statistical analyses used SPSS v.19 (IBM, Armonk NY, USA).

3. Results and discussion

3.1. The inherent tree growth pattern

The first analysis considered the growth patterns relative to tree age. The trees were established in different years and the basal area increments (BAI, Fig. 2) or radial increments (provided in Philipson, 2017) for sequential ages were plotted. This would average the effects from interannual environmental influences and reveal the inherent growth pattern.

These age-based growth increments were very small for the young saplings and increased through the juvenile phase (Fig. 2), as is typical for trees (Fritts, 1976; Monserud and Marshall, 2001), including cottonwoods (Willms et al., 2006; Berg et al., 2007). When the trees were around 40 years old, age-based BAI became relatively constant and remained so until the trees were around 120 years old (Fig. 2). This mature growth phase would be more suitable for the investigation of environmental influences and we assessed the full RI and BAI records, and also the growth of trees exceeding 40 years of age (Table 1).

Unexpectedly, at around 120 years, there was a substantial upturn

in the BAI pattern, reflecting increased trunk growth rates in the very old trees (Fig. 2). This may have been due to several factors, but only ten trees were older than 150 years, limiting the confidence in this assessment. As one likely influence, the very old trees consistently occurred separately (Fig. 1) and there would thus be minimal competition with other cottonwoods for resources including light and water. Thus, as many cottonwoods died after about a century of age, the woodland would be thinned (Weiner and Thomas, 2001), providing growth release for the surviving trees.

The big, old cottonwoods displayed distinctive shoot forms, with prolific epicormic branching (Fig. 1C). These branches commonly emerge from dormant buds that are released with light exposure following pruning or thinning (Remphrey and Davidson, 1992; Meier et al., 2012). Similar to coppice growth, regrowth from epicormic shoots could provide rejuvenation that further increases tree growth and BAI (Dickmann and Stuart, 1983).

3.2. Correspondences between cottonwood growth and environmental factors

The average RI and BAI for mature trees greater than 40 years old were 1.78 mm and 11.6 cm², respectively, which is comparable to the growth of cottonwoods along the nearby Oldman River (Willms et al., 2006; Rood et al., 2013). Both RI and BAI displayed somewhat periodic multiple year patterns of faster and slower growth (Fig. 3). Over the 170 year interval, the average RI pattern was on a flatter baseline, while BAI displayed similar patterns of slow and faster growth, but superimposed on an increasing baseline. The progressive increase may partly reflect the influence from the older trees on the average BAI of all trees. Consistent with other observations that slow-growing trees may live longer (Bowman et al., 2013), the BAI of the oldest trees were comparatively low in their younger years (Philipson, 2017), and this would reduce average BAI in the earlier part of the chronology. The recent part of the chronology would include the faster growth of the older trees in their later years (Fig. 2).

The BAI increase over the past 170 years may also reflect an influence from atmosphere and climate change (Johnson and Abrams, 2009). The regional growth season temperature has been increasing (Fig. 4) and the annual growth interval with mean temperatures above the heat unit base T of about 5 °C has also gradually lengthened (Philipson et al., 2018). This could combine with the increase in atmospheric CO₂ to promote cottonwood growth, especially in the spring and autumn, thus increasing the annual growth increments.

To study interannual correspondences, we removed the progressive increase by detrending with linear regression. This provided the detrended BAI chronology (dBAI), with the intervals of increased or decreased growth superimposed on a flat baseline (Fig. 5).

