Cottonwood Growth and Bosque Restoration

Along the Middle Rio Grande at Santa Ana Pueblo, NM

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Cottonwood Growth and Restoration Along the Middle Rio Grande at Santa Ana Pueblo, NM

Esteban Muldavin P.I., Amanda Browder, and Elizabeth Milford

New Mexico Natural Heritage Program
Museum of Southwestern Biology
University of New Mexico

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ABSTRACT

The effects on the growth of Rio Grande cottonwood (*Populus deltoides* ssp. *wislizeni*) following the understory removal of exotic trees and shrubs from stands along the Rio Grande at Santa Ana Pueblo, NM was addressed in the context of river discharge and precipitation. Complete understory removal of Russian olive (*Elaeagnus angustifolia*) and saltcedar (*Tamarisk ramosissima*) was conducted in 1998 in two stands while two adjacent stands received limited or no thinning. Dendro-ecological methods were applied to measure annual cottonwood tree growth between 1979 and 2002 and then post-treatment growth from 1998 through 2002 was compared between cleared and uncleared stands relative to the previous twenty years. While all four stands superficially looked to be of similar ages, they in fact were established nearly a decade apart beginning around 1939 and becoming progressively younger downstream and as the active channel was approached. The youngest stand was established around 1959. There were definite patterns of growth that corresponded to extremes in growing-season river discharge as regulated by Cochiti Dam (40 km upstream), and, to a limited degree, antecedent winter precipitation. But these factors were not entirely consistent and distance from the river, channel incision, groundwater patterns, soils differences, and tree age, along with intra-annual variation in water availability and temperature may be important. The responses following the understory removals were mixed. The stand with the highest abundance of *Elaeagnus angustifolia* had the poorest growth response after 1998, but the other stand with an intermediate level of *Elaeagnus* following a partial treatment responded well, at least among some trees. When the three outlier trees were removed from the analysis of this stand, its response dropped to that of the fully cleared stands (and above that of densest stand). While sampling depth may be an issue, the analysis of only four years of post-treatment growth during an extreme drought may have masked treatment effects or not accounted for lag effects that require more than four years to become apparent. We stress the need for additional tree-ring studies with additional controls and more in-depth measurements of environmental factors to address efficacy of the ongoing exotic removal program to improve cottonwood productivity and health in the riparian communities along the river.

INTRODUCTION

The Pueblo of Santa Ana has embarked on an extensive riparian restoration project along the Middle Rio Grande that, among other things, is concerned with the maintenance and improved health of its mature Rio Grande cottonwood (*Populus deltoides* ssp. *wislizeni*) bosque stands. In this context, several stands of cottonwoods were targeted for the removal of understory exotic trees, primarily Russian olive (*Elaeagnus angustifolia*) and saltcedar (*Tamarisk ramosissima*), and the restoration of a more 'native' character to the stands (Caplan 2002). The outcome of these treatments in terms of understory composition and structure are detailed in Milford et al. (2002), but little was known about the response to the treatment of the overstory cottonwood trees themselves. The key question was whether tree productivity increased in response to the understory removals or were there other overriding factors such as precipitation, river discharge, site conditions, tree age, and overstory competition that affect tree growth.

We addressed this question using dendro-ecological methods based on cottonwood annual tree-ring growth. The age of cottonwoods has been successfully determined by counting tree-rings, and the width of individual tree-rings has been used to estimate inter- and intra-annual growth in the context of precipitation and river discharge (Reily and Johnson 1982; Clark 1987; Stromberg and Patten 1990, 1991, 1992; Astrade and Begin 1997; Scott, Auble & Friedman 1997; Scott, Lines, and Auble 2000; Disalvo and Hart 2002; Harner and Stanford 2003; Peter Jacobson at Grinnell College and Kiyomi Morino at the Univ. of Arizona, personal communication). Similarly, we used this characteristic of tree rings to do an exploratory study on the effects of the 1998 understory treatments in the Santa Ana Pueblo stands relative to rainfall and river flows. We used a 24-year window between 1979 and 2002 to compare the four post-treatment years (1999-2002) with the previous 20 years of the record. The patterns of growth were also compared to precipitation and river discharge during the same period in the context of the differing ages and structures of the stands.

BACKGROUND

Populus deltoides ssp. *wislizeni* (S. Watson) Eckenwalder, *comb. et stat. nov.* is a subspecies known from the Rio Grande and Pecos Rivers that occupies the transition zone between the primary distribution of *P. deltoides* var. *monilifera* to the east and *P. fremontii* to the west, and hence, has also been referred to as *P. fremontii* ssp. *wislizeni* (Eckenwalder 1977). Regardless, the species of the complex have similar life history strategies with respect to germination, growth, and longevity (Karrenberg, Edwars, and Kollman 2002). As phreatophytes, they are dependent on shallow alluvial groundwater linked to stream flow, particularly in semi-arid climates (Rood, Braatne, and Hughes 2003). Reproduction is also keyed to hydrological conditions whereby light-weight, short lived seeds are distributed in large seed rains typically synchronized to late spring runoff and associated flooding. Germinating on wetted ground only, they quickly extend roots following the wetting front of the receding groundwater as discharge falls in the ensuing summer months (Friedman, Scott, and Lewis 1995). If the groundwater drops below 1 m or more during the first year, establishment success drops off (Shafroth, Auble, and Scott 1995). However, once established, cottonwoods can adjust to falling water tables that might be caused by floodplain accretion, channel incision, or lowered discharges, and they can be found thriving where the groundwater depth exceeds 3 m or more (Everitt 1968; Robinson 1958; Busch, Ingraham, and Smith 1992; Scott, M. L., Auble, and Friedman 1997; Stromberg 1997). Apparently, cottonwoods can also be sustained if there is sufficient surficial moisture maintained through irrigation, precipitation and localized runoff (Reily and Johnson 1982). Overall, they are relatively fast growing but relatively short-lived trees, seldom exceeding 200 years of age, and usually succumbing to effects of fungal heart rot and other diseases and pests (Albertson and Weaver 1945; Burns and Honkala 1990; Taylor 2001).

As fast growing trees sensitive to water stress (Scott, Shafroth, and Auble 1999), cottonwoods often exhibit marked growth responses to moisture factors such as groundwater depth, river discharge, and precipitation, along with temperature. Stromberg and Patten (1990) demonstrated a close correlation between discharge and radial increment growth in *P. tricocarpa* along a California stream. Stromberg and Patten (1991) followed up by showing that lower radial increment growth rates in *P. tricocarpa* and *P. fremontii* were tied to discharges diversions over a twenty-year period. Disalvo and Hart (2002), working on the same stream, but over only a five year period, found no relationship between growth as measured by a basal area increment and stream flow, but did find one based on incremental branch growth. Scott, Shafroth, and Auble (1999), working with *P. deltoides* ssp. *monilifera* on the South Platte River in Colorado, reported significant stem growth reduction following groundwater declines that exceeded a 1 m threshold, often leading to mortality. Scott, Lines, and Auble (2000) also found in southern California among *P. fremontii* a similar pattern of growth reductions (based on radial increment), along with increased mortality, which they attributed to declining water tables driven by recent stream incision. Similarly, Horton, Kolb, and Hart (2001) found significant reduction of physiological growth factors (water potentials, gas exchange) along with canopy diebacks as groundwater exceeded 2.5 to 3.0 m.

The effect of groundwater depth on tree growth can be moderated by soil water-holding capacity as mediated by soil texture (Shafroth, Stromberg, and Patten 2000). Harner and Stanford (2003), working in Montana, uncovered trends of lowered productivity based on radial increment among *P. tricocarpa* along a losing (downwelling) reach with a lower water table and coarser sediments versus a gaining (upwelling) reach with a high water table and fine sediments. Clearly, hydrological factors along with soils and precipitation can strongly influence *Populus* growth, and Shafroth, Stromberg, and Patten (2000) present a semi-quantitative model that relates riparian plant response to groundwater decline as modulated by soil texture and stratigraphy, local climate, and tree age. But to date, there have been no studies that evaluate the effect on cottonwood production status of overstory and understory competition, let alone the effects of non-natives versus natives.

STUDY AREA

The tree-ring growth studies were superimposed over four existing Santa Ana Pueblo monitoring sites established by Milford et al. (2002) on the west side of the Rio Grande, just north of the NM Highway 44 bridge at Bernalillo, NM (Figure 1). These sites are designated as stands 1, 1a, 8, and 8a. While all these stands support gallery forests dominated by *Populus deltoides* ssp. *wislizeni*, they differed somewhat with respect to tree density, basal area and size, and their location relative to the river (Table 1). Stands 1 and 1a were furthest away from the river (approximately 200 m) and presumably had the greatest depth to groundwater. While the densities of *Populus* were similar, Stand 1 had somewhat larger trees and a corresponding greater amount of basal area. Stands 8 and 8a were closer to the river channel at about 100 m and were significantly denser by 250 to 300 more trees per hectare. Along with the highest density, Stand 8 also had the highest basal area. While Stand 8a had high densities, trees tended to be smaller and hence, the basal area of the stand was less than Stand 8.

