

POTENTIAL FOR USE OF COTTONWOODS IN DENDROGEOMORPHOLOGY  
AND PALEOHYDROLOGY

by

Susanmarie Clark

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# POTENTIAL FOR USE OF COTTONWOODS IN DENDROGEOMORPHOLOGY AND PALEOHYDROLOGY

SUSANMARIE CLARK    Laboratory of Tree-Ring Research, University  
                                 of Arizona, Tucson, Arizona 85721

## ABSTRACT

Fremont cottonwoods contain valuable environmental information that can be used to augment knowledge of fluvial systems. Cottonwoods have not been commonly used in dendrochronological studies because of difficulty in determining ring boundaries, uncertainty if growth rings are annual, as well as doubt whether riparian species cross-date. A new method of sample examination utilizing transmitted light permits clear view of ring boundaries, and resampling techniques suggest that the growth rings are annual. The cottonwoods studied are growing along Twentyfive Mile Wash and Harris Wash, both tributaries of the Escalante River in south-central Utah. Cross-dating was found among most of the cottonwood cores, except those from Harris Wash, which were approximately dated by ring counts. After application of rigorous dendrochronological methods, ring counts were deemed to be sufficient to estimate ages of cottonwoods, as the cores contain no missing rings and few false rings. Careful ring counts would accurately estimate the age of these trees to within 1 to 2%. The cottonwoods studied are partially buried by 2 to 4 m of terrace sediments. Dating of the trees provides a minimum age for the terraces of 130 to 227 years. Lack of cross-dating

between the cottonwoods and nearby arid-site ponderosa pines indicates that these species respond to different environmental or climatic factors. The ponderosas are limited by lack of moisture, while correlation analysis suggests that the cottonwoods are limited by excess moisture. Soil saturation often causes a decrease in growth due to insufficient oxygen available to the roots. However, in years with very little precipitation, cottonwood growth appears to be limited by lack of moisture, and in these particular years a small ring occurs in the cottonwood series as well as in the ponderosa series. Growth suppressions in the cottonwoods correlate either with known floods on the Escalante or Paria Rivers, or with droughts. If the suppression is due to drought, a corresponding small ring occurs in the ponderosas. Timing of paleofloods can be inferred from suppressions in the early portion of the cottonwood chronology. Rates of alluviation were estimated at 0.9 to 3.0 cm/yr by dividing the amount of sediment above the basal root flare of the trees by the age of the trees. All of these methods would be especially useful in dendrogeomorphological studies on ungaged watersheds, before periods of record, or in watersheds where cottonwoods are the only tree species available.

## INTRODUCTION

Floods cause an estimated one quarter to over one billion dollars in damages each year (Langbein and Hoyt, 1959). A single storm in the Four Corners area of Arizona,

New Mexico, Colorado, and Utah produced floods that killed 25 people and caused approximately \$11.3 million in damages (Roeske and others, 1978). As more and more people inhabit floodplains, determining the flood history of watersheds will become increasingly important for the purposes of reconstructing dates of floods before periods of record or in areas where no records exist, studying rates of erosion and deposition, and ultimate application to flood control and urban planning.

Dendrochronology, specifically dendrogeomorphology (i.e., the use of plants and plant ecology to date geomorphic events; Alestalo, 1971), can be used to establish dates and extents of past floods. Trees may become scarred, tilted, buried, uprooted, defoliated, or topped by flood waters, or their roots may be exposed. Any of these injuries can affect the growth of a tree and thus will show up as an anomaly in the ring-width pattern. Various anomalies include flood rings (abnormal growth similar to false rings), depauperate earlywood (earlywood containing vessels which are small and diffuse) (Yanosky, 1983a, 1983b), very small rings, groups of small rings, very large rings, crushed cells at a point or in a zone in a ring, and reaction wood. The anomaly will be found either in the ring that corresponds to the date of the injury, or in the following ring, depending on when in the growing season the event occurred (Sigafos, 1964). If a tree was severely damaged, certain types of anomalies may be present in

several rings following the year of the actual event (Alestalo, 1971; Yanosky, 1983a).

Alestalo (1971) and Shroder (1980) present extensive reviews of the literature on dendrogeomorphology. The first use of trees to study aggradation was apparently by Borggreve (1889, in Alestalo, 1971), who measured the rate and amount of peat accumulation on the surface of bogs. Dendrogeomorphological methods for studying floods have been well established for several species in the eastern U.S., including Salix, Fraxinus, and Acer (Sigafos, 1961, 1964; Hack and Goodlett, 1960; and Yanosky, 1982a, 1982b, 1983a, 1983b), and in the western U.S. using conifers (LaMarche, 1966; Stewart and LaMarche, 1967; Stone and Vasey, 1968; Helley and LaMarche, 1968, 1973; Parker and others, 1973; Laing and Stockton, 1976; Smith and McCord, 1986; and McCord, 1986, 1987). Throughout the Southwest, however, Fremont cottonwood (Populus fremontii Wats.) is often the only large tree species found along streams. Cottonwoods have not been precisely dated until now, although Everitt (1968, 1979) used ring counts of Plains cottonwood to map changing meander patterns, and of Fremont cottonwood to study an arroyo cut. Ring counts were used because all attempts at cross-dating failed. Everitt believes the ring counts to be accurate to within 10% of the age of the trees. Harrison and Reid (1967) constructed a flood-frequency graph based on age and height of scars on one cottonwood and two elm trees in North Dakota. Womack and Schumm (1977) used a

ring count from a single Fremont cottonwood to examine an arroyo in Colorado. Boison (1983) used ring counts of Populus fremontii (data from this writer) combined with radiocarbon analysis to date terraces in Harris Wash and Twentyfive Mile Wash near Escalante, Utah. Webb (1985) suggests that channel morphology along parts of the Escalante River has been stable over the past 150 years, partially based on ring counts of Populus fremontii (data from this writer).

The present study is the first known to use precisely-dated cottonwood trees to attempt to gain a more thorough understanding of a fluvial system. Cottonwoods have not been commonly used in dendrochronological studies because of difficulty in determining ring boundaries, uncertainty if growth rings are annual (Everitt, 1968, 1979), as well as doubt whether riparian species cross-date. Cottonwoods were also thought to be short-lived, which would make them of little use in long-term reconstructions.

The objectives of this study are fourfold. The first is to resolve whether cottonwood trees can be used to date fluvial terraces in the canyons of the Escalante River in southern Utah. The second objective is to determine whether the cottonwoods cross-date with ponderosa pine from higher-elevation sites nearby. If they do not cross-date, what different factors are the trees responding to? The third purpose is to determine what caused growth suppressions which occur in the cottonwood cores. If the

suppressions are caused by flood events, cottonwoods could be used to ascertain the flood history of ungaged watersheds, where they may be the only long-lived species available. The fourth and final objective is to use ages of cottonwoods and depth of burial by terrace sediments to estimate the rate of alluviation in the canyons.

## STUDY AREA

The study area is in the Escalante River Basin in south-central Utah, a region described as "one of remarkable grandeur and almost unique in its loneliness" (Marshall, 1889). This area is characterized by a warm, semi-arid climate with great variations in precipitation (Webb, 1985).

