Riparian Forest Age Structure and Past Hydroclimatic Variability,
Sand Creek Massacre National Historic Site

Final Report
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1. ABSTRACT

A dendrochronological analysis of the riparian cottonwood stands at Sand Creek Massacre NHS was undertaken to (1) identify trees that may have been alive at the time of the massacre (1864); (2) describe the overall age and spatial structure of the stands; and (3) attempt to link these patterns of tree establishment with hydroclimatic variability over the last century and longer. While no trees were definitively dated to 1864, the collective evidence suggests that multiple trees were alive at that time, probably as seedlings or saplings. Overall, the current stands can be grouped into three age classes: c. 1865-1885, c. 1908-1925, and c. 1949-1960, the last of which comprises most of the main gallery forest along Big Sandy Creek. There has been very little establishment of trees since c. 1965. The temporal and spatial patterns of tree establishment are consistent with the prevailing flood-driven model of cottonwood establishment in western North America. The initiation dates of the three age classes coincide with probable flood events on Big Sandy Creek inferred from historical, meteorological, and hydrologic data. The paucity of tree establishment in recent decades is typical of natural fluctuations in similar riparian ecosystems, but land use cannot be ruled out as a contributing factor.

2. STUDY OVERVIEW

2.1. Rationale for the study

Sand Creek Massacre National Historic Site (SAND) was created to preserve, protect, interpret, and memorialize the site of a large Cheyenne and Arapaho village that was attacked by troops of the Colorado Cavalry, on November 29, 1864. The authorizing legislation calls for the NPS to protect "the cultural landscape of the site in a manner that preserves, as closely as practicable, the cultural landscape of the site as it appeared at the time of the Sand Creek Massacre." The riparian cottonwood forests at SAND were, and remain, a critical element of this cultural landscape, providing shelter, timber, firewood, forage, and wildlife habitat. In addition, individual cottonwood trees along Big Sandy Creek, both living and dead, have cultural and spiritual significance because of their association with the Indian encampments and the massacre itself.

These riparian ecosystems appear to have changed significantly over the 140 years since the massacre. Photographs of SAND as late as the 1930s show many fewer trees than are now present. Management of the riparian ecosystems at SAND to meet the unit's mandate, as quoted above, require better understanding of the site's environmental history, current conditions, changes that have occurred over time, and possible causes of those change. Thus, the main objectives of this research project were to describe the age structure of the cottonwood stands, targeting in particular trees that may have been alive in 1864 (sections 3.1 and 3.2) and to identify the hydroclimatic factors (e.g. floods, drought) that have influenced development of the stands (section 3.3). By providing information on the ages of the trees, particularly the very oldest ones, the proposed research will assist the park in managing the trees as a cultural resource, including the gathering and use of ceremonial firewood from the site, implementing culturally and environmentally appropriate fuel reduction strategies, and other issues.

2.2. Description of the study area

The study area is a section of the floodplain of Big Sandy Creek within SAND. The northern/western limit of the study area is the boundary with the Bowen property in the northwest part of SAND, and the southern/eastern limit is where the stream channel intersects a line drawn north-northeast from the former Dawson residence. The total length of this reach is about 4 km; the corner of a private parcel divides the reach into northern and southern sections and excluded about 500 m along the channel from study. All of the sampled trees were within 500 m of the current stream channel, and the vast majority were within 200 m of the channel.

2.3. General timeline of work completed

In late October 2005, with Henry Adams of INSTAAR, we traveled to SAND to conduct the fieldwork for old tree analysis and assessing tree establishment patterns (sections 3.1 and 3.2). During four days of fieldwork, we sampled some 110 trees. We were accompanied in the field by Gail Ridgeley, Northern Arapaho Tribe; Tom Meier, historian and consultant to the Northern Arapaho Tribe; Joe Big Medicine and the late Lee Pedro, Cheyenne and Arapaho Tribes of Oklahoma; and Fran Pannebaker and Alexa Roberts, NPS.

From January through March 2006, we prepared and analyzed the SAND samples. Cores were mounted and sanded, and then crossdated to establish exact calendar years for each growth ring. We also conducted a search of the literature and other data necessary to provide context for the tree-ring data, mainly on the life history and ecology of plains cottonwood, and on historical climate and flood events in southeast Colorado. In July 2006, we submitted a draft report for review. The reviewers' comments have been incorporated into this final report.

3. STUDY METHODS AND RESULTS

3.1. Targeted search for trees that may have been alive at the time of the massacre (1864)

3.1.1. Introduction

Photographs of SAND sent to us by Alexa Roberts showed cottonwoods that appeared to have the size and crown characteristics to be over 100 years old. One of the photos showed a dead tree that was believed to have been a bearing tree for an 1880 General Land Office survey, suggesting that it had established by 1864. Friedman and Lee (2002), in investigating the age structure of plains cottonwood (*Populus deltoides* ssp. *monilifera*) stands along three streams in eastern Colorado, found that four out of six study reaches contained individual trees that had established prior to 1864, though none before 1845. In fall 2004, we examined the cores that Friedman and Lee had collected, and found that the trees had good crossdating, i.e., the patterns of wide and narrow rings were easily matched from tree to tree. This raised our confidence that (a) trees that established before 1864 might still be present, whether alive or dead, at SAND, and (b) dendrochronological techniques could be used to date them. Our objective, then, was to locate the oldest trees within the study area and determine their ages.

3.1.2 Methods

The Sand Creek Massacre Project, Volume 1: Site Location Study (NPS 2000) contains a set of aerial photos of the study area taken in 1937. In comparing these photos with contemporary aerial photos, we were able to identify all living trees in the study area that were now at least ~75 years old. Any tree older than 140 years, if present, would necessarily be part of this old-tree population. These old trees appeared to be located in spatially segregated, often linear, clusters of 1-30 trees. On a paper copy of the contemporary aerial photos, we highlighted the old trees, and delineated eight of these clusters. The cluster which was numbered SC1 is a special case, in that it is much farther from the modern stream channel than any other cluster, and is immediately adjacent to the Chivington Canal. Accordingly, our presumption was that the establishment of SC1 trees likely postdated the construction of the canal, which began in 1908.

In the field, we located these clusters, numbered them from SC1 through SC8 (see map, Appendix A.1. and A.2.), and sampled all of the trees within each cluster, living or dead, except in SC7 and SC8. In those two clusters, we sampled selected trees, since we had noted these trees all appeared generally younger (e.g., less furrowed bark, more uniform crowns) than those in the other clusters. For all 49 trees (45 living) that we sampled, we (a) measured diameter at breast height (DBH; ~1.3m from ground) with a diameter tape; (b) recorded location with a GPS unit; and (c) took digital photos of the tree.

From 39 of these trees (all living), we also collected cores, usually one per tree, with an increment borer for age determination. The ten trees that were not cored were clearly hollow and/or rotten and would not produce a useful core.

In our lab, we mounted, surfaced, and crossdated the cores. We also measured the ring-widths of seven of the cores to create a master chronology to confirm the cross-dating and also examine the climate response of the trees (described in section 3.3).