Stands 1 and 1a were subjected to an understory treatment in 1998 whereby all exotics, primarily *Elaeagnus*, were cut to ground level and the stumps treated with herbicide (Kaplan 2002). The debris was then mulched and spread more or less evenly on the soil surface throughout the stands. The remaining *Populus* trees were protected, along with most native understory shrubs. In subsequent years, stump sprouts were retreated with herbicide, but some stems have still persisted, particularly in Stand 1. In contrast, Stands 8 and 8a had only partial or little understory exotic removals, and stand densities of *Elaeagnus* and *Tamarisk* constituted as much as 12.5% of the stand. In this study, Stands 8 and 8a represent the best available "controls" for studying the effect of understory removals on *Populus* growth, i.e., Stands 8 and 8a have understory compositions approaching typical conditions for *Populus* gallery forests described elsewhere in the middle Rio Grande (Milford and Muldavin 2004; Eichhorst et al. 2001), while Stands 1 and 1b are significantly altered.

Precipitation at the study site averages 217 mm (8.5 in) per year as measured in Albuquerque[1], with the majority coming as summer convective thunderstorms and frontal "monsoon" events. There have been significant periods of drought over the past 60 years, and there were particularly poor years following the treatment of the stands in 1998 (Figure 2). In 2001 and 2002, precipitation averaged only 162 mm (6.4 in). Historically precipitation, particularly in winter, was coupled with discharge. Currently discharges are controlled at Cochiti Dam, 40 km upstream, and now vary depending on reservoir storage and irrigation use, along with snowpack and other demands. While most high flows still occur in spring, with the closure of Cochiti Dam in 1972, peak flows are significantly lower, and base flows have generally risen except during drought years.

[1] Albuquerque WSFO Airport, NM (290234) station from 1/ 1/1914 to 6/30/2004.

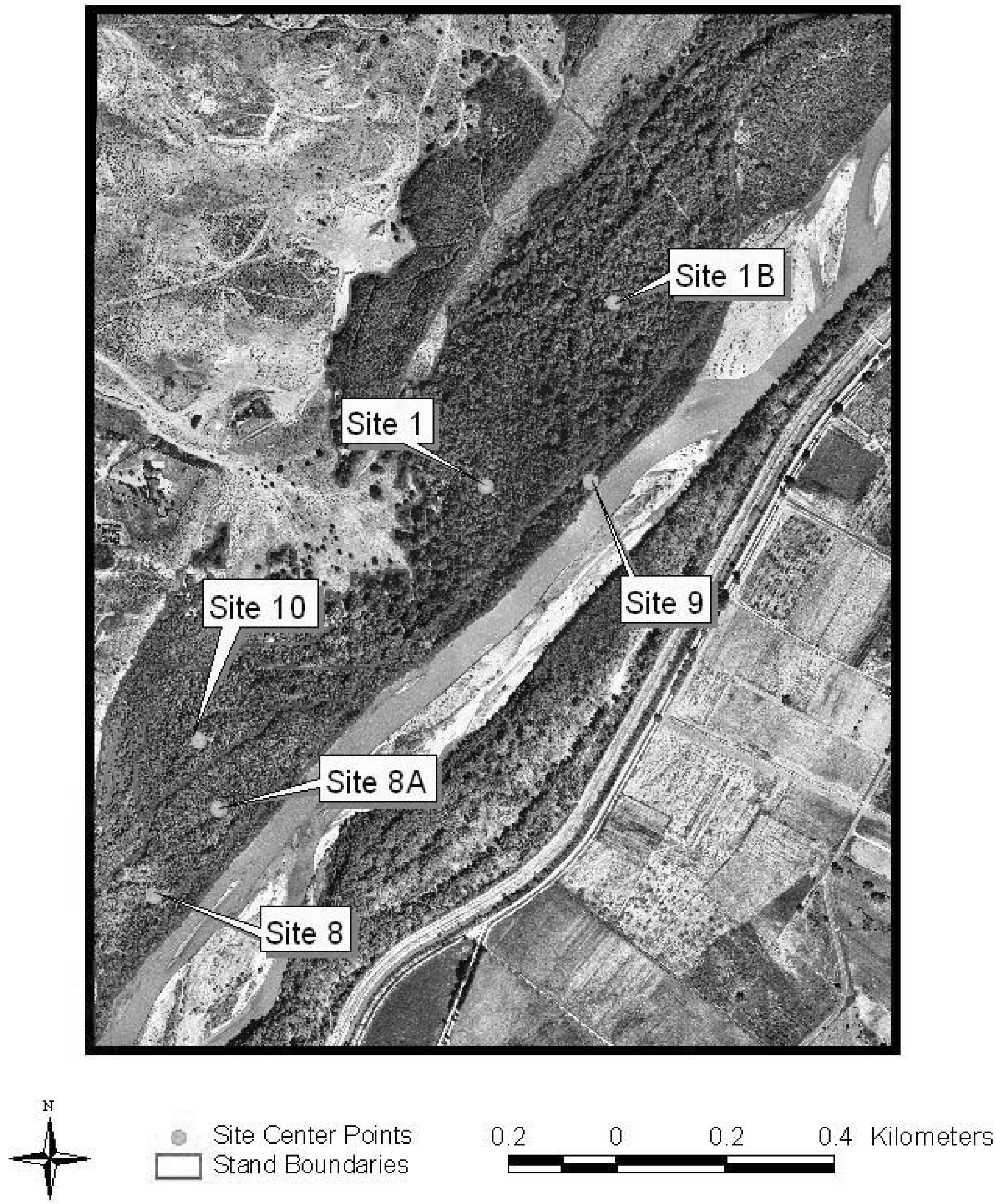


Figure 1. Location of one-hectare tree sampling plots in Stands 1, 1b, 8, and 8a along the Rio Grande at Santa Ana Pueblo, NM.

Table 1. Stand structure by species derived from Milford et al. (2002) for study stands at Santa Ana Pueblo, NM. DRC refers to diameter just above the root crown of the tree. BA refers to the cross-sectional area of the tree boles at DRC. Relative Abund. refers to the percentage of the total basal area occupied by that species.

A) *Populous deltoides* ssp. *wislizeni*

Stand	Density (stems/ha)	DRC (cm)	BA (m^2/ha)	Relative Abund. (%)
1b	393	34.1	37.20	99.54
1	420	35.8	43.61	97.50
8a	673	28.1	42.38	87.13
8	713	34.0	53.30	92.48

B) *Elaeagnus angustifolia*

Stand	Density (stems/ha)	DRC (cm)	BA (m^2/ha)	Relative Abund. (%)
1b	180	2.0	0.05	0.14
1	240	6.8	0.98	2.20
8a	420	12.6	6.08	12.49
8	3733	9.3	4.16	7.23

C) *Tamarix ramosissima*

Stand	Density (stems/ha)	DRC (cm)	BA (m^2/ha)	Relative Abund. (%)
1b	193	2.7	0.12	0.32
1	400	2.2	0.14	0.30
8a	73	5.8	0.18	0.38
8	187	3.0	0.17	0.30

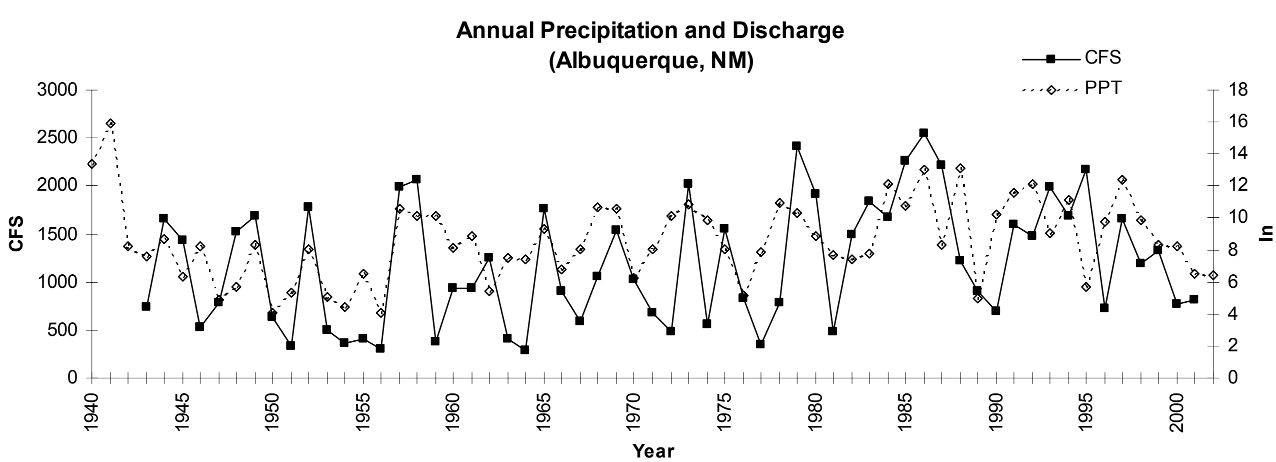


Figure 2. Annual precipitation as measured at the Albuquerque WSFO Airport, NM (290234) and annual mean streamflow in ft^3/s as measured at the USGS 08330000 gauge on the Rio Grande at Albuquerque, NM.