The cottonwoods studied are growing along Twentyfive Mile Wash, an intermittent tributary of the Escalante River, and along Harris Wash, a perennial tributary (Fig. 1). The streams in this area flow in arroyos in their upper reaches and are deeply entrenched into Triassic and Jurassic sedimentary rocks in their lower reaches, including the Carmel Formation, Navajo Sandstone, Kayenta Formation, Wingate Sandstone, and the Chinle Formation (Gregory and Moore, 1931; Hunt, 1956; Hackman and Wyant, 1973). Many of the streams are bordered by a series of alluvial terraces which were formed during floods, either by rapid deposition in slackwater or by gradual build-up from minor overbank flows. The terraces consist of layers of fine-grained sediment, and range from approximately 1 to 17 m in height, and from small remnants to continuous surfaces over 1 km in

length. Three general groups of terraces occur. Low terraces formed under the present hydrologic regime are the most laterally extensive, and range from 1.5 to 4.5 m in height. Intermediate terraces range in age from Recent to several thousand years, and range in height from approximately 5 to 8 m. High terraces are usually over 2000 years old and are found only as isolated remnants at heights greater than 9 m (Boison, 1983). Several of the low terraces contain large living cottonwood trees (Fig. 2). This "cottonwood terrace" is similar to the one described by Hereford (1984, 1986) on the Little Colorado and Paria Rivers. I studied trees from three terraces in Twentyfive Mile Wash and from one terrace in Harris Wash with hopes of dating these deposits for colleagues who are studying the geomorphology of this area (see Patton and Baker, 1981; Boison, 1983; Patton and Boison, 1983, 1986; Webb, 1985; Boison and Patton, 1985; Webb and Smith, 1986; and Clark, 1986, 1987b). Although the terraces may be dated by radiocarbon analysis, dendrochronology gives a much more accurate age because flood-borne sediments may contain fragments of very old material, leading to a  $^{14}\text{C}$ -date which is possibly much older than the deposits.

Originally the cottonwoods were thought to to be growing on the surface of the terraces, in which case the sediment would have to have been deposited before the trees germinated. Upon examination of trees along the stream-side edges of the terraces, it was discovered that the



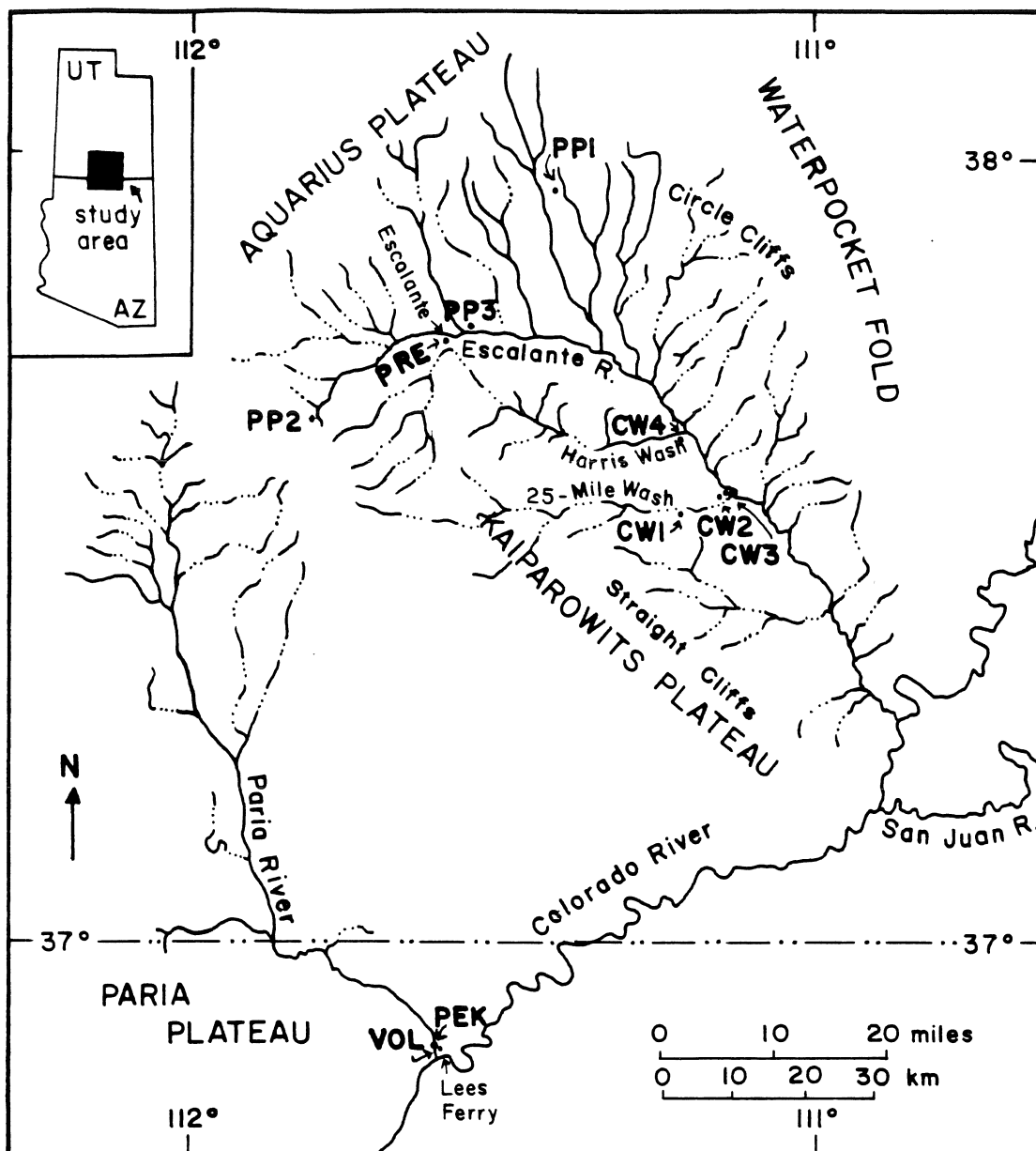


Figure 1. Index map showing locations of tree-ring sites, weather station, and stream gage used in study. CW stands for a cottonwood site, PP stands for a ponderosa pine site, PRE is the precipitation station at Escalante, and VOL and PEK stand for total volume and peak flow, respectively, at the gage near Lees Ferry on the Paria River. These abbreviations will be used throughout the paper.



Figure 2. Partially-buried cottonwood tree along the edge of a terrace in Harris Wash. Part of this tree has been exhumed by erosion of the surrounding sediment. Five levels of adventitious roots are visible and are indicated by arrows. This tree is at least 157 years old, based on a ring count. Trees on this site were approximately dated by ring counts because of weak cross-dating and numerous severe growth suppressions.

cottonwoods have been partially buried by 2 to 4 m of sediment (Fig. 2). Some trees have been exhumed by removal of the surrounding sediment. A distinct change in bark texture marks the separation between that part of the tree which is above ground and that part which was formerly below ground. The above-ground portion has deep furrows, while the formerly-buried portion has very shallow furrows. The rest of the trees are pole-like rather than exhibiting a basal root flare, also an indicator of partial burial (Hadley, 1960). Dating the trees would provide a minimum age for the terraces, as all of the sediment above the basal root flare must have been deposited since the trees germinated.

In addition to cottonwoods, the terraces support rabbitbush (Chrysothamnus spp.), sagebrush (Artemisia tridentata), skunkbush sumac (Rhus trilobata), box elder (Acer negundo) and various grasses. Oak (Quercus gambelli) grows on a higher terrace, and salt cedar (Tamarix chinensis) and willow (Salix spp.) grow adjacent to the streams.