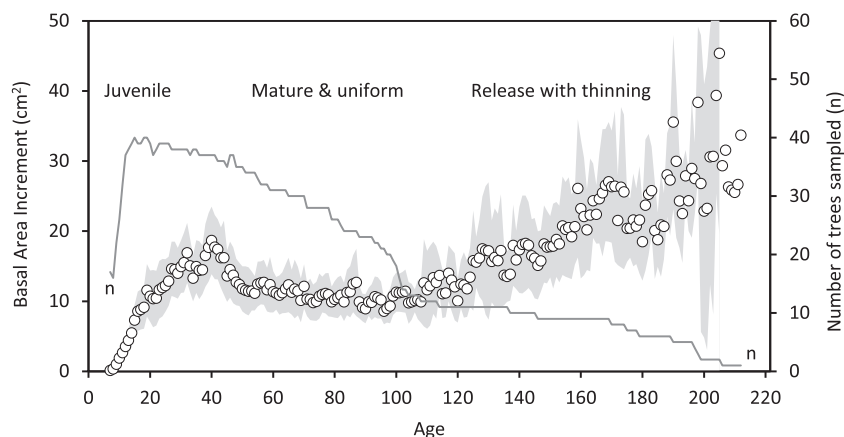


Fig. 2. Average basal area increment (BAI) growth of cottonwoods growing along the Red Deer River, plotted by ring age. The shaded area represents the 95% confidence interval and the number of trees represented at each age is also shown.

Table 1

Bivariate Pearson product correlations (*r*) between environmental factors and the annual growth of riparian cottonwoods along the Red Deer River (RDR) from 1913 to 2013. PDO2: the Pacific Decadal Oscillation index (average of growth year and prior year); T: mean growth season, Apr-Oct; P: summer total, June, July and August; Log*Q*: mean annual discharge (*Q*) of the RDR at Red Deer, with log conversion that approximates river stage; Log*Q*2, (log of average of the growth year and prior year *Q*); RI: radial increment; BAI: basal area increment; dBAI: BAI of trees exceeding 40 years in age, after detrending to remove the progressive increase over time and with three year moving averaging; with analyses for two time intervals. *, *p* < 0.05; ** *p* < 0.01, with positive correlations in red, negative correlations in blue.

	Environmental Factors					Cottonwood Growth			
	PDO2	T	P	Log <i>Q</i>	Log <i>Q</i> 2	RI	BAI	dBAI 1913- 2013	dBAI 1953- 2013
Year	-0.038	.275**	-0.016	-.118	-.174	.258**	.640**	.000	-.054
PDO2		.275**	-.042	-.138	-.193	-.508**	-.488**	-.451**	-.498**
Temperature (T)			-.252*	-.283**	-.319**	-.204	-.149	-.373**	-.429**
Precipitation (P)				.386**	.261*	.102	.116	.064	.063
Log <i>Q</i>					.825**	.246*	.212*	.393**	.481**
Log <i>Q</i> 2						.269**	.237*	.511**	.616**
RI							.743**	.693**	.925**
BAI								.601**	.933**

To explore correspondences between environmental factors and growth, we assessed a large number of bivariate correlations (Philipson, 2017). In Table 1, we present the variables which provided the strongest correlations and were most relevant to our predictions, with two significance thresholds to account for the multiple comparisons. The data series included annual values from 1912 to 2013, reflecting the availability of hydroclimatic records, and the first assessment, ‘Year’, considered trends over this century-long interval. Of the environmental factors, the growth season temperature increased (Table 1, Fig. 4). Consistent with the plots in Fig. 3, RI increased over the past century, with a stronger increase in BAI. This was similarly displayed in the full BAI data and the shortened BAI₄₀ chronology, which avoided the juvenile phases (Philipson, 2017).

Among the environmental factors, the PDO index, and the 2-year average (PDO2) were correlated with growth season temperature (T)

near the study area. The annual PDO was correlated with annual or two-year river flows (Philipson, 2017), and this is consistent with other regional analyses (Rood et al., 2005; Gobena and Gan, 2009; Whitfield et al., 2010; Philipson et al., 2018). However, the association for annual values was only about 5% and not displayed for the 2-year PDO2 (Table 1). The local T and precipitation (P) were correlated with the other environmental factors (associations 9%–15%), revealing correspondence between warm, dry and low-flow years; versus cool, wet and high-flow years, regional correspondences that are well established (reviewed in Philipson et al., 2018).