METHODS

Each of the four monitoring sites contained five parallel belt transects or plots that were 5 m wide and 30 m long with an area of 150 m^2 (see Milford et al. 2002). Within each of these plots, five trees were sampled using a 5 mm increment bore and the cores extracted and stored in straws for later measurement. The trees showing the best growth form and vigor were sampled to increase the likelihood of producing a readable core. Two cores were taken from each tree at right angles to each other primarily to assist in the control for false rings within a tree. The diameters at the root-crown (DRC) were measured with a diameter tape to the nearest cm. In addition, the distance to the nearest tree was measured along with heights using a clinometer and tape. Trees were sampled during the winter of 2002-03 and represent growth through the growing season of 2002.

A total of 200 cores were extracted from 100 trees, or 25 trees per stand. Cores were then mounted in wooden holding frames and surfaced with a razor blade in preparation for reading the annual rings. Ring-width measurements were made on the stage of an Acurite-Velmex linear encoder using a Nikon binocular dissecting scope and internal micrometer. Measurements were taken to the nearest 0.001 mm and stored digitally using the accompanying J2X software. The 100 trees sampled resulted in 78 readable cores with 21 for Stand 1, 17 for Stand 1b, 21 for Stand 8, and 19 for Stand 8a.

Tree ages were determined using standard dendrochronolgical cross-dating methods (Fritts 1976; Stokes and Smiley 1968; Phipps 1985). The key is identifying index years, normally those of low growth, that are easily identifiable across all cores. While younger sapwood of *Populus deltoides* var. *wislizeni* is relatively easy to date, the older heartwood can be difficult to read because stains mask rings and heart rot is prevalent. As a result, index years more than 25 years out were difficult to specify within this small sample. Hence, in those cores read to the pith to determine establishment dates for the stands, have an error rate estimated at ± 2 years. In addition, since cores were taken typically 30 to 50 cm above the root crown of the tree, two years were added to account for germination and growth to the core height.

For the analysis of growth, measurements were post-processed using the Dendrochronolgy Program Library (DPL) software version 6.07p and associated programs from the Laboratory of Tree Ring Research, University of Arizona.[2] Specifically, cores were detrended to remove the inherent growth/age structure using EXTRAP. This program generates a growth index over a specified interval based on either linear or curvilinear regressions that remove the effect of age on tree growth (Figure 3). The detrending regressions were constrained to the range of the most accurate dating, i.e., between 1979 and the 1998 treatment. The years 1999 through 2002 were excluded so as not to mask any treatment effects within the regressions. The DPL subroutine IMP (impact) was then used to evaluate growth before and after the understory removals of exotics in 1998. Detrended growth patterns were also compared to growing (April through September) and dormant season precipitation and discharge as measured at Albuquerque WSFO Airport, NM (290234) weather station and the USGS 08330000 gauge on

[2] All raw and derived data has been stored in an Excel spreadsheet and as ASCII text files compatible with the DPL software and have been made available as a CD data addendum to this report.

the Rio Grande at Albuquerque, NM. To facilitate additional comparisons, growth, precipitation, and discharge values were normalized relative to the means and standard deviations.

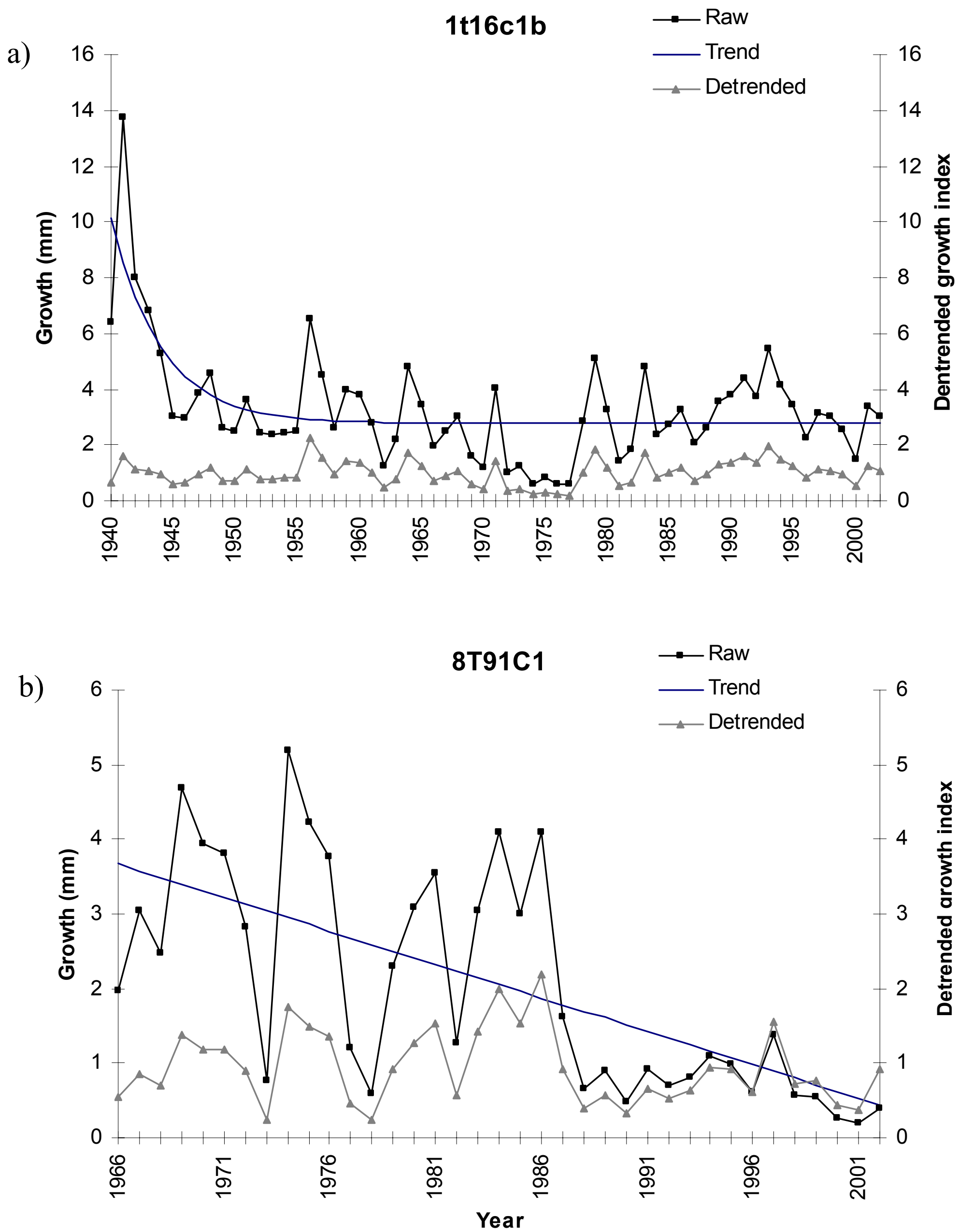


Figure 3. Examples of detrending growth increment for the effects of age using a) curvilinear and b) linear regression procedures in the DPL program Extract. Raw values are in mm.

Results

Stand Ages

While the stands were relatively close to one another and appeared at first glance to have similar stand structures, they had distinctively different establishment histories (Table 2). Stand 1b was the oldest with trees at 72 years with stand establishment occurring between 1931 and 1935 (assuming two years to core height). Stand 1 is approximately a decade younger with the oldest trees established between 1939 and 1941. This stand is the one most coincident with the major Rio Grande flood of 1942. The earliest date for Stand 8a is 1952 and most trees had dates from the early to mid 1950's. Stand 8 was the youngest with the earliest dates between 1959 and 1964. With the exception of one tree established in 1977 in Stand 8, all establishments were before the Cochiti Reservoir impoundment (1972). Spatially, stands become progressively younger going downstream and as they approach the current river channel (See Figure 1). This suggests sequential establishments during high-flow periods when sediments were available and deposited, and when the new sites remained wetted for a sufficient period for cottonwoods to become established (see Shafroth, Auble, and Scott (1995), Shafroth, Friedman, and Ischinger (1995), Stromberg (1997), and Levine and Stromberg (2001) for details on cottonwood establishment requirements).