Two sites of ponderosa pine (Pinus ponderosa) were collected from the semi-arid plateaus above the Escalante canyons (Fig. 1). The sites are both on west-facing, well-drained slopes. Growth of conifers in semi-arid sites is usually very limited by climate (Fritts, 1976). If cottonwood growth is limited by the same climatic factors, then the cottonwoods should cross-date with the ponderosa

pine. A third ponderosa site was collected along the Escalante River (Fig. 1), in hopes of providing a connection between the riparian cottonwoods and the arid-site ponderosas.

## DATA COLLECTION

### Sample preparation

The cottonwood specimens were prepared according to methods described in Clark (1987a). Cores were collected with a 4.3 mm-diameter increment borer and allowed to dry for several days before mounting. The core mounts used are identical to those used for X-ray densitometry (Fig. 3). They are made from poplar or basswood because these species have even grain and little resin, making them easily machinable.

Twisted cores may be straightened by softening and untwisting in steam (e.g., over a boiling tea kettle). With vessels aligned vertically, the straightened cores were glued into the mounts using white glue. The cores can be held securely until the glue dries by wrapping the mount with string, which is later removed.

Using a bandsaw with a clean, sharp 12.7 mm (1/2") plywood blade, that portion of the core which extends above the mount was removed (Fig. 4). Next, the mount was sawn in half lengthwise, parallel to the previous cut. This cut will expose the other side of the core and will remove a small amount of it. The resulting specimen will be approximately 2 mm thick.

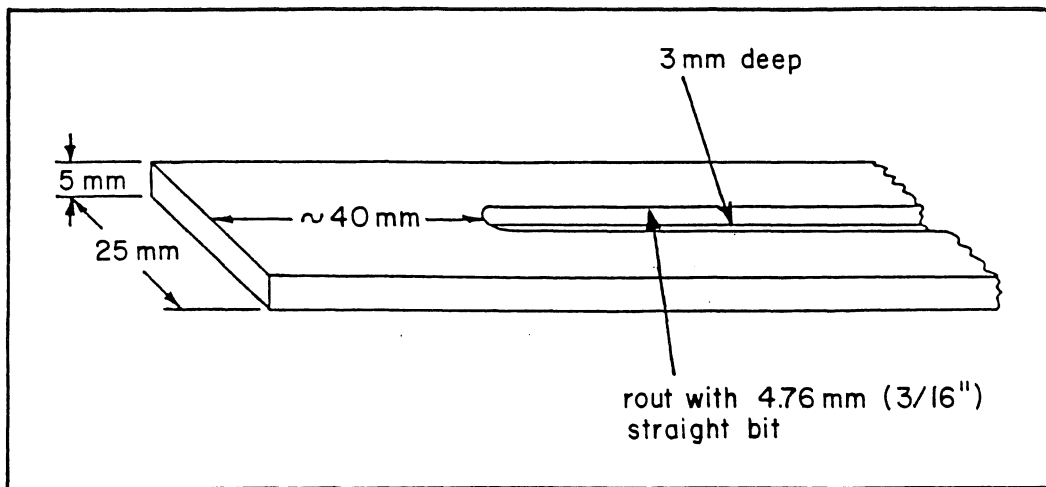


Figure 3. Densitometry mount used in sample preparation. (After McCord, 1984).

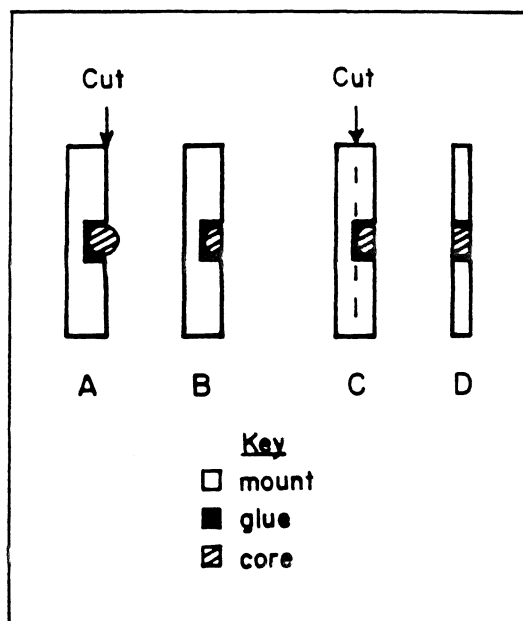


Figure 4. Sawing sequence showing end view of mount and core.

The samples were sanded with an electric orbital sander. 100 grit paper was used until the cells were clearly visible under a microscope (the specimens will be about 1 mm thick at this point). 220 and 320 or 360 grit papers were used next, then a polish was applied by hand with 400 grit paper. It is a good idea to sand both sides of the samples in order to have two clear surfaces for examination.

### **Sample examination**

The cores were examined under a microscope, first using reflected light, then transmitted light. While under reflected light, all potential ring boundaries were indicated on the mounts with pencil marks (Fig. 5). Next, the cores were re-examined in transmitted light. Possible sources of transmitted light include a rectangular microscope light or a light table. Actual ring boundaries are represented by a vertical line of single small cells, which are easily distinguishable in transmitted light (Fig. 6). This type of light is especially useful for resolving problems in areas of very small rings, where there are injuries or false rings, or where there is depauperate earlywood. After the wood was examined alternately in both types of light, decisions were made on ring boundaries and the cores were dated.

The ponderosa pine samples were prepared and examined using standard methods as described in Stokes and Smiley (1968), Swetnam and others (1985), and Phipps (1985).

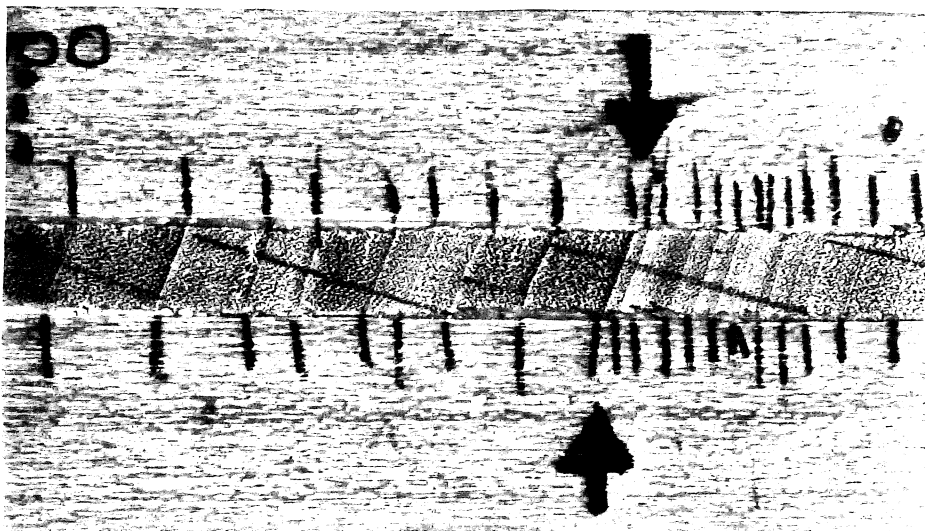


Figure 5. Cottonwood sample seen under reflected light. The arrow points to the beginning of a growth suppression.