3.1.3 Results and Discussion

(The Excel file **SAND Tree Data.xls**, worksheet "SC", contains all of the data from the sampled old tree clusters, SC1-SC8)

3.1.3.1 Diameter

The 49 sampled trees were generally very large, with DBH ranging from 68 cm to 161 cm (mean: 106 cm). While there turned out to be no relationship ($R^2 = 0.00$) between DBH and age among the reliably aged trees, DBH can be used with few exceptions to discriminate these older trees from the younger trees (<60 years old) that comprise nearly all of the gallery forest described in section 3.2. Other distinctive features of the older trees include large and deep furrows in the bark, gnarled limbs, and, in many cases, asymmetrical crowns.

3.1.3.2 Age determination

Unfortunately, most of the 39 trees cored for age determination had significant heartrot or were partly hollow, and cores from only nine trees extended close enough to pith to reliably estimate the pith date from the curvature of the inner rings. We used a "pith locator", with concentric circles printed on a transparency, to do this estimation (Applequist 1958). Based on work by others (J. Friedman, personal communication), we used a correction of one year for the trees to reach the sampling height, to estimate the germination date from the pith date. (This correction is conservative, in that the tree may take more than one year to reach sampling height.) Of these nine trees, three have estimated germination dates between 1865 and 1874. The other six trees have estimated germination dates between 1909 and 1921. The error in this method is proportional to the estimated number of years between the inside date and the estimated pith date, and a rough approximation of the uncertainty would be half of this number. For example, core SC3-03B has an inside date of 1870 and estimated pith date of 1866, so the true pith date is probably between 1864 and 1868 (1866±2), and the germination date, between 1863 and 1867 (1865±2).

Cores from another nine trees, though they did not reach as close to the pith, were long enough (~60-110 rings) that we could estimate their pith and germination dates using DBH to estimate the additional distance to pith from the inside of the core, and the average growth rates of that tree, and trees in the same cluster, to estimate how many rings were within this additional distance. There are two main sources of error in this method: uncertainty in the relationship between the DBH and the length of the radius along which the core was taken, because the pith may be off-center; and uncertainty about the true growth rate of the tree prior to the inside date of the core (Norton et al. 1987). Accordingly, these pith/germination dates are much less reliable than those estimated from ring curvature, with overall uncertainty on the order of ±10-15 years, (Table 1).

3.1.3.3. The timing of establishment of the old trees

From the 18 estimated germination dates there appear to be two broad age classes represented by the old trees we sampled: the oldest age class (A1), establishing from ~1865-1885; and a relatively younger age class (A2), establishing from ~1910-1925 (Figure 1). This apparent division is reflected in the observed bark and crown characteristics; the age-determined A1 trees tend to have larger bark furrows, more gnarled limbs, and more asymmetrical crowns (in a few cases, only a single living limb), than the age-determined A2 trees. Also, each cluster contains either A1 trees (SC3, SC6) or A2 trees (SC1, SC7, SC8) trees, but not both. From the observed bark and crown characteristics we infer that the non-age-determined trees in the five clusters mentioned above are probably of the same age class as the age-determined trees. In those clusters (SC2, SC4, and SC5) with no age-determined trees, the bark and crown characteristics suggest that all of these trees are probably in A1. Finally, although the two age-determined trees from SC1 site fit within the A2 age class, their estimated germination dates (1909 and 1914) correspond well to the construction of the Chivington Canal, next to which they are located. A plausible scenario is that soil disturbance from construction, combined with leakage from the canal, created a favorable environment for establishment and survival of the SC1 trees. The influence of hydroclimatic factors on the establishment of the other old trees is discussed in section 3.3.

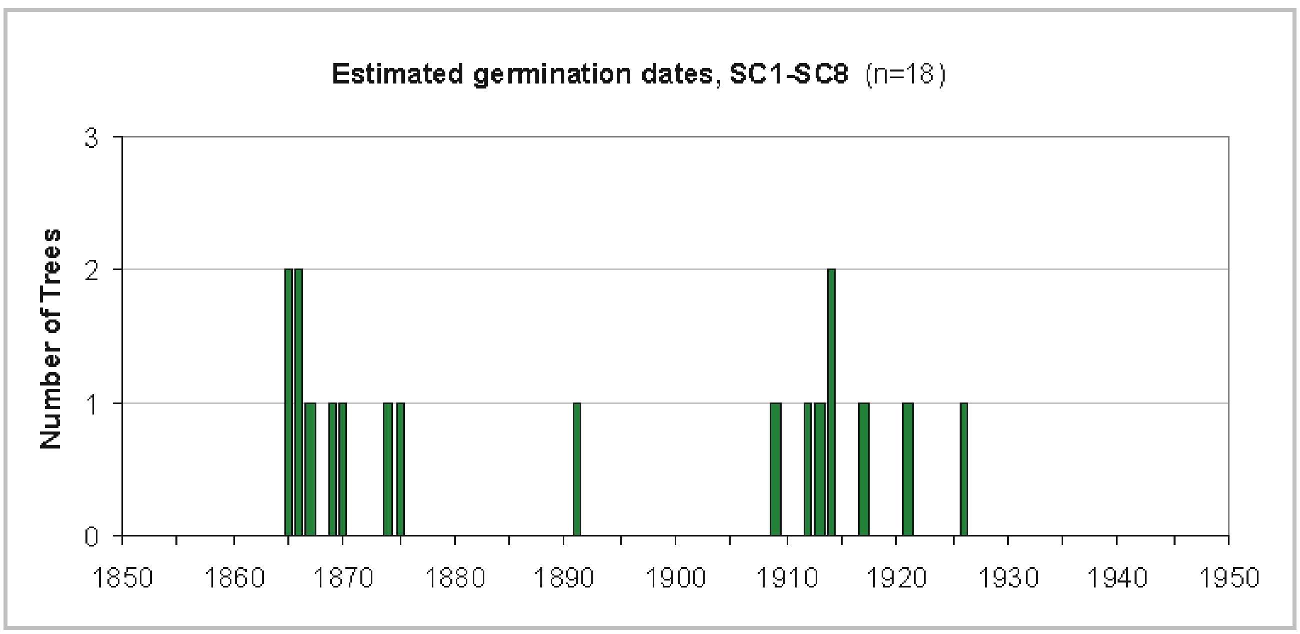

Figure 1. Estimated germination dates for trees in the old-tree clusters (SC1-SC8).

3.1.3.4. Were any of the trees alive at the time of the massacre?

We found no conclusive proof (i.e., cores containing the 1864 growth ring) that any of the trees were alive in 1864. However, the collective evidence strongly suggests that multiple trees now present at SAND were alive in November 1864. Two trees (SC3-03 and SC3-12) have absolutely dated inside rings of 1870 and 1868, respectively. From the ring curvature, we have estimated a germination date of 1865 for both trees, and the uncertainty around this date in both trees encompasses the year 1864 (1865±2, and 1865±1, respectively). It seems improbable that these two trees would be older than all of the other 15 trees that we sampled in SC3. Four other trees in SC3 have germination dates less reliably estimated from partial cores, and the uncertainty (±10-15 years) around three of these dates (which range from 1867 to 1875) includes 1864. If other clusters (SC2, SC4, SC5, SC6) are, as we believe, contemporaneous with SC3, then it is possible that some of these trees also date to c. 1864. SC6 has three trees with less-reliably estimated germination dates from 1866 to 1870, again potentially encompassing 1864 when the uncertainty in these dates (±10-15 years) is considered. The dead tree that was believed to have been a survey tree in 1880 is SC6-07. Unfortunately, the wood of this tree was too shattered to be cored. Table 1 lists the sampled trees that, based on direct or inferential evidence as described above, may have been alive in 1864.