While tree ages were dramatically different among stands, there was little relationship between tree sizes as measured by stem diameter at the root crown (DRC) (Figure 4) and height (Figure 5). Although there was a suggestion of a trend of increasing age corresponding with the larger diameter trees in Stand 1b versus smaller ones in Stand 8, there is a great deal of overlap within and among stands. In addition, Stand 1 and Stand 8a actually had the largest and smallest trees on average, respectively, based on stand measurements, but intermediate ages (see Table 1). There was no relationship between height and age. These stands all had similar maximum heights irrespective of age.

Tree Growth

Within the analysis period of 1979 and 2002, there were clear index years of low growth that appear to be tied to low growing-season discharges (April-September) and sometimes coupled with low precipitation (Figure 6). The most consistent years were 1981, 1989, 1996, and 2000, years with very low discharges and usually low precipitation (the exception was 1996 with average precipitation). Higher growth years tended to correspond to the highest discharges and precipitations, e.g., 1991 through 1995. But this was not a consistent pattern across all years or stands. For example, the drought low-flow year of 2000 showed very low productivity, but the succeeding low flow years of 2001 and 2002 (the sixth and third worst within the analysis window), tree growth actually rebounded and approached the levels of high discharge and precipitation years. This rebound may have been aided by somewhat higher precipitation. There were also differences among stands within periods, e.g., from 1985 through 1987, Stands 1, 1b, and 8 had low growth rates despite above-average discharge and precipitation, while Stand 8 had above average growth. Conversely, Stand 8a had the highest growth between 1991 and 1995 while Stand 8 had the lowest.

Table 2. Estimated establishment dates and ages of *Populus* among Santa Ana study stands based on tree-ring measurements through 2002.

Stand	*n*	Earliest Year	Age Max	Age Min
1b	7	1931	72	68
1	6	1939	64	62
8a	6	1952	51	48
8	7	1959	44	41

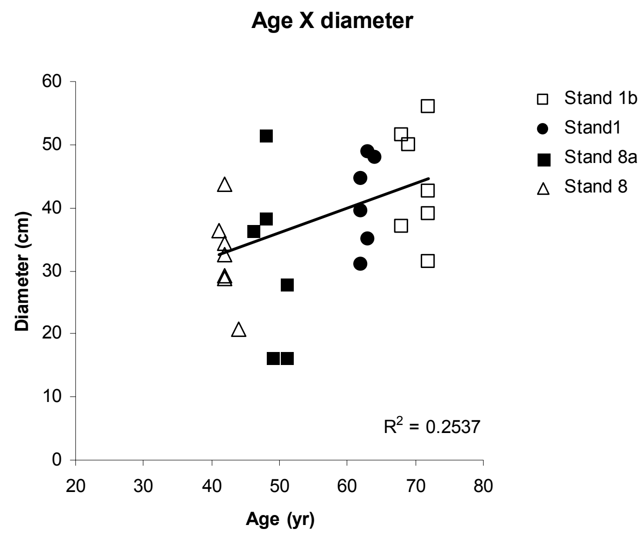


Figure 4. Individual tree age versus diameter root crown by stand.

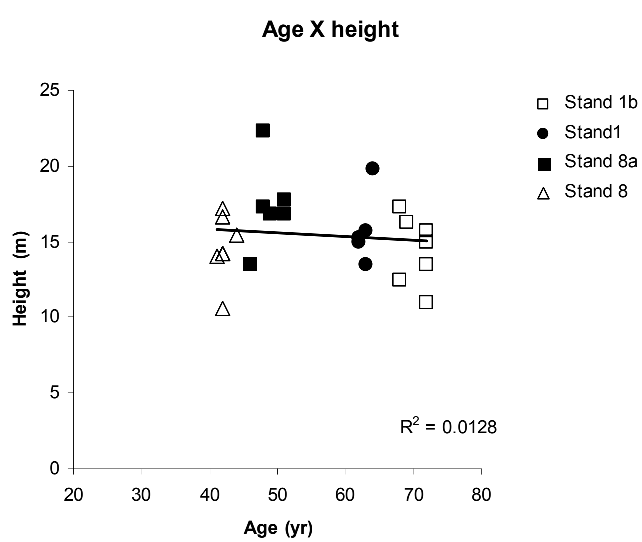


Figure 5. Individual tree age versus tree height by stand.

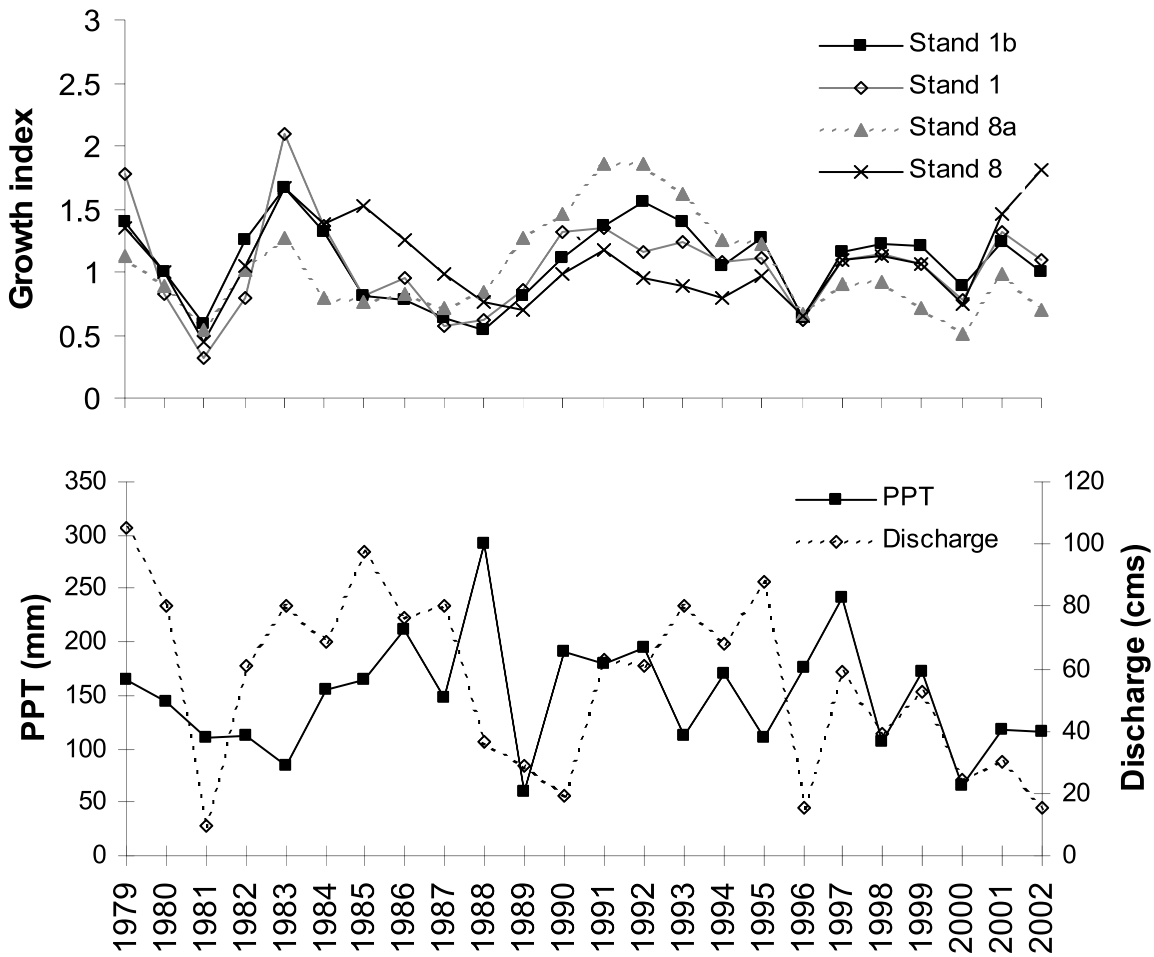


Figure 6. a) Average annual growth based in tree rings for *Populus deltoides* var. *wislizeni* per stand versus growing season (April-September) total precipitation and total discharge in m^3/second (cms). Complete understory Russian olive removals occurred in Stands 1 and 1b during 1998. Sources: Albuquerque WSFO Airport, NM (290234) weather station and the USGS 08330000 gauge on the Rio Grande at Albuquerque, NM.