The cottonwood trunk growth measures were all strongly correlated and the RI and BAI displayed 55% association (Table 1). The two measures were strongly correlated with the PDO2, with associations of 26% and 24%. Following detrending, the BAI was correlated with T, with 14% association. Growth was not correlated with summer

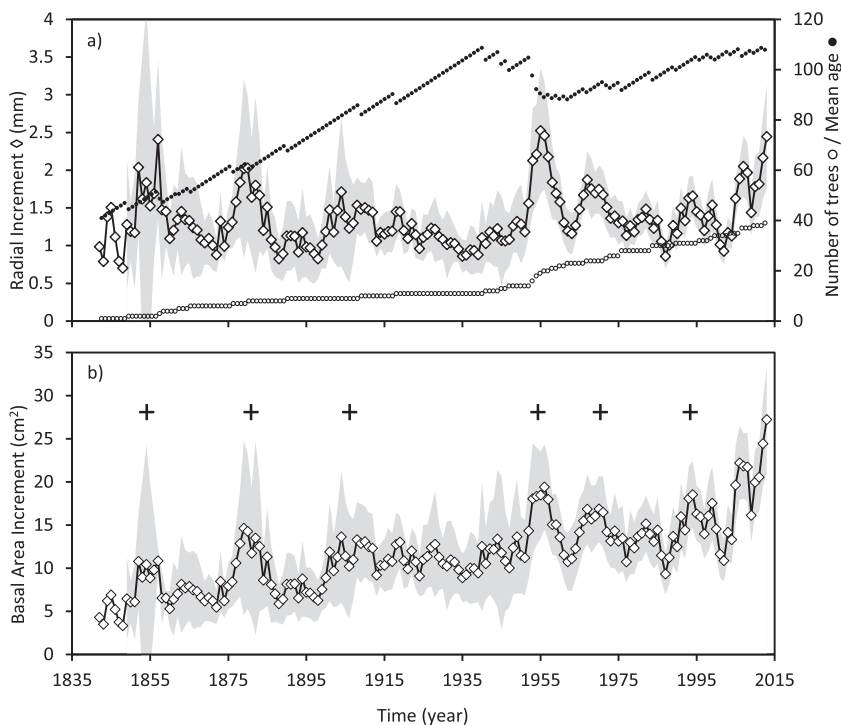


Fig. 3. (a) Average annual radial increments (RI) and (b) basal area increments (BAI) through the mature phase when cottonwoods were at least 40 years old, along the Red Deer River. The average tree age and number sampled are plotted along with RI, and shaded areas represent the 95% confidence intervals. Along the BAI plot, intervals of increased growth are indicated with ‘+’.

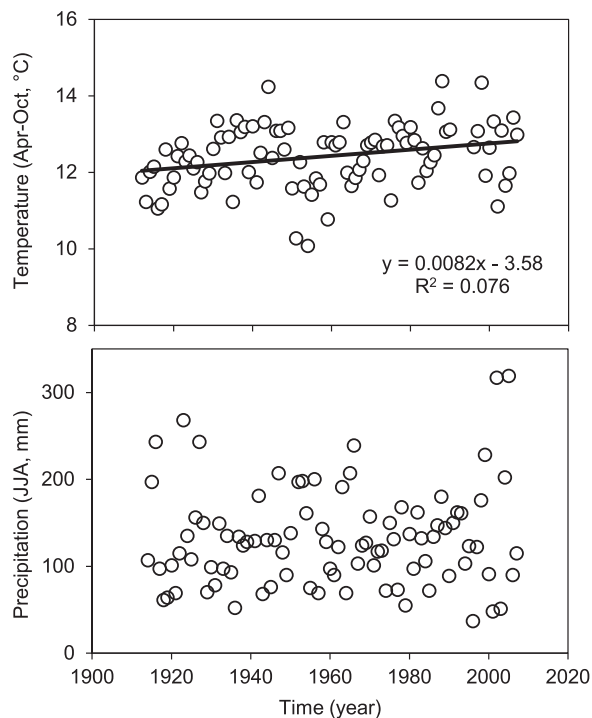


Fig. 4. Historic summer weather conditions at upland locations near the cottonwood study sites in the Red Deer River valley. Mean temperatures through the cottonwood growth season at Brooks, AB, (top), and (bottom) total precipitation for June, July and August at Vauxhall, AB, which provided more complete records.