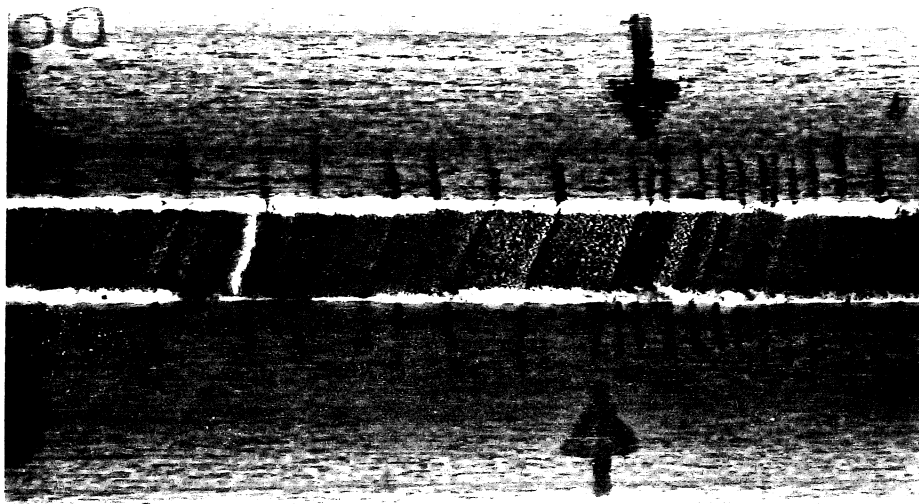


Figure 6. Same cottonwood sample seen in transmitted light. Note how distinct the ring boundaries are in this type of light.

## **Weather and runoff records**

Precipitation records from Escalante, Utah (from National Oceanic and Atmospheric Administration's Climatological Data, Annual Summaries for Utah, and supplemented with local records) were selected for comparison with the tree-ring series. Monthly rainfall records were grouped into water years (October 1 to September 30) to correspond with the seasonal effect on hydrological phenomena (Chow, 1964). Since the water year begins and ends when soil moisture is at or near minimum, this arrangement may relate well to tree growth (C.W. Stockton, personal commun., 1987).

Runoff data from the Paria River gaging station at Lees Ferry (from U.S. Geological Survey) were selected for comparison with the tree-ring records. The Lees Ferry record was chosen because of proximity and because the data are reasonably long and complete. Data from the Escalante River gaging station were rejected because of incompleteness. Monthly runoff records for the Paria River were also grouped into water years.

## **TREE-RING CHRONOLOGY DEVELOPMENT**

In order for dendrochronological methods to be applicable, trees must have annual rings (Stokes and Smiley, 1968). Since some species produce several growth layers per year (Glock, 1951; Schulman, 1951; Glock and others, 1960), I returned to the field two growing seasons later and collected more cores from the same cottonwood trees. These



new cores have two more rings than those collected previously. Based on this information, it is assumed that Fremont cottonwoods have annual rings, although two years is a short sampling interval.

Cross-dating was found in almost all specimens examined, indicating that some climatic or environmental factor is limiting the growth of these trees (Fritts, 1976, p. 21). According to Everitt (1979), cottonwood growth depends on availability or quality of groundwater.

After the cores were dated, ring widths were measured, and age trends were removed by standardization. The resulting indices from all trees in each site were then averaged to obtain site chronologies (Fritts, 1976). Three cottonwood chronologies were developed, as well as three ponderosa pine chronologies (Fig. 7). The chronology statistics are presented in Table 1. The mean, standard deviation, and first-order autocorrelation for each ponderosa series fall within one standard deviation of the mean value of these statistics for 21 Pinus ponderosa chronologies from the western U.S. (Fritts and Shatz, 1975) with the exception of the autocorrelation for PP2, which falls within two standard deviations of the mean. The percent variance accounted for by climate (%Y or signal) is 76% for PP1, 59% for PP2, and 46% for PP3, compared to an average value of 60% for 102 western arid-site chronologies (DeWitt and Ames, 1978). As expected, the riverside ponderosas (PP3) contain less climatic signal than their

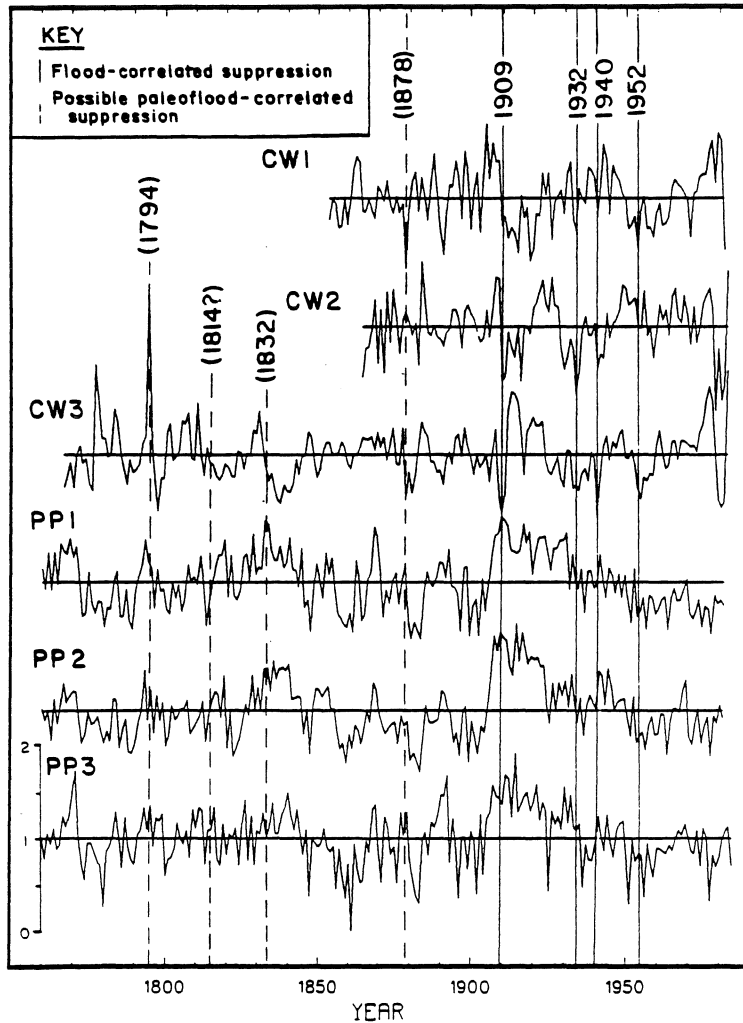


Figure 7. Plots of indices of the three cottonwood and three ponderosa pine chronologies. Suppressions which occur in all cottonwood sites are indicated by vertical lines, and are correlated with local flooding. Paleoflood events are inferred from cottonwood suppressions that do not correspond to small rings in the ponderosa series.