These mixed trends lead to relatively weak overall correlations between growth and discharge or precipitation (Figures 7 and 8). With respect to discharge, the growing season values show a modest trend of increased growth with increased flows. Antecedent winter discharges do not appear to be important. Winter flows tend to be very low, particularly under regulated conditions, and thus unlikely to affect the soil moisture of adjacent bars and terraces. In contrast, antecedent winter precipitation shows a slight upward trend and may provide additional soil moisture to spur spring growth regardless of discharge.

Treatment effects due to the clearing of the understory exotic trees and shrubs in 1998 were equivocal (Figure 9). While the pre-treatment densities of *Elaeagnus* within the stands were not measured, the pre-treatment growth index was more or less uniform among the stands, ranging from 1.00 to 1.08, and suggesting that there were no significant differences with respect to growth rate among stands before treatment. After the treatment in 1998, the growth response was mixed. Stand 8a, the stand with the greatest abundance of understory *Elaeagnus* (basal area 6.08 m^2/ha), had significantly less production after 1998 than the other stands, suggesting a treatment effect. In contrast, Stand 8, with the next highest amount of *Elaeagnus* (4.16 m^2/ha), had significantly greater growth and the greatest proportion of trees with better growth after than before 1998 (Figures 10 and 11). But, if we remove from the analysis the three outlier trees in Stand 8 (92, 95, and 102), the after/before growth ratio drops to 1.00, more or less equivalent to that of the treated Stand 1 or Stand 1b, but still above Stand 8a. Hence, the sampling depth may be an issue with respect to detecting treatment effects.

Intra-specific competition among trees (as opposed to understory treatment) also did not appear to be a factor in growth as measured by nearest neighbor distances between *Populous* (Figure 12). While the trees in Stands 1b and 1 tended to be further apart, this did not translate into greater growth either before or after the treatment compared to Stands 8 and 8a. Tree height also did not appear to play a role (Figure 13). Trees in Stand 8a tended to be taller, but not particularly more productive.

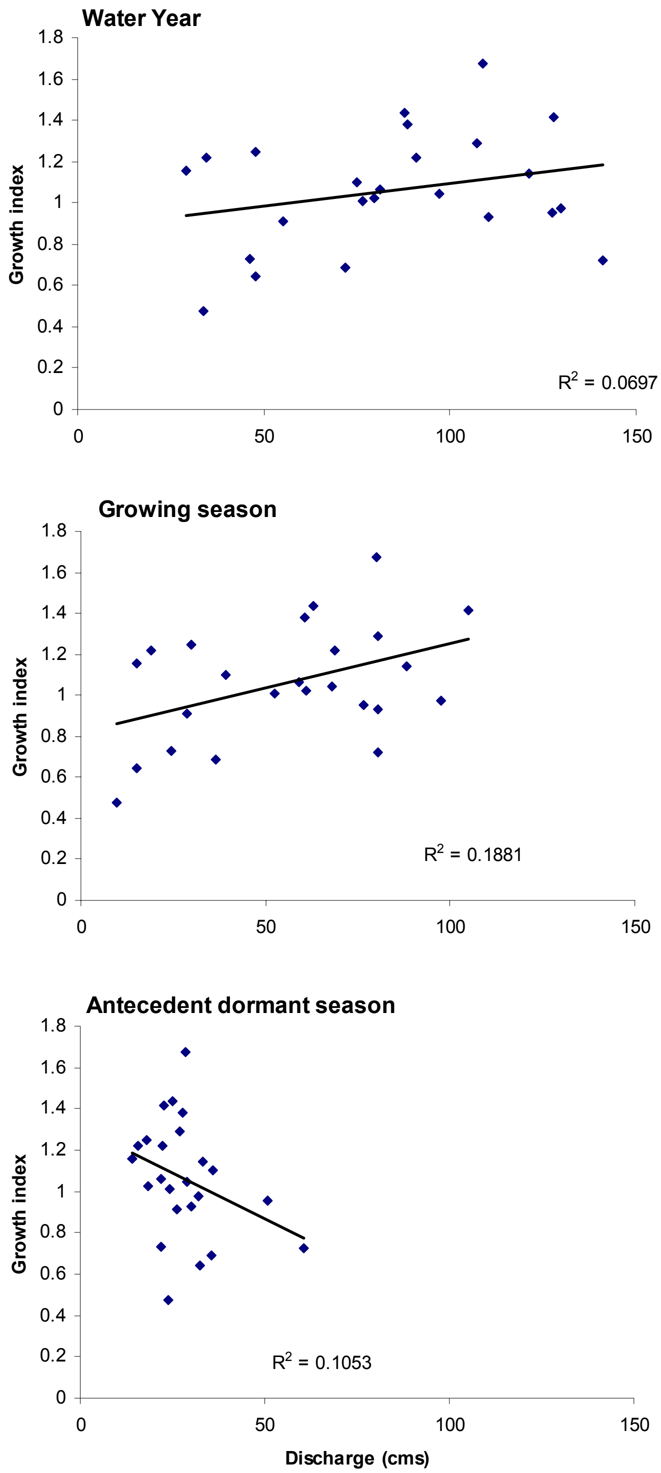


Figure 7. a) *Populus deltoides* var. *wislizeni* growth versus Rio Grande discharge: water year (October to October), growing season (April-September), and antecedent dormant season (October-March). Source: USGS 08330000 gauge on the Rio Grande at Albuquerque, NM.

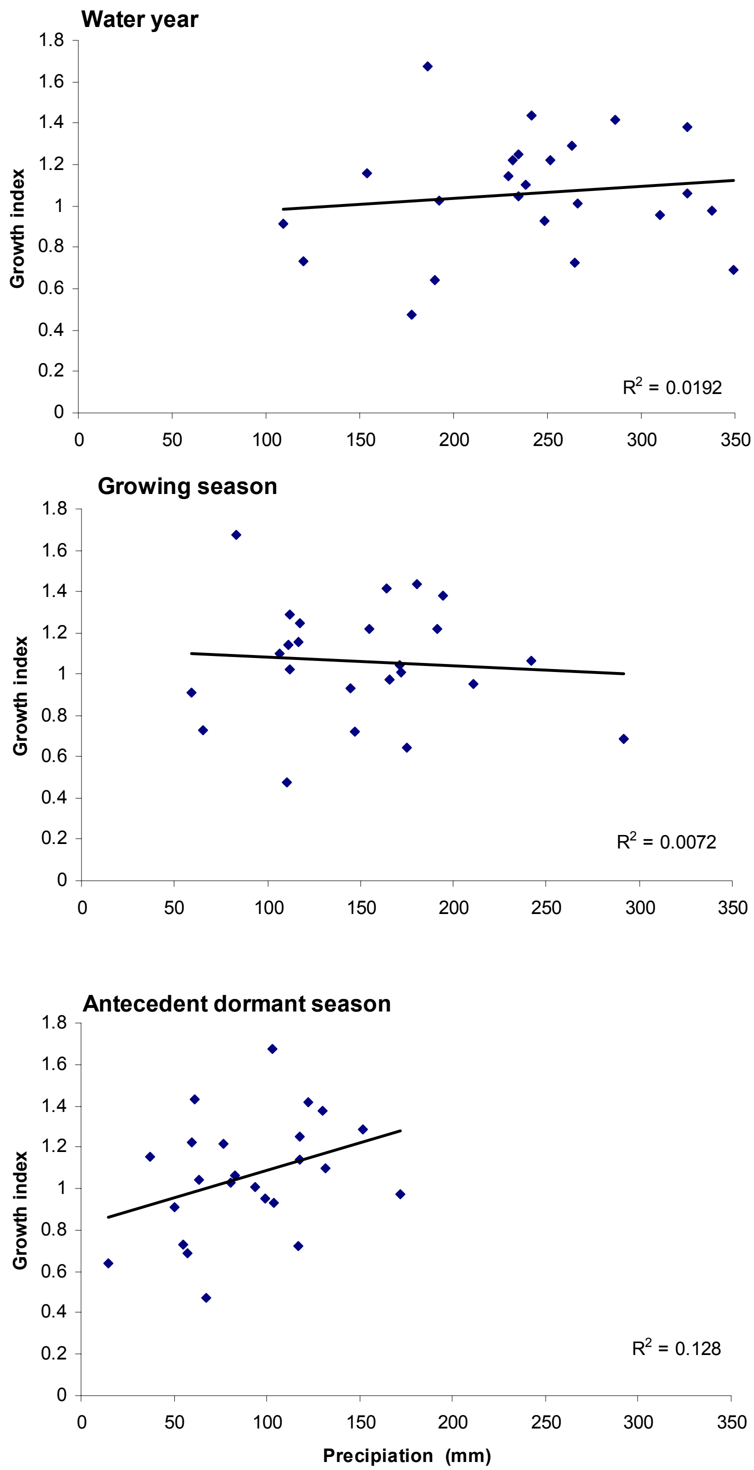


Figure 8. *Populus deltoides* var. *wislizeni* growth versus precipitation: water year (October to October), growing season (April-September), and antecedent dormant season (October-March). Source: Albuquerque WSFO Airport, NM (290234) weather station