precipitation (Table 1) but the precipitation measurements were from a prairie site 85 km away, and could have differed from the river valley study site. Cottonwood growth was correlated with Q , and the log transformation (Meko et al., 2015), that approximates the conversion from flow rate to river stage, improved the correspondence (Philipson, 2017). The correspondence was further increased for the 2-year $\log Q$, which provided the strongest environmental association of 26% for the dBAI. This suggests carry-over of some hydrological components and of the ecophysiological response. Annual discharges (Q) were included in these analyses (Table 1), and slightly lower correspondences were observed for monthly or growth season Q (Philipson, 2017). Winter flows of the RDR are very low and provide slight contribution to the annual flow (Philipson et al., 2018), but may contribute to groundwater recharge and thus provide some influence (Stromberg, 2001; Stromberg and Patten, 1990). Ice jamming and localized overbank flooding occurs along this river reach and provides another hydrological complexity (Smith and Reynolds, 1983). This is not tracked in these environmental records and could influence cottonwood growth.

Correlation analyses for the shorter, recent 60 year chronology provided increased associations (Table 1). These confirmed the correspondences and ranking across the environmental factors with the closest correlation with $\log Q_2$ and then PDO2.

Subsequent step-wise multiple linear regression considered the significant environmental factors. The favored two-factor model included $\log Q_2$ and PDO2 to provide 39.1% association with the dBAI. The addition of T slightly improved the adjusted model fit to 43.9%. The same analysis with the shorter recent time series resulted in a three factor model fit of 51.5%.

In addition to the Pearson r correlations, the non-parametric Kendall τ and Spearman ρ rank-order correlations provided very similar outcomes. Again, the strongest growth correspondences were with the river Q and PDO. For the PDO2, the Spearman ρ correlation of -0.426 was slightly lower than the Pearson r value of -0.451 and for $\log Q_2$, the Spearman ρ correlation was greater (0.583 vs. 0.511).