TABLE 1. CHRONOLOGY STATISTICS AND SITE INFORMATION

<u>ID</u>	<u>Species</u>	<u>elev</u> <u>(m)</u>	<u>Range</u>	<u># of</u> <u>trees</u>	<u># of</u> <u>cores</u>	<u>MS*</u>	<u>SD*</u>	<u>AC*</u>	<u>% rings</u> <u>missing</u>
CW1	<u>Populus fremontii</u>	1426	1864-1981	6	17	.23	.24	.33	0.0
CW2	<u>Populus fremontii</u>	1378	1864-1981	10	20	.22	.24	.28	0.0
CW3	<u>Populus fremontii</u>	1378	1767-1982	6	12	.23	.34	.46	0.0
PP1	<u>Pinus ponderosa</u>	2268	1631-1981	8	16	.43	.45	.52	1.6
PP2	<u>Pinus ponderosa</u>	2280	1600-1981	9	18	.33	.40	.59	2.0
PP3	<u>Pinus ponderosa</u>	1676	1630-1984	10	20	.27	.31	.51	1.8

TABLE 1, CONTINUED

<u>ID</u>	<u>ANOVA</u>	<u>period</u>	<u>ZY*</u>	<u>ZYT*</u>	<u>ZYC*</u>	<u>ZYCT*</u>	<u>S/N*</u>	<u>long.</u>	<u>lat.</u>	<u>Chron.ID</u>
CW1	1905-1975	24.2	12.8	.23	62.8	1.9/1	37°34'	111°12'	TMFPS9	
CW2	1898-1981	29.9	25.4	-.11	44.8	4.3/1	37°34'	111°09'	TMS290	
CW3	1880-1982	38.0	16.6	-.65	46.1	3.6/1	37°35'	111°08'	TMT290	
PP1	1800-1981	76.3	11.8	-.01	11.9	25.7/1	37°58'	111°26'	BDR640	
PP2	1700-1981	58.5	25.9	.03	15.6	12.7/1	37°40'	111°48'	SHO640	
PP3	1860-1984	46.3	31.9	.16	21.7	8.6/1	37°47'	111°33'	ESP640	

\* MS - mean sensitivity

SD - standard deviation

AC - first-order autocorrelation

ZY - % variance accounted for by climate

ZYT - % variance accounted for by differences between trees

ZYC - % variance accounted for by differences between cores

ZYCT - % variance accounted for by differences between cores  
within trees

S/N - signal to noise ratio

arid-site counterparts. No chronology was developed for the Harris Wash cottonwood site because of weak cross-dating and numerous severe suppressions. This site was approximately dated by ring count only.

#### AGE OF TERRACES

Most of the cores from Twentyfive Mile Wash dated at 120 rings or thereabout; the oldest has 217 rings. The cores from Harris Wash are slightly older, with most having 140 rings or thereabout; the oldest has 157 rings. Since

few of the cores include the pith, but include the innermost, highly curved rings, the trees are probably between 5 to 10 years older than the cores indicate, judging by comparisons with cores that do contain the pith. Based on this information, the approximate minimum age of the cottonwood terrace is between 130 to 227 years. Fremont cottonwood is considered to be a short-lived species (Little, 1976, 1980; Elias, 1980), but the old age of the studied trees suggests otherwise. No data were available on how short-lived they are, but literature on Plains cottonwood (Populus sargentii Dode) which is also considered to be short-lived, states that this species matures in 40 to 50 years, then begins to die, rarely reaching 100 years old (Read, 1958; USDA, 1965; and Elias, 1980). The cottonwoods studied in this work are still healthy despite their age and partial burial.

#### CORRELATION ANALYSIS

A cross-correlation analysis was performed using nine different time series in an attempt to determine what climatic variable is limiting the growth of the trees. Comparisons were made among the three cottonwood chronologies, the three ponderosa pine chronologies, the Escalante precipitation record, and the two flow records from the Paria River at Lees Ferry (peak flow and total volume). These comparisons were made using both unfiltered data (Table 2) and data which were processed through a low-pass filter (Table 3). Since the flow records range

only from 1924 to 1981, all of the series were shortened to this length. The correlation analysis was done for comparison purposes only, recognizing that the filtered data have fewer degrees of freedom than the unfiltered data. Only those correlation values which are significantly different from zero will be discussed.

#### **Unfiltered data**

The two arid-site ponderosa chronologies correlate positively with each other, with the river-side ponderosa chronology, with precipitation, and with both flow records. This correlation suggests that growth of trees from these two sites is limited by precipitation and by precipitation minus evapotranspiration in a fashion similar to runoff. The river-side ponderosa chronology exhibits positive correlation with the arid-site ponderosa chronologies, and the precipitation record. Trees from this site seem to be responding to rainfall, but not to water in the stream course. The chronology from the most-downstream cottonwood site in Twentyfive Mile Wash (CW3) correlates negatively with precipitation and both flow records, suggesting that trees on this site do poorly in times of large amounts of rainfall and streamflow. The CW3 chronology exhibits positive correlation with the two other cottonwood chronologies, but neither of these remaining cottonwood chronologies correlate with any other series. This suggests that the two most upstream cottonwood sites are responding to something other than precipitation and streamflow,

TABLE 2. RESULTS OF CROSS-CORRELATION ANALYSIS OF NINE

<u>UNFILTERED TIME SERIES</u>									
	CW1	CW2	CW3	PP1	PP2	PP3	PRE	VOL	PEK
CW1	1.000								
CW2	.022	1.000							
CW3	.381*	.553*	1.000						
PP1	.064	-.147	-.250	1.000					
PP2	.185	-.186	-.103	.823*	1.000				
PP3	.091	-.155	-.024	.702*	.716*	1.000			
PRE	.012	-.141	-.269*	.541*	.566*	.424*	1.000		
VOL	.031	-.244	-.394*	.376*	.326*	.137	.716*	1.000	
PEK	-.208	-.178	-.327*	.431*	.279*	.227	.469*	.682*	1.000

\* Value significantly different from zero at the 95% confidence limit.

TABLE 3. RESULTS OF CROSS-CORRELATION ANALYSIS OF NINE

<u>FILTERED TIME SERIES</u>									
	<u>CW1</u>	<u>CW2</u>	<u>CW3</u>	<u>PP1</u>	<u>PP2</u>	<u>PP3</u>	<u>PRE</u>	<u>VOL</u>	<u>PEK</u>
CW1	1.000								
CW2	-.363*	1.000							
CW3	.445*	.441*	1.000						
PP1	.030	-.195	-.430*	1.000					
PP2	.270*	-.223	-.221	.860*	1.000				
PP3	.158	-.211	-.085	.803*	.805*	1.000			
PRE	.086	-.376*	-.593*	.766*	.769*	.464*	1.000		
VOL	.246	-.468*	-.452*	.700*	.576*	.456*	.719*	1.000	
PEK	-.110	-.217	-.540*	.891*	.707*	.561*	.749*	.729*	1.000

\* Value significantly different from zero at the 95% confidence limit but only if degrees of freedom were equal to that of the unfiltered data.

possibly to groundwater availability. Flow in upper Twentyfive Mile Wash is intermittent, while it is perennial in the lower reaches of the wash. This may relate to why only trees from the most-downstream site exhibit any relationship with streamflow.

## Filtered data

The data for all nine time series were processed through a low-pass filter removing variations with wavelengths less than eight years (Fritts, 1976). This was done so low-frequency variations and trends in the data could be compared and studied. The two filtered arid-site chronologies compare similarly to the unfiltered arid-site chronologies, with the following exceptions: there is a negative correlation between PP1 and CW3 and a positive correlation between PP2 and CW1. The results are probably an artifact of the filtering process or there may be low-frequency climatic information in the cottonwood series similar to that in the arid-site ponderosa pine series. Since CW1 is the most upstream cottonwood site and it is located in the intermittent portion of the wash, growth of trees on this site may be limited by lack of moisture, similar to the ponderosas. The filtered river-side ponderosa chronology positively corresponds with the precipitation record, and the two flow records, as well as the two arid-site ponderosa chronologies. The long-term trends of rainfall and runoff are preserved in these trees from talus-slopes adjacent to the Escalante River. The cottonwood chronologies also exhibit more correlations in their filtered form than in their unfiltered form, although they may not all be statistically significant. CW1 correlates negatively with CW2 and positively with CW3. CW2 and CW3 correlate negatively with precipitation, suggesting

that growth of cottonwoods in some sites is limited by excessive water availability. There is a positive correlation between CW2 and CW3, and a negative relationship between the runoff records and CW2 and CW3. The inverse relationship between high flow and growth of cottonwoods is therefore apparently preserved in the long-term trends of these series.