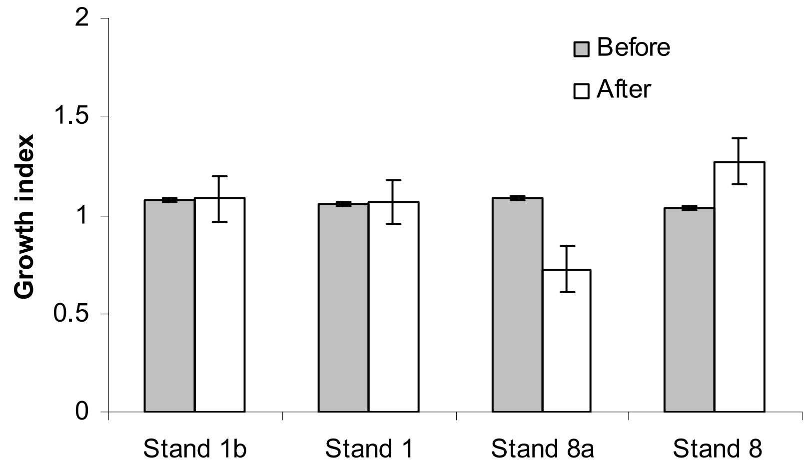


Figure 9**.** Average growth (+/- 1 SE) before and after understory exotic removal treatments in 1998. Stands 1 and 1b received complete understory removals of Russian olive. Stands 8 and 8a received minor or no removals. Pre-treatment values cover 1979-1998; post-treatment, 1999-2002.

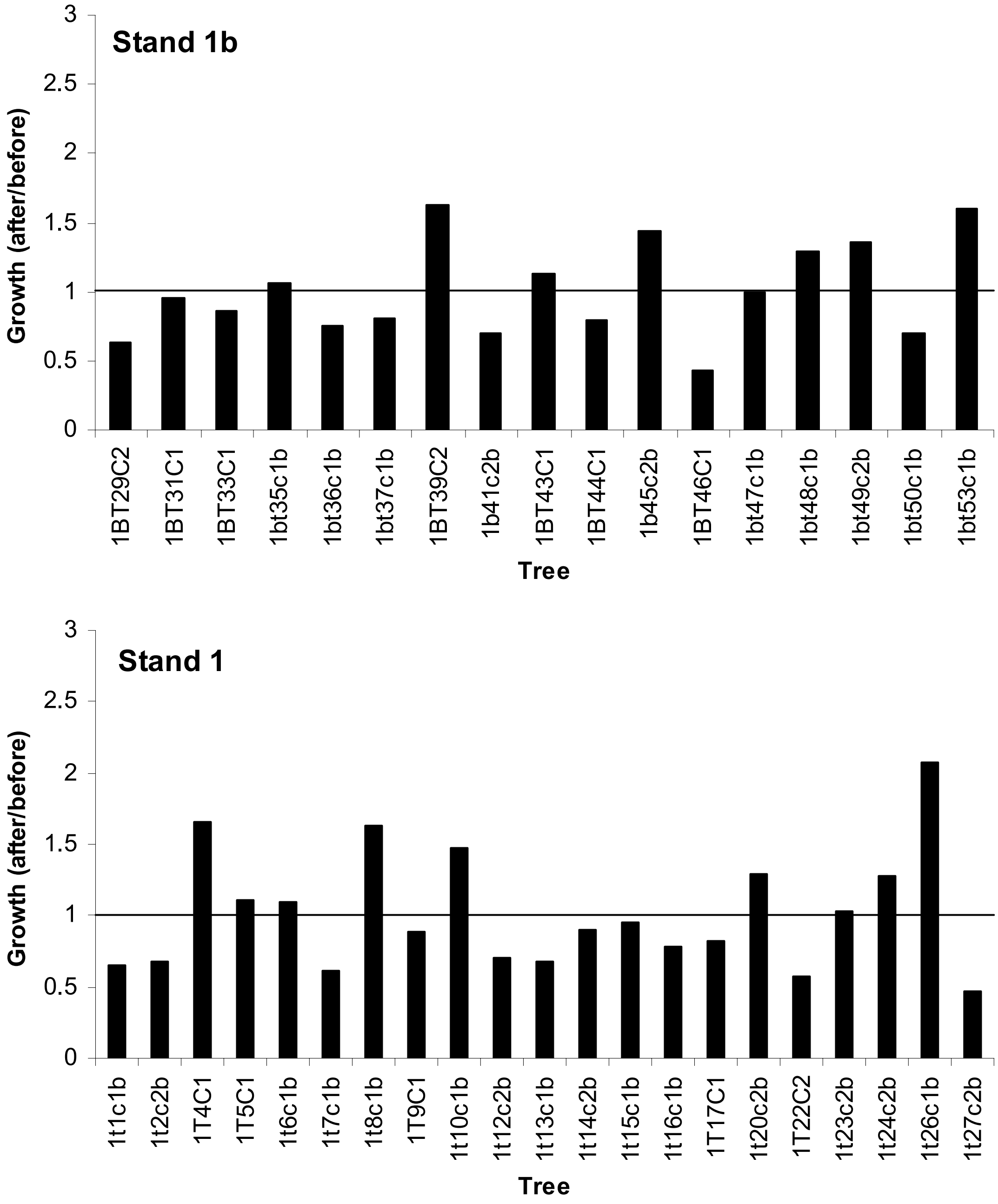
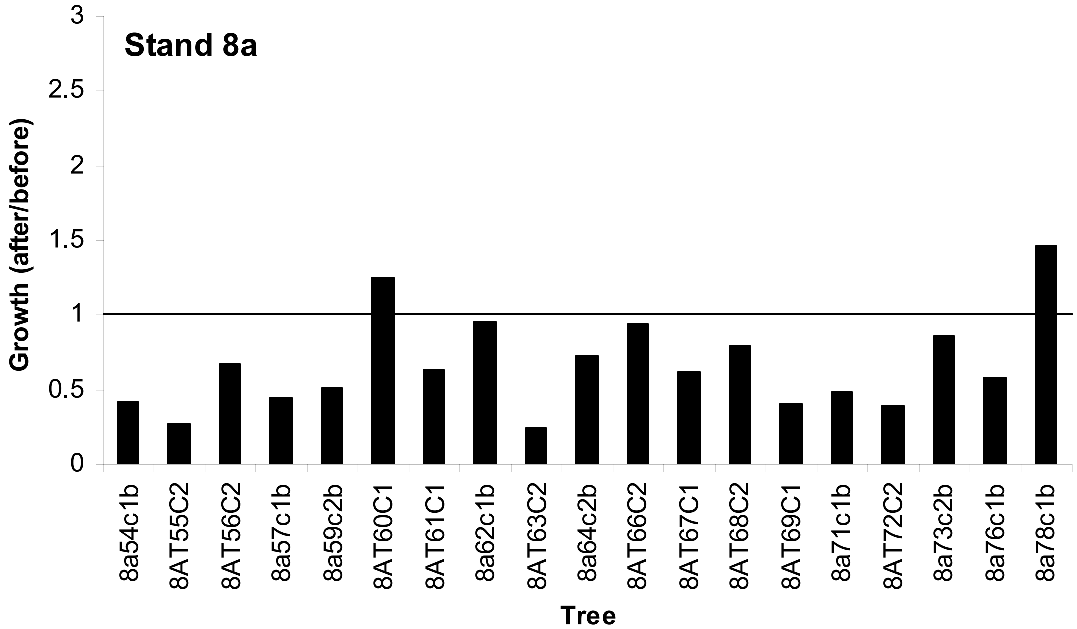


Figure 10. Ratio of tree growth from 1999-2002 (after treatment) to growth 1979-1998 (before treatment) by tree in Stands 1 and 1b (full Russian olive removal in the understory).