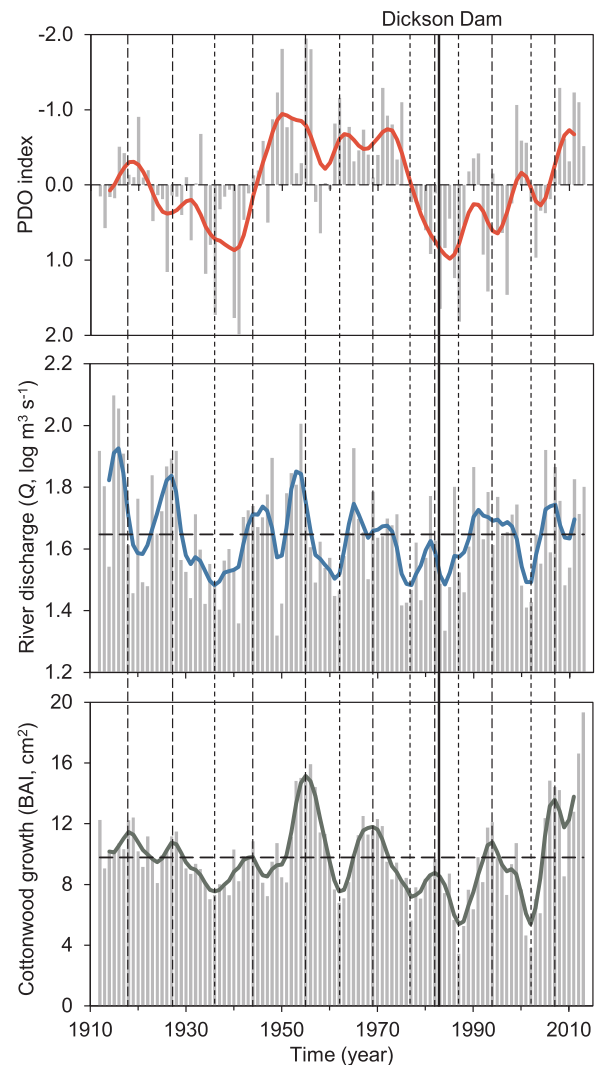


Fig. 5. (a) Interannual Pacific Decadal Oscillation indices (top), mean annual river discharges ($\log Q$, middle), and cottonwood growth (residual BAI after detrending, bottom) over the past century, from 1908 to 2013. Annual values are plotted and for smoothing, lines show centre-weighted 5-year moving averages. Vertical lines indicate times of increased (dashes) or decreased (short dashes) growth, and the black line identifies the Dickson Dam completion.

Following from these analyses, the key interannual patterns over the past century are represented in Fig. 5. The PDO varied considerably, including year-to-year variation and broader, multi-decade phases, with a warm phase associated with the major western North American droughts of the 1930s and 1980s, and a cooler and wetter phase from around 1950 to 1975. There was some interannual correspondence between the PDO index and RDR Q (Fig. 5), but this correspondence was much lower than for the southern Alberta rivers with greater drainage from the higher Rocky Mountains zones (Rood et al., 2005; St. Jacques et al., 2010).

The cottonwood growth pattern corresponded with both the PDO and Q (Fig. 5). Over the century, there were intervals of high versus low growth and some of these were associated with a corresponding pattern in the PDO, or especially the RDR Q , and in some cases, both of the hydroclimatic drivers. Prior researchers have also reported correspondences among cottonwood growth, river discharge and sometimes weather, but the correspondences have varied substantially (Reily and Johnson, 1982; Stromberg and Patten, 1990; Dudek et al., 1998; Willms et al., 1998; Rood et al., 2013; Edmondson et al., 2014; Schook et al., 2016a, 2016b).

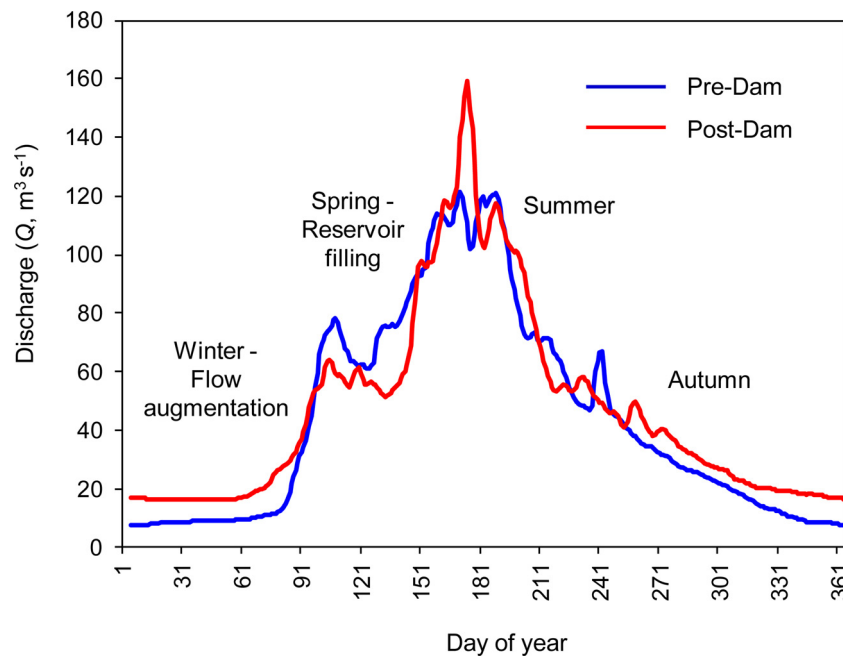


Fig. 6. Five-point moving averages of mean daily flows for the RDR at Red Deer before (1953–1982, pre-dam) and after (1982–2013, post-dam) the completion of the Dickson Dam (July 1 = Day of Year 182).