#### **Lack of cross-dating between cottonwood and pine**

Since very little correlation was found between the ponderosa pine series and the cottonwood series, this suggests that different factors are limiting the growth of these trees. The ponderosas respond to rainfall and correlate with runoff in a positive manner, while the most-downstream cottonwood site (CW3) responds to these factors in a negative manner. For example, in a year with large amounts of rainfall, the ponderosas grow well and produce a large ring, as their growth is not limited by lack of moisture. But the cottonwoods would produce a very small ring in this same wet year, as their growth is limited by excess moisture. Since only the cottonwood site closest to the Escalante River (CW3) is negatively correlated with flow, close proximity to a river seems to be desirable in studying the relationship between high streamflow and growth suppression.



## SUPPRESSION ANALYSIS

### Methods

Upon further examination of the samples, I noticed many zones of small rings, or suppressions. Growth suppressions in conifers have been previously used to study events such as landslides (Shroder, 1978), debris flows (Hupp, 1984), and floods (Laing and Stockton, 1976). Nearly every cottonwood specimen contains a suppression beginning in 1909, the year of a severe flood on the Escalante River, and of the worst storm "either of record or tradition" in Utah (Thiessen, 1909, p. 505). Suppressions occur in other years, as well. To analyze the possible connection between suppressions and floods, suppression data was gathered by visual inspection of the cores, looking for abrupt decreases in ring width (Fig. 5). The suppression events were then tabulated by the year in which they began, first by cores, then by trees, and then by sites. So that undue emphasis was not placed on suppressions in the early part of a chronology where there are fewer trees, the number of trees containing a particular suppression was divided by the number of trees available at that point in the chronology, thus giving the percentage of trees exhibiting a suppression in a particular year. Since no chronology was developed for Harris Wash, the suppressions were tallied by determining how many rings existed between the suppression and the bark. The trees from Harris Wash exhibit a high random "noise" component, indicated by the large number of short lines on

the Harris Wash plot. This may explain why cores from this site could not be cross-dated. The suppression data is shown in Figure 8, along with flood data compiled by Webb (1985) for the Escalante and Paria Rivers, and tropical storm data compiled by Smith (1986). Rings containing scars, discoloration, or abnormal growth are also indicated in Figure 8.

### **Discussion**

Gill (1970) and Kozlowski (1984) have summarized the literature on responses of trees to flooding. Growth of trees near streams appears to be negatively affected by flooding during the growing season, because of decreased photosynthetic rates, decreased shoot, cambial, and root growth, and morphological changes, the end result often being death. Growth reduction may occur as a result of these changes, but may not be apparent for such a long time after the flooding that other causes are sought (Kozlowski, 1982, 1984). Many trees lose their leaves as a result of being flooded (Marth and Gardner, 1939), which may be followed by decreased cambial growth (Tang and Kozlowski, 1982). Flooding may cause a reduction in root growth (Kozlowski, 1984), as well as some deterioration of the original root system (Sena Gomes and Kozlowski, 1980). Roots often decay due to invasion of fungi (Stolzy and others, 1965). In flooded but unsaturated soils, root decay results from lack of oxygen (Stolzy and others, 1965). As a result of decreased root-shoot ratio, trees are often

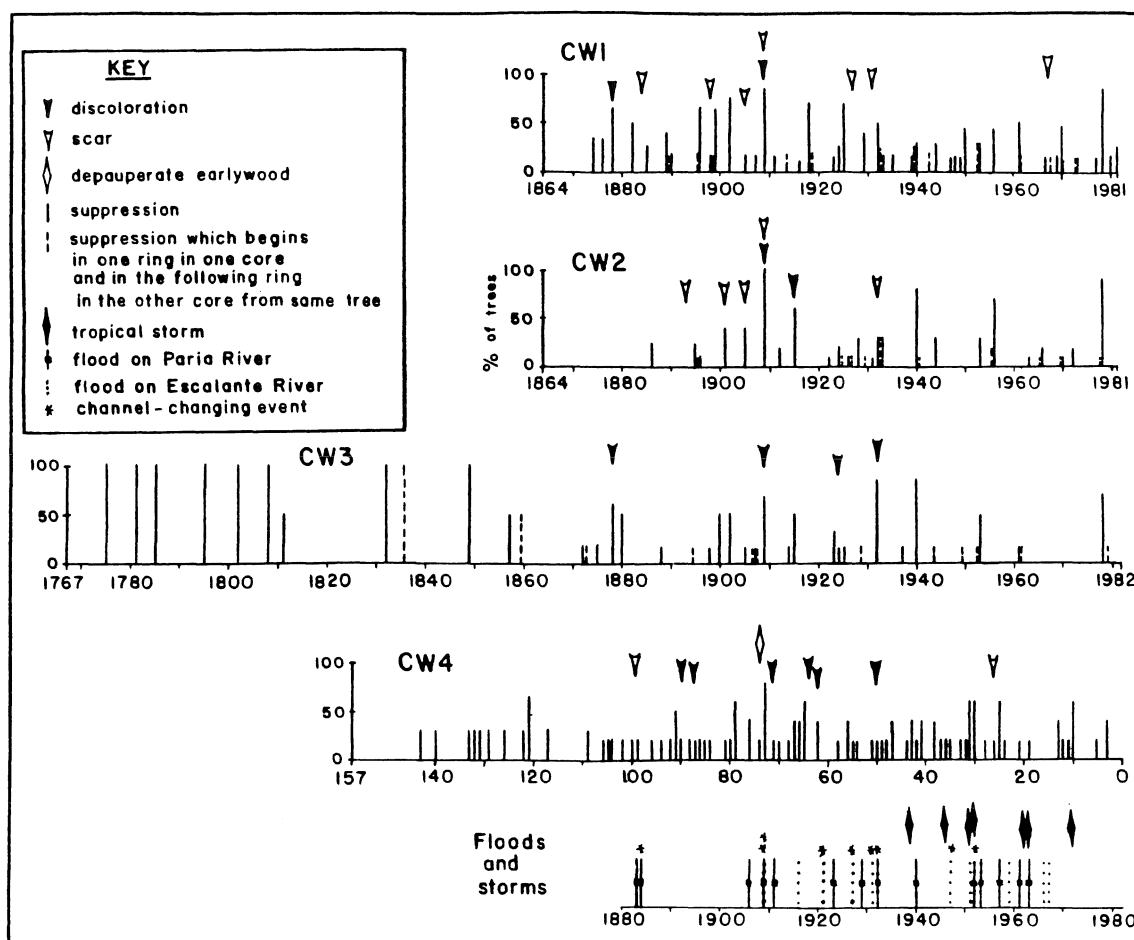


Figure 8. Results of analysis of growth suppressions in the cottonwoods. Suppressions are plotted in the year in which they begin. Suppressions which begin in one year in one core and in the following year in the other core from the same tree are shown by dashed lines and are plotted between the two years represented. Only those zones of discoloration and depauperate earlywood wood which occur in at least 50% of the trees in a site are indicated. They are plotted in the year in which they begin. All data on scars is included.

predisposed to drought injury when flood waters recede (Kozlowski, 1984). Many kinds of toxic compounds accumulate in saturated soils and most of the oxygen is consumed by microorganisms and roots within a few hours after flooding begins (Ponnamperuma, 1972, 1984). Very little gas exchange occurs between flooded soils and the atmosphere (Armstrong, 1979). Poor soil aeration is also a problem with many unflooded fine-textured soils (Stolzy and others, 1975). According to Kozlowski (1984), root growth is often restricted to the soil surface in poorly-aerated soils, leaving trees susceptible to drought injury because the roots occupy too small of a volume of soil to supply water to the shoots. Trees flooded only during the dormant season may not be adversely affected, and growth may even be stimulated (Broadfoot, 1967).