Summary of Evidence		**Tree ID** (Germination date if estimated, with uncertainty around date)
Tree has estimated germination date for which uncertainty around the date includes the year 1864	*(A) Inner ring near pith; pith estimated from ring curvature*	**SC3-3** (1865±2) **SC3-12** (1865±1)
	(B) Inner ring not near pith; pith estimated from diameter/growth relationship	**SC3-1** (1867±10) **SC3-11** (1875±15) **SC3-13** (1869±15) **SC6-6** (1866±15) **SC6-8** (1870±15) **SC6-9** (1866±15)
No estimated pith or germination date for tree	*(C) In cluster (SC3 or SC6)with trees in above two groups; has physical characteristics of oldest trees*	**SC3-2, SC3-4, SC3-5, SC3-6, SC3-8, SC3-9, SC3-10, SC3-14, SC3-15, SC3-16, SC3-17, SC6-1, SC6-2, SC6-3, SC6-5, SC6-7, SC6-10**
	(D) In cluster without reliably dated trees; but has physical characteristics of oldest trees	**SC2-1, SC2-2, SC2-3, SC4-1, SC4-2, SC4-3, SC5-1**

Table 1. Sampled trees that may have been alive in 1864, and a summary of the evidence for that supposition. The sets of trees are listed in order of the strength of the evidence, from (A) (strongest) to (D) (weakest).

3.1.3.5 Location of historic stream channel

The location of the older clusters of trees may also allow us to reconstruct changes in the location of the active channel over time. The ~50-year-old gallery forest is immediately along the modern channel, suggesting no change in the location of the channel since ~1950. However, the old tree clusters in age class A1 (SC2, SC3, SC4, SC5, SC6) are all some distance (~50-150m) from the modern channel. Plotting a path along these clusters may represent the location of the active channel ~120-140 years ago, or around the time of the massacre. The 1880 General Land Office survey map of the area may help confirm if the location of the main channel has changed.

3.2. Timing and spatial patterns of establishment of the present-day riparian forests

3.2.1. Introduction

Comparison of the 1937 and contemporary aerial photos clearly shows a large increase in the number of trees in the study area in the last 70 years. The additional trees form dense sections of gallery forest immediately adjacent to the current stream channel. There are also other scattered clusters of post-1937 trees along the channel. Our objectives were to sample the stands of younger trees to identify their age structure, and together with the age data collected from the old trees (section 3.1), characterize the timing and spatial patterns of establishment of the present riparian forests at SAND.

3.2.2. Methods

We had originally proposed to identify within the main gallery forest differently-aged patches, based on bark characteristics and stem size, and then sample trees around random points within these patches. But in the course of sampling for Part 1, however, we could see no apparent age-differentiation among the trees which comprised the gallery forest, and no patches. Since the gallery forest is essentially a linear feature enclosing the stream channel, we decided instead to use transects perpendicular to the channel to sample the gallery forest, which has two main sections and a ~1.5km gap between them.

We began the 12 transects (numbered ST1-ST12) in the southeast corner of the study area, and worked our way upstream (see maps, Appendix A.1. and A.2.). Transects ST1-ST4 were in the southern section of the gallery forest, and ST5-ST12 were in the northern section. The point of origin for each transect was in the middle of the main stream channel, and we ran 200m of measuring tape directly up the channel to determine the distance between each transect. From each point of origin, we selected six trees so that they were relatively evenly spaced through the full width of the gallery forest along a transect perpendicular to the point of origin. If a tree had multiple stems from a single base, we selected the largest stem. In some cases, the transect was evenly split, with three trees on either side of the channel; in other cases, where the forest was only on one side of the channel, all six trees were on that side. Because the forest was more sparse along two transects (ST3 and ST4), we selected only five trees for those transects.

At each point of origin, we recorded the location with a GPS unit, and took 2-4 photos (along the transect in both directions, and up and down the stream channel). For each of the 70 selected trees along the 12 transects, we (a) measured DBH and (b) collected one core for age determination.

We also sampled seven trees, in three clusters (SC9, SC10, SC11), within the gap between the two main sections of gallery forest. We located each tree with a GPS unit, measured DBH, collected one core for age determination, and took a photo of each tree.

3.2.3. Results and Discussion

(The Excel file **SAND Tree Data.xls**, worksheet “ST”, contains all of the data from the transects. Worksheet “SC” contains the data for clusters SC9-11.)

The age data from the gallery forest dramatically confirmed our impression of an even-aged stand of trees. Of the 70 sampled trees in the transects, 67 either contained pith or were close enough to reliably estimate pith from the curvature of the innermost rings. As with the old trees, we used a correction of one year for the time it took the tree to reach sampling height. Of these 67 trees, 62 (93%) have estimated germination dates between 1948 and 1959 (age class A3; Figure 2). Within this main peak in the age distribution, there are two apparent sub-peaks, starting in 1949 and 1954. Most of the trees in the earlier sub-peak are in the farthest upstream transects (ST11 and ST12). The five trees germinating outside of the 1948-1958 period have estimated germination dates of 1911, 1920, 1923, 1928, and 1976. The first four of these are in the northern “limbs” of transect ST2 and ST3; here, the transects run very near cluster SC7. These dates correspond well with the estimated germination dates for SC7. The seven trees from the clusters (SC9-11) between the two sections of gallery forest mostly overlapped in age with the A3 age class, with estimated germination dates (from ring curvature) ranging from 1952 to 1963.

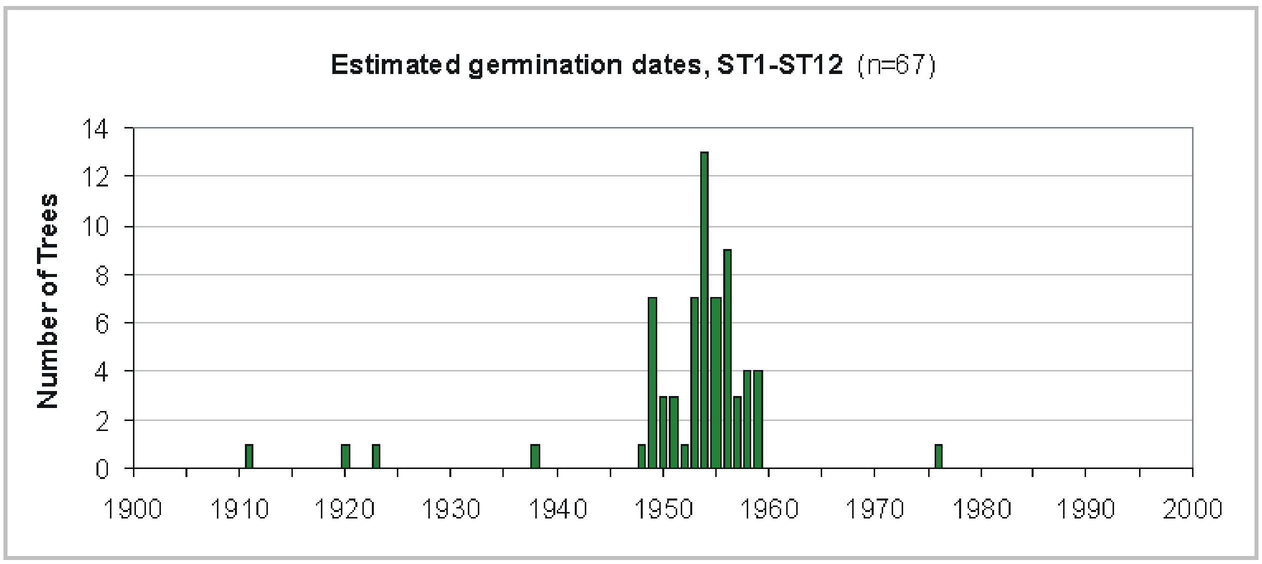

Figure 2. Estimated germination dates for trees in the SAND transects (ST1-ST12).