3.3. River damming, flow regulation and cottonwood growth

We also investigated the possible influence of the Dickson Dam on RDR flow patterns and cottonwood growth. We and others have recognized the decline and mortality of riparian cottonwoods along other dammed rivers in Southern Alberta and elsewhere in the western prairies of North America (reviewed in Rood and Mahoney, 1990). Those dams were often involved in water storage and diversion for agricultural irrigation, and had imposed drought stress due to: (1) insufficient flows through the warm and dry interval of mid- to late summer (Albertson and Weaver, 1945; Rood et al., 2000), and (2) abrupt flow declines following the spring peak, and these could have led to rapid recession in the alluvial water table (Rood et al., 1995).

In contrast to those other regulated rivers, the operation of Dickson Dam has not substantially reduced summer flows or altered the post-peak recession (Fig. 6). The annual flows are unaltered (Table 2) and dam operation has produced two seasonal flow changes. Flow augmentation approximately doubled the winter flows (Fig. 6), gradually drawing down Gleniffer reservoir. Subsequently, with the spring snowmelt and rainfall runoff, some flow was trapped and the reservoir was refilled. This especially reduced the early spring peak (Fig. 6), which represents snow-melt from the lower elevation foothills, boreal and

prairie zones. The second, larger peak originates from mountain snowmelt and run-off from heavier rains across the watershed. There was some flow trapping during the rising limb of this major peak (Fig. 6) but the reservoir is proportionally small and would generally fill before the crest of the major peak. This sequence would reduce the downstream RDR flow during reservoir filling but this coincides with the mid-spring interval that is typically cool and wet, avoiding drought stress on the riparian cottonwoods.

The critical summer flows of the RDR were relative unaltered, and generally similar in the pre-dam and post-dam intervals (Fig. 6). In both intervals, there was gradual post-peak recession and generally similar flows in late summer and into autumn, with some interannual variation. Accompanying the sustenance of downstream RDR flows through the summer season after damming, the cottonwood growth patterns were similar in the pre-dam versus post-dam intervals, with some alternation of high and low growth sequences (Fig. 5).

Relative to weather patterns, the local P was quite similar in the three decades before and after damming (Table 2). Temperatures were also similar, and the two combine to provide similar growth season ET (Table 2). There was a significant difference relative to the PDO (Table 2), with a phase transition coinciding with the implementation of the Dickson Dam (Fig. 5). With this transition there was an interval of lower river Q and reduced cottonwood growth but the trees subsequently rebounded, and there were generally similar patterns with intervals of high versus low flow and growth in the pre-dam versus post-dam intervals (Fig. 5).

Thus, the operation of the Dickson Dam produced minimal alteration in the summer flows of the RDR. With the slight alteration, there was no apparent growth decline. This opposes the prediction that cottonwoods might suffer following damming, but that was based on an expectation of some flow reduction and flood flow attenuation (Cordes et al., 1997). The observed pattern further confirms the association between sufficient river flows and cottonwood condition in the semi-arid prairie regions and it demonstrates that the fate of downstream riparian woodlands is largely dependent upon the pattern of instream flow regulation, and not solely on the presence of a dam *per se*. Along with alterations to downstream flows, river damming leads to the trapping of alluvial sediments. This reduces sediment deposition downstream, which can influence cottonwood recruitment (Bradley

Table 2

Mean values of environmental variables and growth of riparian cottonwoods along the Red Deer River over thirty years before and after the implementation of the Dickson Dam. Q, discharge; PDO, Pacific decadal oscillation; BAI, basal area increments. Differences were assessed with the Wilcoxon signed-rank test, **, $p < 0.01$.

	Mean		Z
	Pre-dam 1953 - 1982	Post-dam 1984 - 2013	
Precipitation (mm)	341	332	-0.681
Evapo-Transpiration	4.17	4.21	-0.874
Annual Q (m ³ /s)	44.8	46.8	-0.771
PDO index	-0.364	0.159	-2.58**
BAI (cm ²)	13.6	13.2	-0.339
BAI residuals	-0.166	0.115	-0.566

and Smith, 1986; Scott et al., 1997) and probably also alters the nutrient status (Bayley and Sparks, 1989), which could subsequently influence cottonwood growth.