Stone and Vasey (1968) noted weakening and decay of roots of partially-buried redwoods. Partial burial of a tree can also cause a decrease in growth because less oxygen is available to the roots and there are various stresses from the sediment. This decrease is often temporary, because ecological circumstances are likely to be more favorable in the accumulated material, and the tree forms adventitious roots to benefit from the increased living space (Alestalo, 1971).

The data in Figure 8 strongly suggest a relationship between growth suppressions in the cottonwoods and high flow events on two nearby streams. In every case where all four

cottonwood sites have a suppression beginning in a particular year, a flood occurred in that year on the Escalante River and/or Paria River. This happened in 1909, 1932, 1940, and 1952. In three of the four cases, 1909, 1932, and 1952, the flood was a channel-changing event (Webb, 1985). Copious amounts of precipitation from a hurricane and two tropical cyclones in September 1939 may have caused the 1940 suppression by saturating the soil. These storms produced a total of 131.3 mm (5.17") of rain in Escalante (Smith, 1986). A hurricane and a high flow event on the Paria River in 1951 may be related to the 1952 suppression. A few of the suppressions are found in the ring which corresponds to the year of the flood in one core, and in the following ring in the other core from the same tree. According to Kozlowski (1982, 1984), initial growth reduction may appear several years after the actual flood damage. An abrupt change in color marks the beginning of the 1909 and 1932 suppressions in many of the cores. In addition, two scars occur in the 1909 ring, probably recording damage done to the trees by floating debris in the flood of August 1909 (see Sigafos, 1964).

Whenever three of the four cottonwood sites exhibit a suppression beginning in a particular year, the causal mechanism is not so clear. This occurs in 1878, 1895-96, 1902, 1915, 1956, and 1978. There is no record of a high flow event in any of these years, although some of the dates are before the period of record. The 1878 suppression is

marked by discoloration and may have been caused by a paleoflood on Twentyfive Mile Wash or the Escalante River in 1877 or 1878. The 1895-96 and 1902 suppressions are probably recording droughts. While there are no precipitation records from 1895 or 1896, both years correspond to small rings in the arid-site ponderosa pine series (Fig. 7). The 1902 suppression is probably recording a drought from water years 1901 and 1902. Water year 1901 was the second-driest year on record in Escalante, with only 92 mm of precipitation. Water year 1902 had a very dry summer, with only 67 mm of rain, compared to an average summer rainfall of 120 mm. 1902 shows up as a very small ring in both arid-site ponderosa chronologies. The 1956 and 1978 suppressions appear to be recording droughts which occurred in 1956 and 1977, both of which are small rings in the arid-site ponderosa pine chronologies. Water year 1956 was the driest in Escalante during the period of record (1901-1982). Only 81 mm of precipitation fell, compared to an average of 291 mm/yr. Maximum peak discharge on the Paria River was 40.2 cms, compared with an average of 150.8 cms for the period of record (1924-1981). The roots may have died back as a result of lack of oxygen following a series of high flow events between 1951 and 1953 inclusive, leaving the trees very susceptible to damage by drought (see Kozlowski, 1984). The 1978 suppression is probably related to droughts in 1977 and 1978. Only 133 mm of precipitation fell during water year 1977, and the summer of 1978 was the

driest ever, with only 25 mm of rain falling between June and September, compared to an average summer rainfall of 120 mm. In fact, precipitation was below average for each year between 1973 and 1978, inclusive. The cause of the 1915 suppression remains a mystery. Precipitation for water year 1915 was 339 mm, which is above normal. No large floods had occurred since 1909 on the Escalante or since 1912 on the Paria River. Low summer and fall precipitation may have been the causal mechanism. Only 66 mm of rain fell between June and September, and 70 mm fell between October and December 1915. Or the cause may have been an isolated high flow event.

There are several cases in which two of the cottonwood sites show suppression events. The 1901 suppression probably relates to the drought in that year. The 1961 suppression is probably recording a high flow corresponding to a flood on the Paria River and high summer precipitation at Escalante. No explanation is offered for the other suppressions. Growth suppressions which occur in only two of the four cottonwood sites do not appear to be an accurate indicator of flood or even drought events. They may be recording some microsite condition, whether related to climate or environment. Therefore, the best results for correlating growth suppressions and flood events are obtained by using only those suppressions which occur in all sites or in most of the sites, and which do not show up as a corresponding small ring in the arid-site Ponderosas. The

presence of scars or zones of discoloration corresponding to the beginning of a suppression increases the probability that the growth suppression was caused by a high flow event.

The longest cottonwood series, CW3, may provide some information concerning paleofloods on Twentyfive Mile Wash or the Escalante River. Five suppressions are evident in the early portions of the CW3 chronology (Fig. 7). Two of these, 1775 and 1786, are probably recording droughts, as corresponding small rings occur in the ponderosa chronologies. The suppression which begins in 1795 may be recording a paleoflood from 1794. The anomalously large ring width for 1794 may be a response to flooding (Broadfoot, 1967; Williston, 1973). According to Alestalo (1971), the level at which a ring grew to exceptional thickness indicates the level of the surface at the time the ring was developing. Diameter growth is most marked at this part of the stem to offset the strain caused by wind pressure. Although 1813 is a relatively small ring in the ponderosas and is probably the result of below-average precipitation, this probably was not enough to cause a growth reduction of the length of the 1814-1822 suppression. The final suppression in the early part of the chronology begins in 1832, a period of fairly large ring widths in the ponderosa series. Both the 1814 and 1832 suppressions may have been caused by paleofloods on Twentyfive Mile Wash or the Escalante River.



## RATES OF ALLUVIATION

Besides providing information about past floods, cottonwoods growing along water courses can also be used to study rates of sediment deposition. By measuring the amount of sediment that has accumulated above the basal root flare of the trees and comparing this to the age of the trees, the rate of sediment deposition can be estimated. Most of the trees are approximately 130 years old, with the oldest being about 227 years old, and they are buried to a depth of 2 to 4 m. This indicates that the sediment was deposited at an average rate of between 0.9 and 3.0 cm/yr. These figures are presented as averages because the sediment may have been deposited as the result of a few large flood events or several small ones. The presence of at least five levels of adventitious roots on one of the exhumed trees from Harris Wash (Fig. 2), indicates that the alluviation was episodic, as these roots form only near the current geomorphic surface (Gerhardt, 1900; Alestalo, 1971). According to Kozlowski (1984), such roots supplement absorption in the somewhat aerobic zone of the soil, whereas the original root system does not function normally. Ponnampetuma (1984) reports that the highest concentration of oxygen in flooded soil occurs in the surface layer or film, while the remainder of the soil is practically devoid of oxygen.