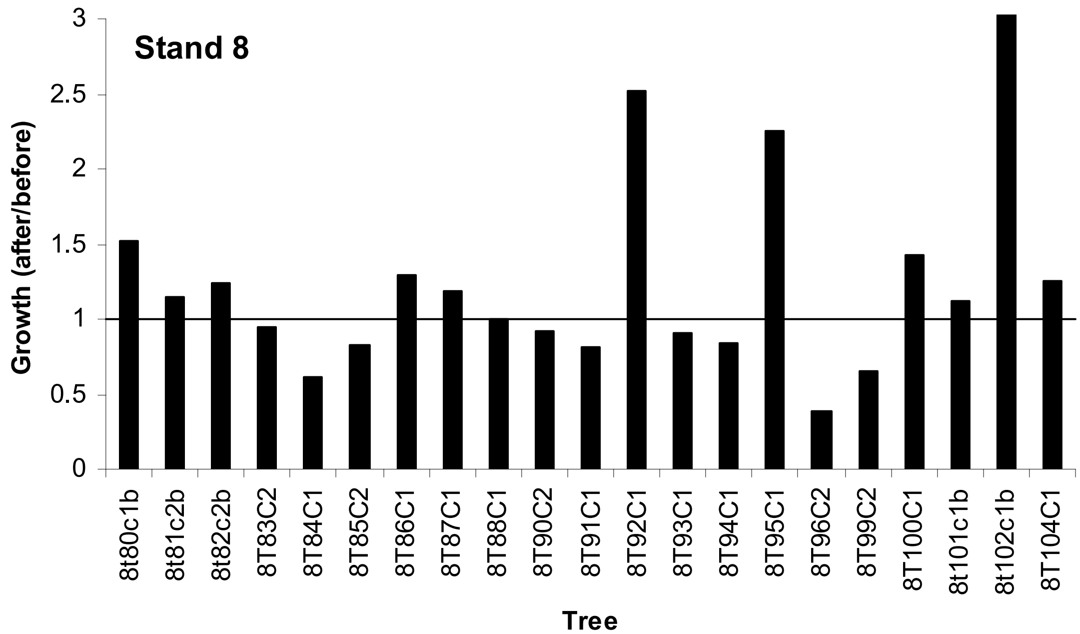


Figure 11. Ratio of growth from 1999-2002 (after treatment) to growth 1979-1998 (before treatment) by tree in Stands 8a and 8 (little or no Russian olive removal in the understory).

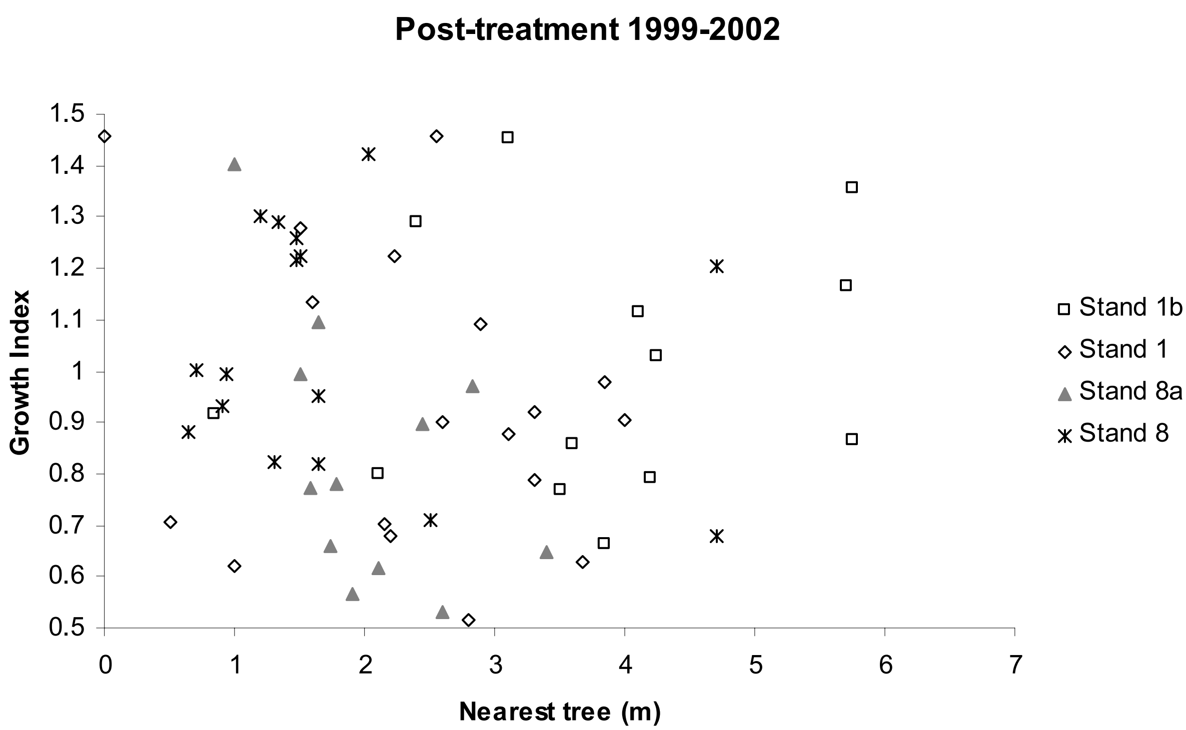
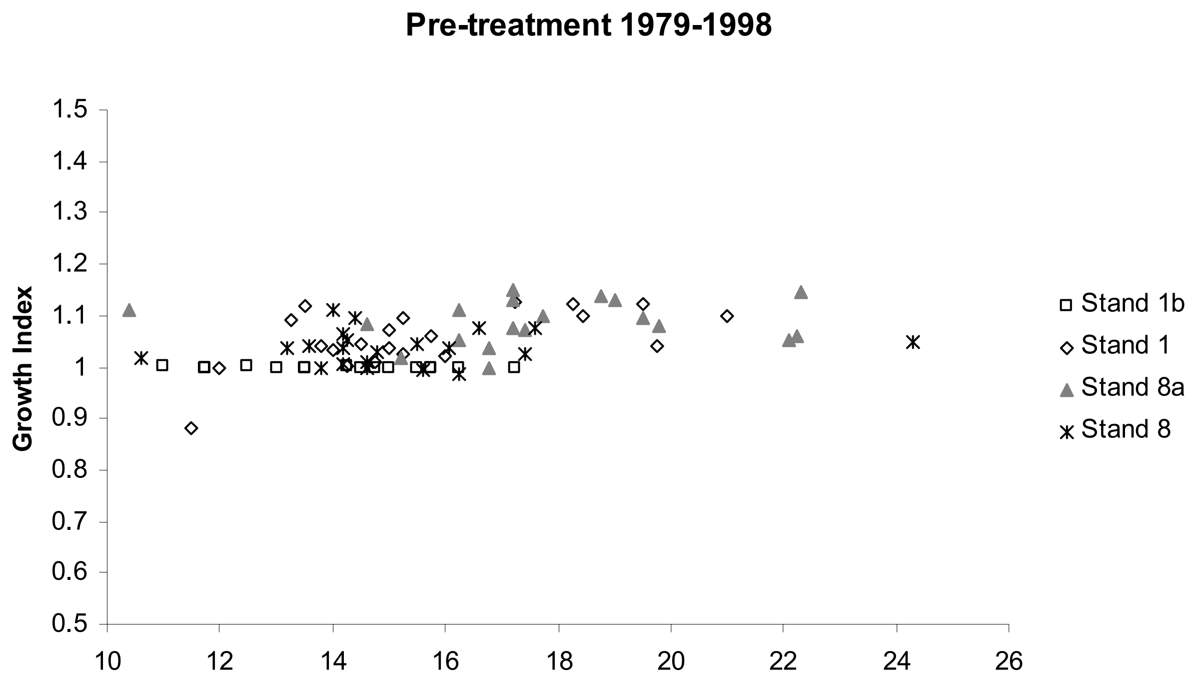


Figure 12. Average growth by tree before and after understory removals in 1998 versus intra-specific density as measured by the distance of cored trees to their nearest neighbor.