Combining the age data from these trees and the old trees in clusters SC1-SC8, we have a more complete picture of the development of the cottonwood forest at SAND (Figure 3; maps in Appendices A.3. and A.4.). A single “patch” of ~50 year old trees—probably composed of two sub-patches—dominates the landscape, with a lesser presence of older trees (~80-140 years old), and virtually no younger ones. We sampled only one tree, out of 116 total, whose estimated age is less than 40 years, and while we didn’t specifically search for seedlings or saplings (trees <10cm diameter), we did not encounter any while conducting the fieldwork. It appears that there has been virtually no cottonwood establishment within the study reach since ~1965.

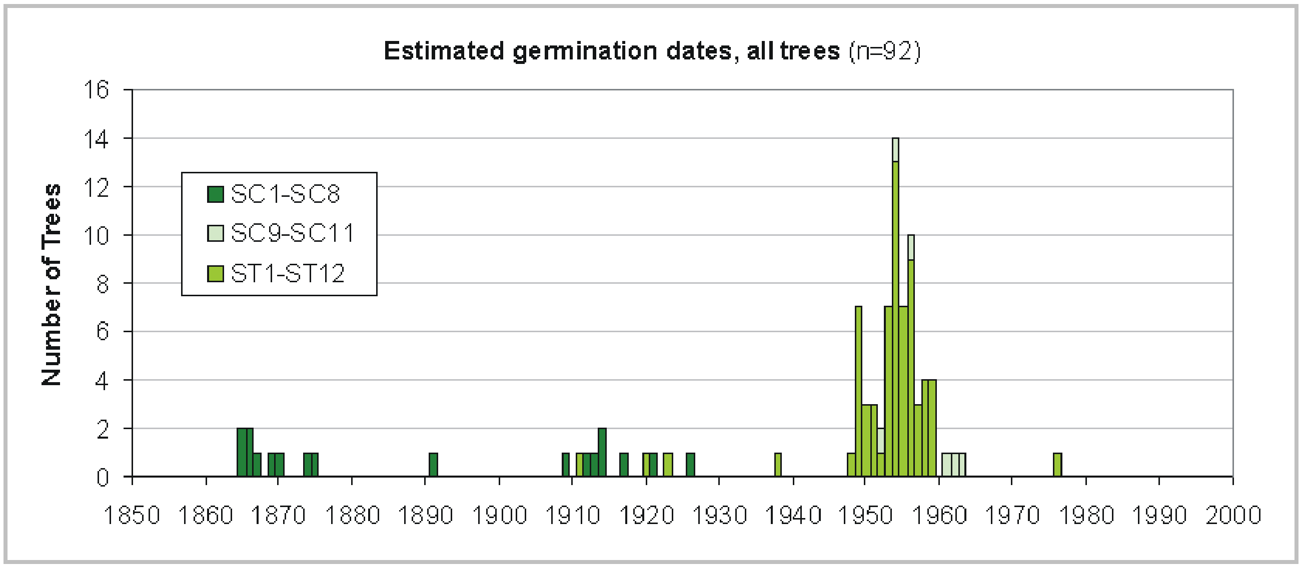

Figure 3. Estimated germination dates for all trees at SAND for which age could be reliably estimated. Note that since the sampling schemes for SC and ST were different, the relative abundance of SC and ST trees on the landscape cannot be inferred from these data.

3.3. Hydroclimatic context of ecosystem change

3.3.1. Introduction

In sections 3.1 and 3.2, we identified the temporal and spatial characteristics of changes in the riparian forest ecosystem at SAND. In this part of the study, our objectives were to present the hydroclimatic context of these changes, and to link the ecosystem changes (e.g., pulses of tree establishment) with events in the hydroclimatic records.

We began with an expectation that one type of hydroclimatic event—floods—would be most important. Numerous studies (e.g., Baker 1990, Cordes et al. 1997, Friedman et al. 1996, Friedman and Lee 2002, Scott et al. 1996, Scott et al. 1997) have documented a close coupling between flood events and riparian cottonwood establishment on streams of varying sizes in western North America. These studies indicate that a flood event is a necessary precondition to widespread cottonwood establishment, through removal of competing vegetation, deposition of fresh sediment as a seedbed, and temporary elevation of the water table. But successful establishment also depends on timing of the flood with respect to seed availability (late spring and early summer is ideal), and maybe also on weather and flow conditions after the flood so that the seedbed remains relatively moist. Many of the seedlings will germinate during the year of the flood, though establishment can continue for years afterwards during a period of channel narrowing, particularly on smaller streams. Consequently, episodes of successful establishment occur periodically, about every decade on larger streams (Scott et al. 1997) and every several decades or more on smaller streams (Friedman and Lee 2002). The cohorts of trees resulting from these periodic establishment episodes tend to occur along bands parallel with the stream channel, representing point bars and similar fluvial features created by a flood and then colonized by seedlings. This temporal and spatial model of cottonwood establishment was used as a frame of reference for considering the results of the study.

3.3.2. Methods

We gathered a number of instrument-based hydroclimatic datasets for southeast Colorado, covering portions of, or all, of the period 1893-2005. These include daily, monthly and annual precipitation; monthly and annual temperature; and daily, monthly, annual, and peak streamflow. Together, these data provide a picture of changes in the hydroclimatic environment in which the trees at SAND established and grew. The data are in the following files:

- **SAND Daily Climate Data.xls**
  Data for the following stations: Limon 10 SSW (1907-1971); Aroya 6NE (1940, 1943-1972); Kit Carson (1893-1896, 1939-2005); Cheyenne Wells (1893-2005); Eads (1907-2005); Chivington (1893, 1953-1954) (Source: NOAA National Climatic Data Center)

- **SAND Annual and Monthly Climate Data.xls**
  Data for the following: Arkansas Drainage Climate Division (1895-2005) (Source: NOAA National Climatic Data Center); Eads (1907-2005) (Source: Colorado Climate Center, Western Regional Climate Center)

- **Big Sandy Creek Streamflow.xls**
  Data for the following sites: Big Sandy Creek near Lamar (1968-1982, 1995-2005) (Source: U.S. Geological Survey, Water Resources Division); Big Sandy Creek near Calhan (Snipes et al. 1974); Big Sandy Creek near Ramah (Friedman et al. 1996); Big Sandy Creek at Kit Carson (Snipes et al. 1974)