3.4. Using cottonwood growth to extend the hydroclimatic record

With fixed locations and relatively long lives, trees can act as sentinels of environmental change (Briffa, 2000). In locations where growth is limited by specific environmental factors, such as the availability of water in semi-arid regions, the tree ring records can provide proxies for climatic conditions (Fritts, 1976; Monserud, 1986).

Dendroclimatological analyses of riparian cottonwoods have often been disfavored since the tree rings are faint, creating problems with missing rings or false rings that reflect intra-year growth variations (Everitt, 1968; Fritts, 1976). Also, riparian woodlands are often heavily impacted by human activities (Auble et al., 1997), and many populations have relatively few trees older than a century, which are required to extend the instrumental weather and river flow records (Bradley and Smith, 1986).

This is not always the case and for some tributaries of the Missouri River in the western Great Plains, researchers were able to investigate tree-ring sequences of plains cottonwoods to reconstruct chronologies extending back about four centuries (Edmondson et al., 2014; Meko et al., 2015; Schook et al., 2016b). Their success was attributed to a cold, dry climate resulting in slow-growing and long-lived trees, with substantial inter-annual variability that corresponded with the instrumental record for the past century. These tree ring chronologies provide an in situ climate proxy in otherwise treeless regions (Edmondson et al., 2014; Schook et al., 2016b).

Similar to eastern Montana and North Dakota, the prairies of western Canada have few tree-ring chronologies with most analyses being limited to conifers in the eastern slopes of the Rocky Mountains (Axelson et al., 2009). Along the lower RDR, riparian woodlands contain the most northern and westerly extension of plains cottonwood, and like cottonwoods along the Missouri River tributaries, the climate has allowed the survival of some very old trees (Shaw, 1976). In Dinosaur Provincial Park, the oldest cottonwoods were found to have diameters up to 167 cm with ages likely exceeding 250 years. Our analysis allowed us to produce a 172-year tree ring chronology, with confidence for the 155 years after 1858.

Fig. 7 provides a chronology based on the oldest ten trees, which displayed reasonable correspondences across the record. This indicates ten intervals of low or high growth and while this type of record has been used to reconstruct river flows prior to hydrometric gauging, it provides a more direct record of environmental favorability for regional vegetation, which would relate to aspects such as wildlife habitat and

natural resource availability. This contributes to our understanding of the regional history of agricultural development and drought (Marchildon, 2007; Marchildon et al., 2008). The observed pattern is generally consistent with other regional analyses with upland conifers (Watson and Luckman, 2006; St. George et al., 2009; Sauchyn et al., 2015), but also provide some instructive differences.

Following exploration from 1857 to 1860 (1; Fig. 7), John Palliser regarded the region as uninhabitably dry, and it became known as the ‘Palliser Triangle’. Our tree ring record suggests a fairly normal interval relative to cottonwood growth, and prospectively, river flow, but analyses of tree rings in upland conifers in the foothills to the west indicate more severe regional drought at that time (Watson and Luckman, 2006; St. George et al., 2009; Sauchyn et al., 2015). In marked contrast to Palliser’s interpretation, the dominion botanist John Macoun visited the region from 1872 to 1881 (2) and described it as lush and highly suitable for settlement. Our cottonwood record indicates that this interval was especially favorable for cottonwood growth, likely with abundant river flows and rain.

A drought apparently followed in the late 1800s (3) and this was the interval when major irrigation development commenced in southern Alberta. This would have been encouraged with a dry interval. In the early 1900s (4) there was extensive promotion for settlement and home-steading in the region, with extensive prairie cultivation for wheat production. However, with the severe and widespread drought of the ‘dirty thirties’ (5), those farms were largely abandoned and the adjacent zone become known as the ‘Special Areas’ (Marchildon, 2007).