The sedimentary layers illustrated in Figure 2 all dip around the trunk of the tree, probably the result of being deposited in water swirling around the tree. Dating of

adventitious roots can provide minimum ages and heights for former geomorphic surfaces (Alestalo, 1971; Parker and others, 1973). A core from one of the adventitious roots near the present terrace surface contains approximately 16 rings, indicating that this level of the terrace has been in place for at least 16 years. The rings are even more difficult to see than rings in the trunk. Removal of the adventitious roots to obtain cross-sections would be the best, albeit the most destructive, sampling method.

#### ARROYO CUTTING

Widespread arroyo cutting has characterized the minor drainages of the Southwest since about 1880. Quasiperiodic shifting from periods of aggradation to periods of degradation has produced a series of fill terraces ranging in age from late Pleistocene to Recent. There is much disagreement over the cause of arroyo initiation, but there are five general hypotheses: 1) human impact and livestock grazing (Bailey, 1935; Thornthwaite and others, 1942; Antevs, 1952), 2) climatic change or fluctuation (Bryan, 1925; Hack, 1939, 1942; Euler and others, 1979; and Dean and others, 1985), 3) climatic change coupled with livestock grazing (Bryan, 1940; Leopold, 1951), 4) large floods (Dellenbaugh, 1912; Thornthwaite and others, 1942), and 5) intrinsic geomorphic factors (Schumm and Hadley, 1957; Schumm and Parker, 1973; and Patton and Schumm, 1975, 1981). Cooke and Reeves (1976), Graf (1983), and Webb (1985) present extensive reviews of the voluminous literature on

arroyo cutting. In general, the climate and grazing models favor a simultaneous shift from aggradation to degradation throughout the drainage basin, while the intrinsic geomorphic factor models favor a shift which propagates upstream in a wave-like fashion, partly influenced by the supply of sediment from the adjacent hillslopes. According to McCord (1987), detailed long-term information concerning changes in alluviation and sediment yield is very important to interpretation of these models, but is generally unavailable. Reconstruction of sediment yield, transport, and storage on the time scale available by tree-ring dating would aid in evaluation of these models, and would provide valuable insight into the dynamics of drainage basins in semi-arid regions. The present work indicates that cottonwoods can be used to study fluvial processes, and thus could aid in evaluation of these models.

Laing and Stockton (1976) studied growth suppressions and other injuries in Pinus ponderosa from Pine Creek near Escalante. The suppressions were due to exposure of roots caused by flooding. They found that flood damage is very infrequent between 1700 and 1880, more frequent between 1880 and 1909, and very frequent between 1909 and 1976. This change in frequency may relate to settlement of the town of Escalante in 1876 and to maximum stocking of the range around 1904. Woolsey (1964) reports that streamflow on the Escalante River increased after settlement of the town, and that overgrazing caused extensive damage to the range.

According to a pioneer from Escalante, there was no arroyo on the Escalante River until the flood of August 1909, the "first and biggest" flood on the river (E. Alvey, personal commun., 1985).

## SUMMARY AND CONCLUSIONS

This study demonstrates that Fremont cottonwoods growing along water courses in south-central Utah are useful for augmenting knowledge of a fluvial system. A new method of preparing and examining cottonwood cores permits clear view of ring boundaries, a condition prerequisite for cross-dating. Resampling techniques suggest that these trees have annual rings, also a prerequisite for cross-dating. Cross-dating was demonstrated in cottonwood for the first time, indicating that some environmental or climatic factor is limiting the growth of these trees. There are no missing rings in any of the cottonwood samples, but there are false rings in several specimens. Approximate dating of Fremont cottonwood could be accomplished by careful ring counts and would be accurate to within 1 to 2% of the actual age of the tree in most cases. If specimens are to be approximately dated by ring count only, they can be mounted in standard mounts (see Stokes and Smiley, 1968), greatly reducing the sample preparation time, as well as time required to estimate the age of the cores. For samples with severe suppressions, cross-dating in transmitted light is very helpful for determining ring boundaries which may not be visible under reflected light.

Minimum dates for fluvial terraces along Twentyfive Mile Wash can be estimated at 130 to 227 years, while terraces along Harris Wash began to form approximately 167 years ago (minimum date). These dates may be "pushed back" by searching for and finding older cottonwood trees, although the cottonwoods in this study are older than any referenced in the literature.

Since very little correlation was found between the cottonwood and ponderosa chronologies, these species are apparently responding to different environmental or climatic factors. The arid-site ponderosas are limited by lack of moisture, while the riparian cottonwoods are limited by excess moisture. However, in years with very little precipitation, cottonwood growth appears to be limited by lack of moisture, and in these particular years a small ring occurs in the cottonwood series as well as in the ponderosa series.

Growth suppressions which occur in all four cottonwood sites correspond with known floods on the Escalante and/or Paria Rivers in 1909, 1932, 1940, and 1953. Suppressions which occur in three of the four cottonwood sites correspond either with floods or with droughts. Comparisons with nearby arid-site ponderosa pines could confirm a drought if a small ring appears in the same year in both species. This method would be useful for determining flood events which occurred on ungaged streams or before the period of record. Examination of growth suppressions in the longest cottonwood

chronology suggests that paleofloods may have occurred in 1794, 1813 or 1814, 1831 or 1832, and 1877 or 1878. All of these dates except 1877-78 are based on suppression data from a single core because that was all that was available. Correlation among suppressions in many cores would increase the likelihood that the suppressions are related to actual events. Collection of several sites which are in close proximity to a major stream would be ideal for studying the relationship between growth suppressions and high flow. Only those suppressions which occur in all or most of the sites should be used to "pinpoint" the timing of geomorphic events, and of these, only those which do not correspond to small rings in nearby arid-site conifers should be used to infer high flow events. Within each site, only those suppressions which occur in several trees (usually over 50%) are used. Suppressions that are found in only one or two series are probably reflecting microsite conditions rather than a widespread event such as a flood or severe storm. It should be noted that flood-caused suppressions record a minimum number of high-flow events. Only floods over a certain threshold value would cause saturation of the terraces, resulting in growth reduction in the cottonwoods. Floods which occur during the dormant season would not adversely affect tree growth. The presence of scars or zones of discoloration corresponding to the beginning of a suppression increases the probability that the growth suppression was caused by a high flow event. If a series

has been ring-counted rather than cross-dated, an apparent "smearing" of flood events over two or more years may occur. This "smearing" effect is often noted in undated series as compared to dated series (Fritts and Swetnam, 1986).

Rates of alluviation were estimated at 0.9 to 3.0 cm/yr by dividing the amount of sediment which has accumulated above the basal root flare of the cottonwoods by the age of the trees. The rate is only an average because the sediment may have been deposited by a few large floods or several small ones. The presence of at least five levels of adventitious roots indicates that the alluviation was episodic, as these roots form only near the current surface. Destructive sampling of adventitious roots might provide actual dates for different terrace levels, although rings in roots are even more difficult to see than rings in the trunk.

Laing and Stockton (1976) found cross-dating between riparian angiosperms and semiarid-site conifers, but did not include angiosperms in their final study because of difficulty in determining ring boundaries and the belief that riparian trees offered no particular advantage over arid-site trees. The present study suggests that Fremont cottonwood trees contain valuable environmental information, and should be studied in greater detail, especially in cases where they are the only species available.

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