We also gathered two tree-ring-based climate reconstructions for the region including the study area, archived by the NOAA National Climatic Data Center Paleoclimatology Branch: (1) a reconstruction of summer (April-September) temperature from 1600-1980 for two gridpoints in western Kansas (40N, 100W) and north Texas (35N, 100W) (Briffa et al. 1992), and (2) a reconstruction of summer Palmer Drought Severity Index (PDSI) from 1550-1979 for a gridpoint in southeastern Colorado (37.5N, 102.5W) (Cook et al. 2004). These data would provide useful hydroclimatic information for the period prior to the beginning of the instrumental records in c.1900. The paleoclimate data are in the following file:

- **SAND Paleoclimate Data.xls**

We also received datasets from the Colorado Climate Center and the U.S. Bureau of Reclamation listing major precipitation events in Colorado since c.1890, and data from the U.S. Bureau of Reclamation listing indirect measurements of flood discharges in Colorado since c.1880. These data were helpful in identifying the probable 1908 flood event. These data are not included with the report, since little of the data applies to the study area. Finally, we reviewed two USGS publications (Follansbee 1948, Snipes et al. 1974) that together describe historical and observed floods in Colorado and the Arkansas Basin from the mid-1800s to 1965.

3.3.3. Results and Discussion

3.3.3.1. Floods and establishment

The finding of two apparently discrete age classes in section 3.1. fits the flood-driven model of cottonwood establishment described above, as does the finding that most of the old-tree clusters are linear features along the current or abandoned stream channels. If the flood-driven model does apply at SAND, then the A1 and A2 age classes would represent post-flood responses to two flood events, one c.1865 and the other c.1908, respectively. Is there evidence for major floods on Big Sandy Creek at those times? The first event would predate the instrumental records of streamflow and climate, and the tree-ring-based paleoclimate records integrate annual climate conditions and cannot be used to infer a single precipitation/flooding event. However, on May 19-20, 1864, catastrophic flooding occurred on Cherry Creek and Plum Creek, destroying a large portion of the nascent city of Denver. Severe flooding also occurred along the Arkansas River on June 11, 1864 (Follansbee and Sawyer 1948). It is possible that the storms that caused these floods also produced flooding on Sand Creek in May and/or June 1864. Analogous widespread flooding across eastern Colorado occurred in June 1965. As for the second event, while we found no historical records of flooding on Sand Creek around 1908, there are records of an intense rainfall event on October 18-19, 1908, in southeast Colorado (Follansbee 1948). On October 19, 15 cm of rain fell in Eads, 25 km west of the study area, and 11.5 cm of rain fell in Cheyenne Wells, 30 km north of the study area. There was a severe flood on the Arkansas River at Holly resulting from this storm, and it is likely that there was a flood in the study area as well.

The large A3 age class, establishing within a period of about 10 years along the current stream channel, also fits the flood-driven establishment model well. Two scenarios could explain this cohort and its peaks in establishment in 1949 and 1954: (1) A single flood around 1949, with establishment continuing for about a decade as the channel narrowed post-flood, or (2) two floods, one around 1949 and the other around 1954, each generating a pulse of establishment in the several years following the flood.

We were not able to find records of flooding specific to the study area for these periods. The gage on Big Sandy Creek downstream from SAND near Lamar did not begin regular operation until 1968, while another downstream gage, near Kornman, operated from 1941-46 and not again until 1996. We did find records of floods on other streams and reaches, however, pointing to the likelihood of floods in the study area in 1949 and 1954:

- On June 5, 1949, there was widespread flooding recorded in the lower Arkansas Basin, particularly on the Arkansas River at Lamar, and Wild Horse Creek near Holly. From June 3-5, 6.3 cm of rain fell in Kit Carson, 30 km upstream from the study area, and 18.5 cm fell in Lamar, 50km south of the study area.

- On the night of August 5-6, 1954, a very large flood discharge of 1260 m^3/s (44,600 cfs) was estimated at Big Sandy Creek at Ramah, roughly 250 km upstream from the study area (Snipes et al. 1974). While this peak would have been greatly diminished as it moved downstream, heavy rains in the downstream region (6.1 cm in Limon on August 5) may have maintained flood flows through the study area.

We should note that the lack of direct observation of flows in the study area creates a risk of circular reasoning in the attribution of tree establishment to floods. If we only look for flood events that correspond to the timing of establishment pulses, we may overstate the significance of flooding. Table 2 below summarizes all potential flood events since 1900 at SAND inferred from the hydroclimatic data. Note that flood events not on this list may have occurred in the study area but could not be identified from the hydroclimatic data.

Date	**Evidence of flood in study area**	**Instantaneous Peak Discharge, m^3/s *(cfs)***	**Location**	**Confidence that flood >70 m^3/s (>2500 cfs) occurred in study area (7)**
Oct. 19, 1908	Floods elsewhere in SE Colo (1)., rainfall at Eads (2)	Na	Na	High
May 31, 1935	Floods elsewhere in SE Colo (1).	Na	Na	Medium
June 5, 1949	Floods elsewhere in SE Colo (3), rainfall at Kit Carson (2)	Na	Na	High
Aug. 6, 1954	Observed flows upstream; rainfall at Limon (2)	1260 *(44,600)* (4)	Ramah	High
June 17, 1965	Observed flows upstream and downstream	1720 *(60,700)* (5) 225 *(8,000)* (5) 100 *(3,600)* (5)	Calhan Kit Carson near Lamar	Very high
Aug. 21, 1965	Observed flows downstream	85 *(3,000)* (6)	near Lamar	Very high
Sep. 16, 1976	Observed flows downstream	71 *(2,520)* (6)	near Lamar	Very high
May 4, 1999	Observed flows Downstream	81 *(2,850)* (6)	near Lamar	Very high

Table 2. Potential major flooding events at SAND since 1900 recorded or inferred from the hydroclimatic data. The USGS gage near Lamar is about 50km downstream of the study area; median annual peak discharge at this gage over 24 years of record is 8.8 m^3/s (310 cfs). Calhan and Ramah are roughly 250km upstream from the study area, and Kit Carson is about 40km upstream. There are no gages at Calhan, Ramah, and Kit Carson, and no other peak discharges are available from these sites besides those listed here.