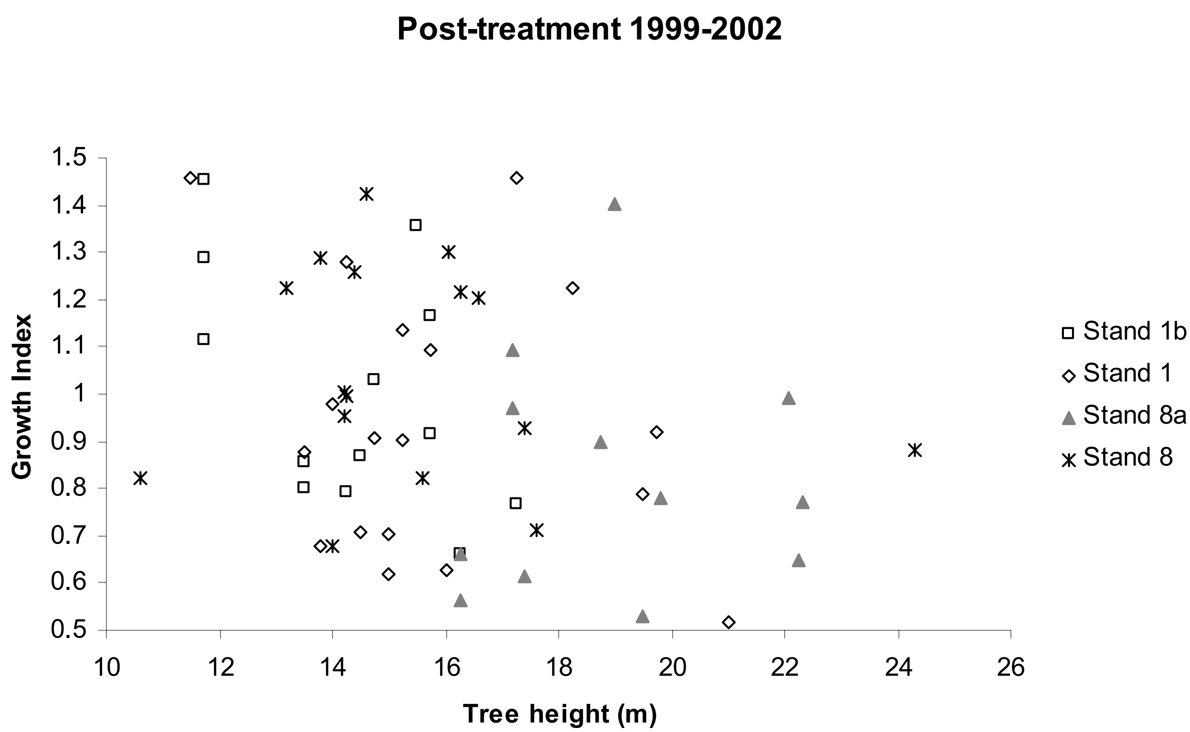


Figure 13. Average tree growth before and after understory removals in 1998 in relation to tree height..

Discussion

While there were indications that *Populous deltoides* ssp. *wislizeni* was somewhat sensitive to both high and low water availability, either as precipitation or discharge-fed groundwater (Figure 14), the complex patterns suggest that the tree growth was not a simple linear relationship to water availability over a growing season. Such factors as stand age, the spatial structure of groundwater through time, substrate differences, growing-degree-days, and intra-annual variation in flow and precipitation likely play roles. Stromberg and Patten (1991) found low-flow volumes to correlate well with low growth, but high volumes did not necessarily generate good production, and suggested that soil saturation and anaerobic conditions during high flow periods may limit growth. Clearly, depth to groundwater and its temporal pattern are crucial, and the use of surface water discharge here as a surrogate for groundwater availability is likely insufficient to track all growth patterns. This particularly is the case in a losing reach such as this and where river channel incision is ongoing, further deepening the water table through time. Harner and Stanford (2003) found that basal areas in *P. trichocarpa* stands in losing reaches were half that of gaining reaches. Scott, Lines, and Auble (2000) demonstrated that channel incision can lead to declining water tables and cottonwood stress and mortality. Along the Santa Ana reach of the Rio Grande, channel incision is actively occurring in response to the reduction of sediment inputs following the impoundment of the river behind Cochiti Dam. While we had no groundwater data available, the implications are that water table heights are likely lowering relative to the terraces where the trees are growing, leading to a decoupling between surface water discharge and growth as seen in our data. Hence, the issue of groundwater declines and cottonwood growth and health remain an important issue and reflect the early sentiment of Reily and Johnson (1982) that riparian declines were driven primarily by altered river hydrology.

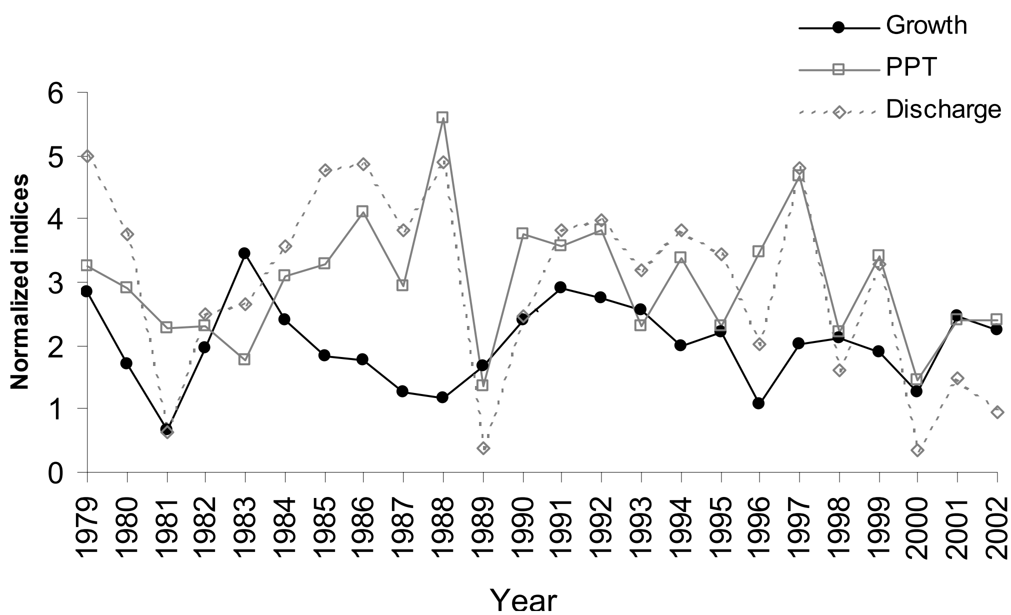


Figure 14. Normalized average growth across all stands compared to normalized growing season (April-September) discharge and precipitation from 1979 through 2002 (sources: Albuquerque WSFO Airport, NM (290234) weather station and the USGS 08330000 gauge on the Rio Grande at Albuquerque, NM). A constant of 3 has been added for presentation purposes.

With respect to inter-stand variability, soil differences may be important. Harner and Stanford (2003) suggest that finer sediments positively influence water holding capacity and enhance growth. Superficially, the surface soils of our sites appeared uniform, but subsurface sand or clay lenses are common in the middle Rio Grande and might be responsible for some of the inter-stand variability. Stand age might also be important. Stand 8, the youngest, had the highest growth during the1985-1987 high-discharge period. This was particularly apparent in the non-detrended data where trees in Stand 8 showed considerably higher oscillations in growth response to discharge and precipitation than the older stands. Hence, younger trees may be more sensitive to fluctuations in water availability, but this effect would be masked by the detrending process. It should also be noted that Stand 8 was nearest the river and hence may also be subject to less decoupling between surface discharge and groundwater availability, possibly leading to better growth during the period in question.

The complex growth patterns may also reflect subtle trends in seasonal moisture and temperature. Intra-annual growth responses, while not quantified here, were evident within rings, i.e., spring discharges and the onset of the summer rains could be discerned. The timing and duration of discharges and summer precipitation may be critical to growth responses (in this respect, fast-growing cottonwoods might be ideal for detecting long-term changes in climate seasonality). Furthermore, antecedent moisture, particularly during the previous winter, may spur spring production despite discharges, but the trends presented here need further confirmation, and multi-year feedbacks need to be addressed. Similarly, temperature, as it reflects both daily heat patterns and growing season lengths, is an interaction that needs to be considered here. We set the growing season comparison to discharge at April through September, but in the Southwest U.S. seasons can be quite variable in length and may not consistently correspond to our marker, thus weakening the correlations.

Aside from the issues of sample depth, the lack of a treatment response to understory clearing may also be a function of only having four years of post-treatment growth available for analysis, i.e., there may be a lag effect in growth response yet to be measured. This may be compounded by an age-dependent lack of response to thinning, a phenomenon reported in for eastern cottonwoods under plantation conditions (Taylor 2001). In addition, the four years of post-treatment measures were during a period of severe drought accompanied by low discharges, which may have overridden significant treatment responses. Another consideration is the relatively low abundance of exotic trees and shrubs in the “control” stands--the less than 12% relative abundance may not be a significant competition issue. But this was also difficult to assess because the pre-treatment densities and basal areas were unknown in the treatment stands and, hence, the initial degree of understory competition was unknown. Yet, given the accelerated movement towards exotic tree removal throughout the Middle Rio Grande, the question of impact (or lack thereof) of the removals on growth and health of the cottonwoods remains an important question (along with myriad other biological issues associated with these restoration techniques). Therefore, we stress the need for additional tree-ring studies with additional controls and more in-depth measurements of environmental factors to address the efficacy of the ongoing exotic removal program to improve cottonwood productivity and health in the riparian communities along the river.

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