The cottonwood chronology subsequently tracks patterns that are verified by instrumental records (Fig. 5), including the regional wet-phase of the PDO (6) and regional droughts (7, 8, 9). The record ends (10) with a high growth interval with increased growth following the flood of 2005. The large, old trees used for this longer-term assessment were situated further from and higher above the river than the younger trees, and they could consequently be especially promoted by supplemental water with the major, overbank flooding.

Thus, the cottonwood record provides insight and confirmation of the regional record of human activity. This study also provides important information for the future of this region since the RDR is the only tributary in the South Saskatchewan River Basin which remains open for the licensing of further water withdrawal (Pentney and Ohrn, 2008). There is currently a proposal to develop a diversion and/or pumping system to bring water from the RDR to the dry Special Areas and this would be for human use, livestock watering and limited irrigation. This cottonwood growth record provides information about the extent of river flow reduction that would likely result in decline of the rich and biodiverse riparian woodlands.

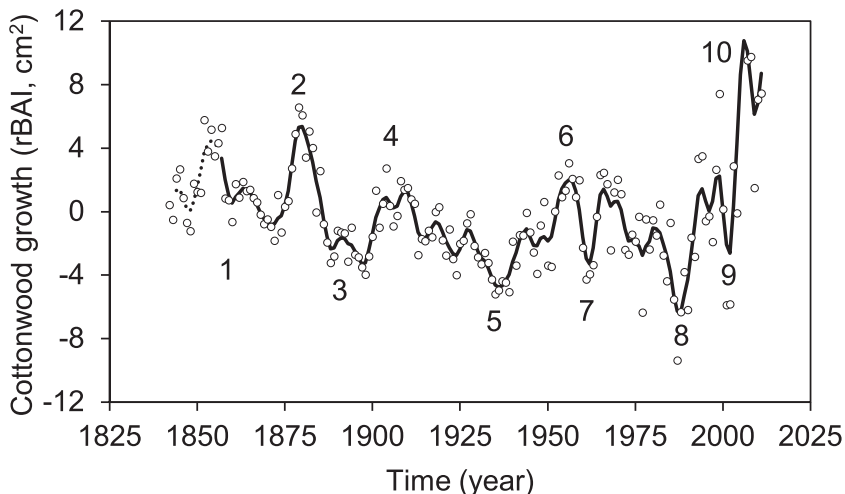


Fig. 7. Growth rate (residual BAI after detrending and subtracting the mean) for the ten oldest cottonwood trees sampled along the lower RDR. The plotted line is the 5-year centre-weighted moving average, solid where the SSS exceeded 0.85 in 1858 (four trees) and later, and dotted before that. The numbers highlight periods of higher- or lower-growth as referred to in the text.

4. Conclusion

In summary, this study investigated the historic growth of riparian cottonwoods along the lower reach of the Red Deer River. This is situated at the northwestern limit of the North American Great Plains, an ecoregion that will likely expand northward with climate warming. An important prior study of this system revealed fundamental aspects of riparian community ecology and the influences of floods and floodplain dynamics (Cordes et al., 1997), and anticipated some challenges to these riparian woodlands due to river damming. This follow-up study confirmed the coordination between cottonwood growth and river flows, in addition to associations with the major hydroclimatic influence from the Pacific Decadal Oscillation. This indicates that these cottonwoods are phreatophytic and dependent upon alluvial groundwater that is coupled with river water. Consequently these trees and the riparian woodlands would be highly vulnerable to declining river flows that could result from increased water withdrawal for irrigation and other human uses, which is currently proposed. Impacts from climate change will also be relevant since river flows from the central Rocky Mountains have declined over the past century, and especially during the summer interval (Rood et al., 2005, 2008). This study encourages caution relative to increasing water withdrawal from the RDR, and the study approach would be instructive for other regulated river systems to characterize the dependency of cottonwoods or other obligate riparian trees on river flows, and their subsequent vulnerability to river flow decline.

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