Data sources:
(1) Follansbee 1948
(2) Daily precipitation data, **SAND Daily Climate Data.xls**
(3) USGS gage data, Wild Horse Creek at Holly, Arkansas River at Lamar
(4) Friedman et al. 1996
(5) Snipes et al. 1974
(6) USGS gage data, **Big Sandy Creek Streamflow.xls**
(7) Authors' judgement

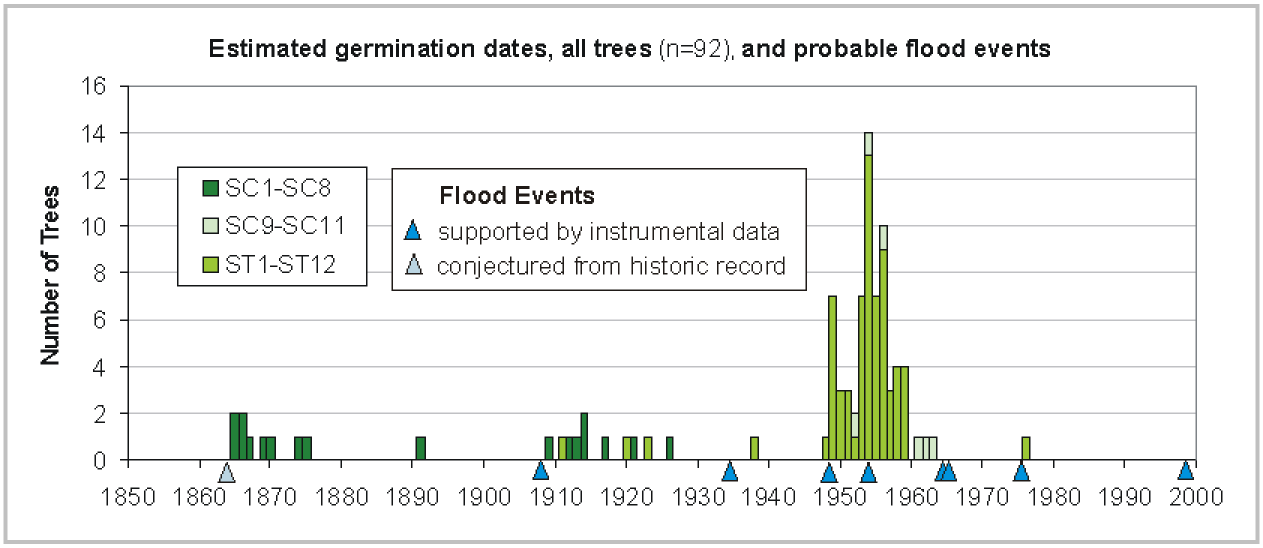

Figure 4. Estimated germination dates for all trees, plotted with dates of probable flood events since 1900 from Table 2, and the conjectured 1864 flood.

If periodic floods *are* the primary influence on the timing of cottonwood establishment, we need to ask why the flood events in 1935, 1965, 1976, and 1999 on Big Sandy Creek did not have a greater effect on the stand age structure. One possibility is that the peak discharges in those years were simply not large enough to move and expose sufficient sediment to encourage seedling establishment. The peak discharges in 1965 (two events), 1976 and 1999 were probably ~85 m^3/s (~3000 cfs) in the study area, based on the discharges at downstream gage near Lamar. While 73 m^3/s (2577 cfs) has been adopted as the 100-year discharge for this gage (Noon et al. 2005), much larger flows have been recorded on the upper reaches of Big Sandy Creek (Table 2), and on other intermittent streams (e.g., Wild Horse Creek near Holly) in southeast Colorado. Perhaps the 1908 (probable), 1949, and 1954 floods were much also much larger than 3000 CFS at SAND, with a commensurately greater impact on establishment. The apparent ecological ineffectiveness of the 1935 flood is perplexing, since the 1937 aerial photos appear to show large areas of newly exposed sediment along Sand Creek, presumably from a recent large flood. One tree in ST2 does have an estimated germination date of 1938, so some recruitment probably did occur as a result of this flood, but it seems disproportionately small compared to the area of potential seedbed seen in the 1937 photos.

3.3.3.2. Climate variability and establishment

What role do precipitation and temperature have in influencing tree establishment and modifying the ultimate impact of floods? Baker (1990) found that cottonwood seedling frequency was significantly linked to cool and wet conditions during the 12 months centered on the early summer germination period. We developed a site ring-width chronology from seven of the oldest sampled trees at SAND, and correlated the chronology with monthly precipitation and temperature for the Arkansas Drainage climate division. Tree growth was significantly (at $p<0.05$) and positively correlated with April, June, and September precipitation, and significantly and negatively correlated with June temperature. In other words, tree growth tends to be favored by wetter and cooler conditions during the growing season. We would expect, then, that establishment at SAND will be favored by wetter and cooler conditions. However, if we look at the age class A3, which represents most of the sampled trees at SAND and has the largest and most reliable set of estimated germination dates, the instrumental data do not support a major role for these climatic factors. The large majority of A3 trees established during an abnormally warm and dry period from 1950-1956 (Figure 5); the summers of 1952-1956 were particularly hot and dry. Yet there appears to be no curtailment of the pulse of establishment during this period. This observation also makes it difficult to invoke the similarly hot and dry weather of the late 1930s to explain why so few trees date from that period. Perhaps the four years of drought prior to 1935 had desiccated the floodplains soils to the extent that flooding did not add sufficient moisture to support establishment.

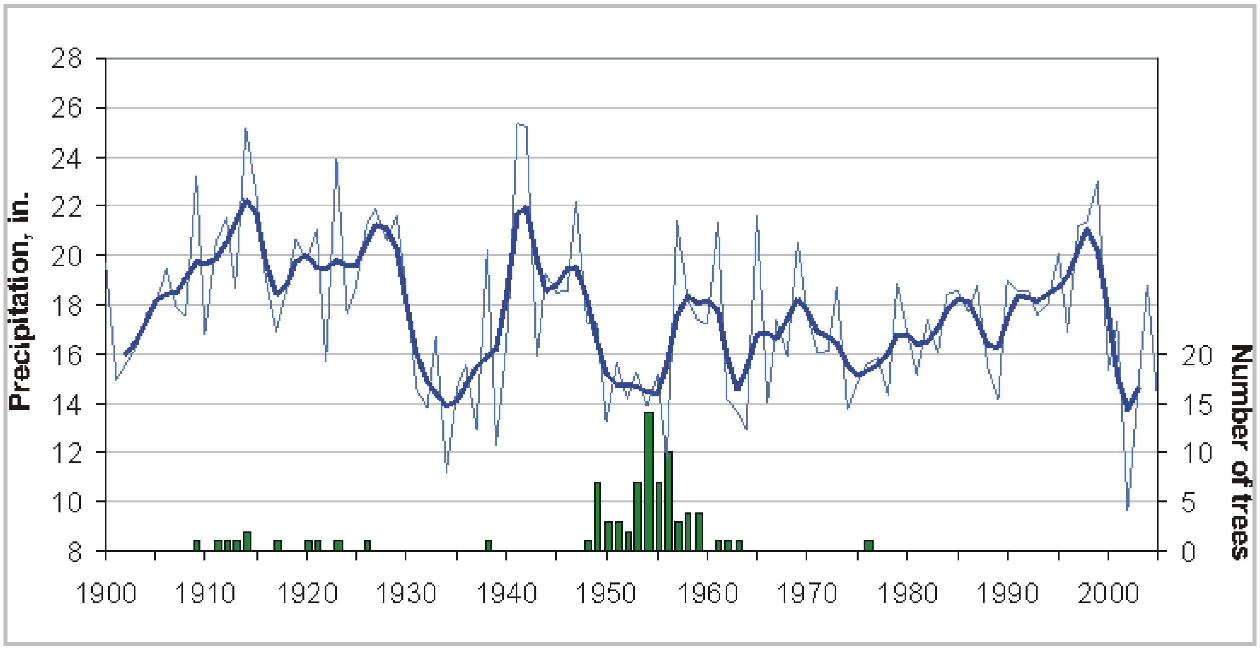

Figure 5. Estimated germination dates for sampled trees at SAND after 1900 (green bars; n=92), plotted with water year (October-September) precipitation for the Arkansas Drainage climate division (thin blue line), with 5-year weighted mean (dark blue line) to emphasize multi-year anomalies.

The next oldest age class (A2) established during an extended wet and cool period from about 1905-1930 (Figure 5). The general climatic context of the oldest age class (A1) can be described using the tree-ring reconstructions of summer temperature and PDSI. These suggest that during 1865-1885, the climate in the study area was on average somewhat drier than normal. Drought conditions prevailed from 1859-1865, and returned in the mid-1870s, followed by an extreme drought year in 1880. Because the age data for both A1 and A2 are sparse, it is hard to assess how this variability in climate may have influenced the establishment of the oldest trees at Sand Creek. But the experience of the A3 age class suggests that droughty conditions may not be a strong deterrent to establishment, and conversely, wet and cool conditions do not appear to be a precondition for establishment.

3.3.3.3 Summary and Conclusion

The instrumental climate and streamflow data recorded since 1893 support the model that establishment of cottonwoods at Sand Creek has been driven mainly by infrequent large flood flows. The daily precipitation data and records of peak flow suggest major flood events affecting the study reach in at least eight years since 1900. Three of these years (1908, 1949, 1954) correspond well to peaks in the age-distribution of the sampled trees.

The past 140 years has seen dramatic changes in the appearance of the riparian forests at Sand Creek, and large variability in levels of recruitment into the stands over time. Much of the current forest is dominated by a cohort that established over a period of about a decade, 40-50 years ago, with very little recruitment since then. But this is likely a natural consequence of a system driven by periodic flooding. Friedman and Lee (2002) studied cottonwood forests along other intermittent streams in eastern Colorado. Their concluding sentence can be readily applied to SAND:

> Because tree reproduction along smaller streams of eastern Colorado is controlled by infrequent floods, the age and width of forest can be expected to vary greatly from one decade or one century to the next even in the absence of water management, tree planting, or climate change (Friedman and Lee 2002, p.423).

However, we cannot discount the possibility that human activities are at least partly responsible for the lack of establishment at SAND since c.1965. First, the hydrologic environment for germination (i.e., flood events) may have been affected by upstream land use. Other streams in eastern Colorado have experienced a substantial decline in the magnitude of annual and periodic peak flows, apparently related to land use changes (J. Friedman, personal communication). The record of peak flows at Big Sandy Creek is too short and sparse to determine whether such a decline may have occurred. Also, establishment may have been more directly impacted in the past several decades by heavy grazing, trampling, or mowing within the study area.

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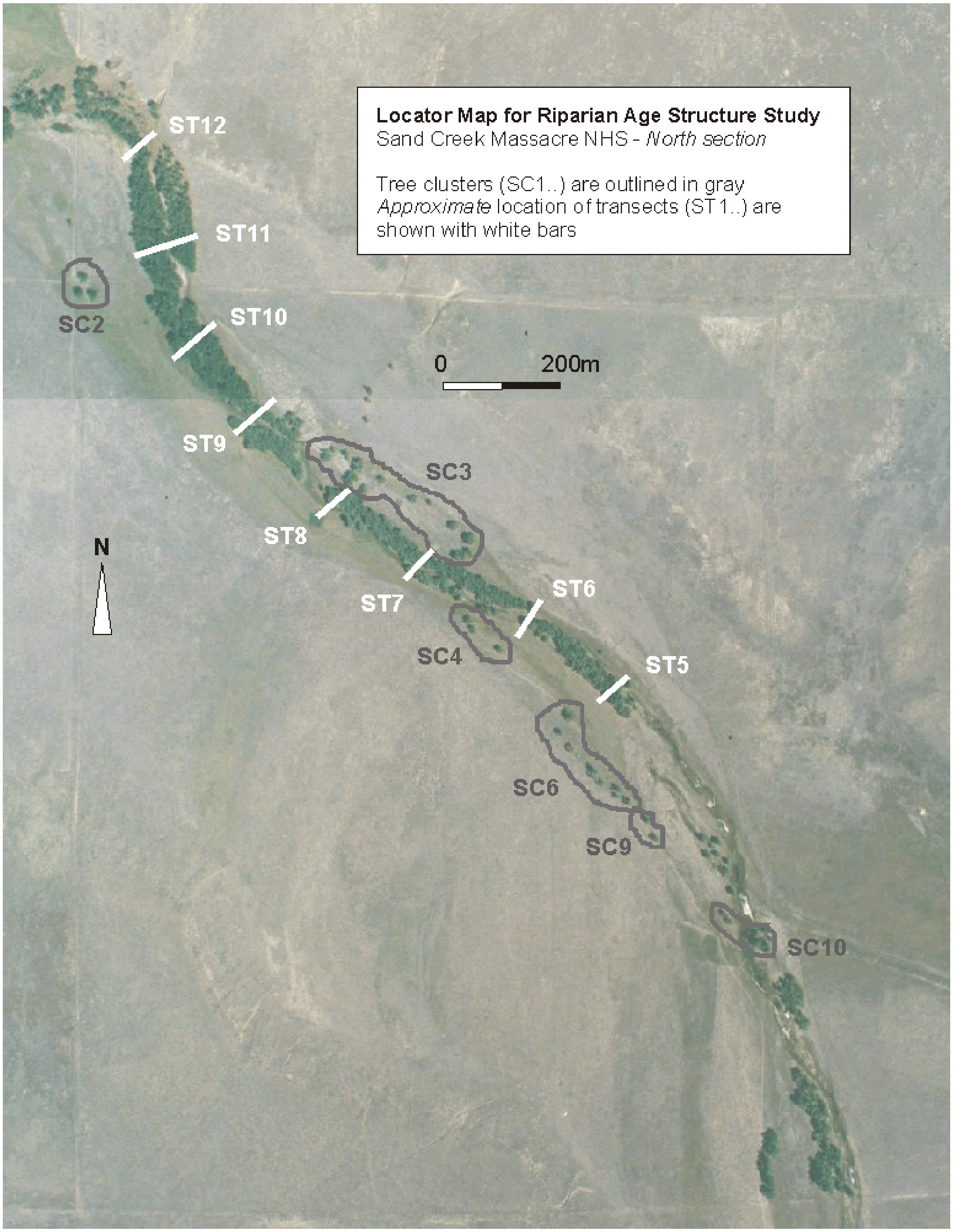
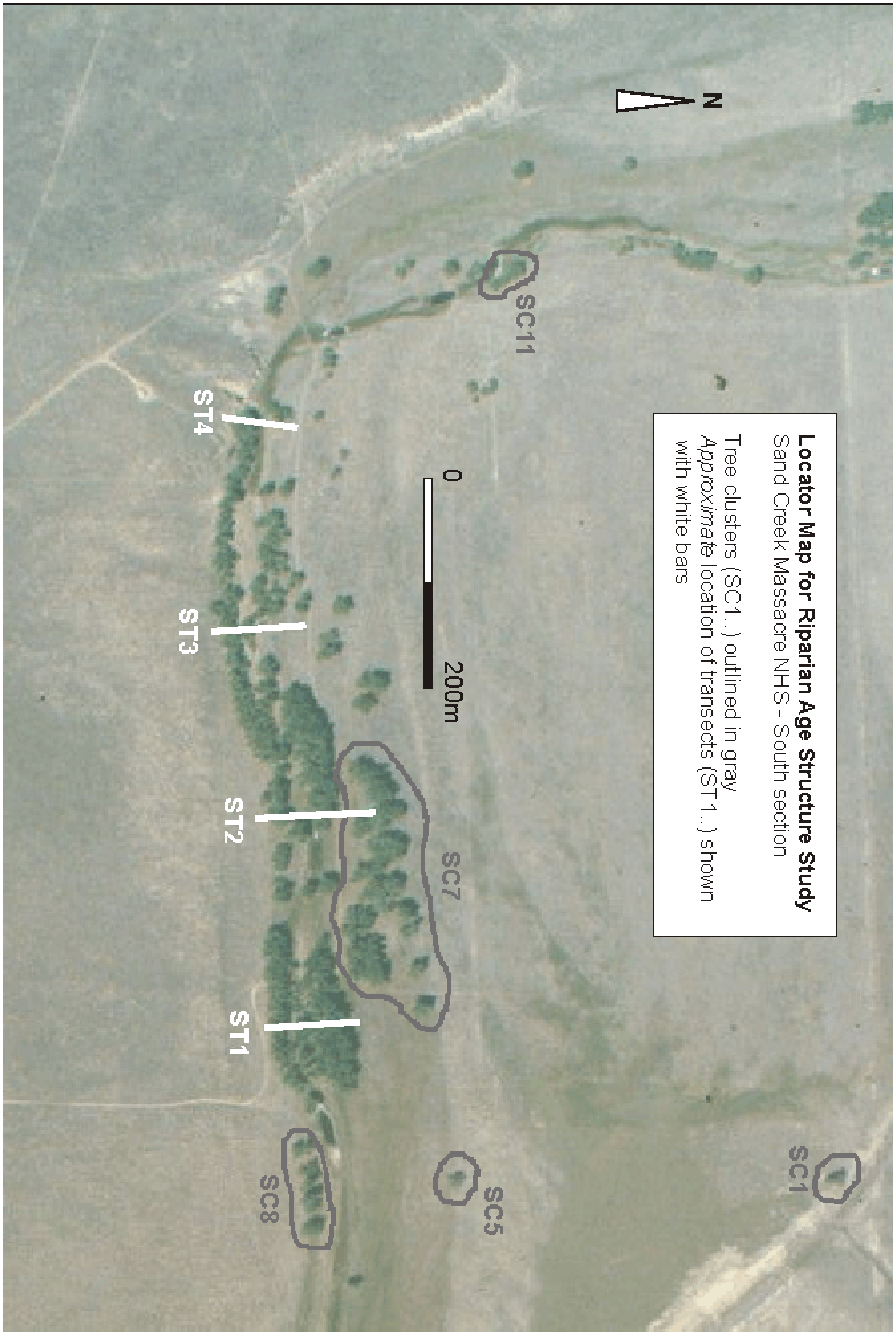
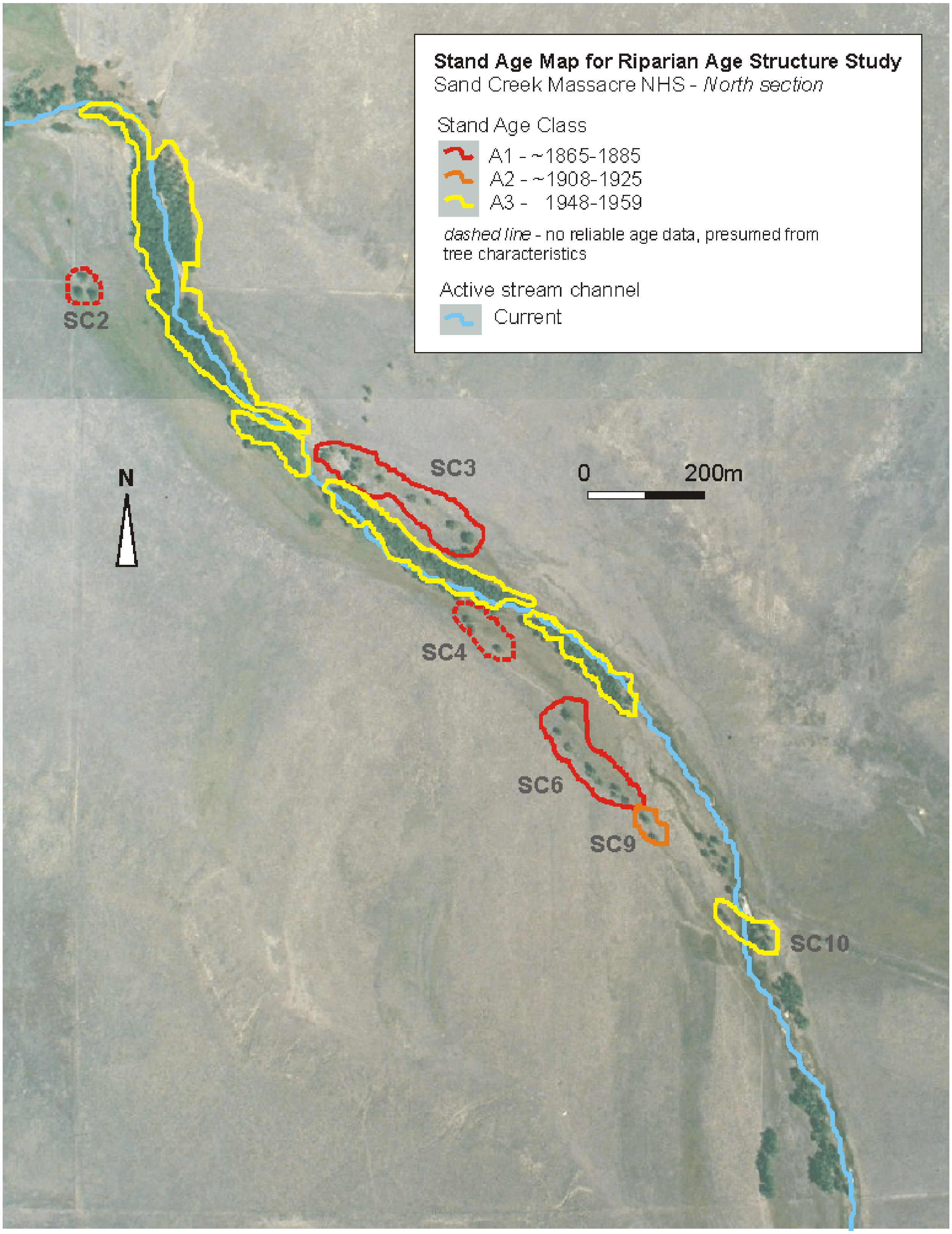
Appendix A.1. SAND Locator Map -North



Appendix A.2. SAND Locator Map – South



Appendix A.3. SAND Stand Age Map – North



Appendix A.4. SAND Stand Age Map – South