Major Changes in Riparian Habitat Along the Upper San Pedro River and Other Southwestern Waterways as a Result of the Alluvial Cycle

By

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Example of massive habitat change. Babocomari River near junction with San Pedro River. Left ca. 1890, showing marshy, treeless conditions. G. Roskruge. **(C**ourtesy of the Arizona Historical Society/Tucson, AHS Photo Number PC114_B2_F31_46404.) Right, 1962, showing entrenched river on left with trees. Stake 150. J. R. Hastings. Brush obscured view of San Pedro River.
(Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

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Abstract

This survey of the extensive literature on the subject, details how the alluvial cycle in the Southwestern United States produced major changes in riparian habitat along the Upper San Pedro River in Southeastern Arizona and along other waterways of the Southwest. The alluvial cycle here means all significant changes that occurred in Southwestern waterways and in riparian habitats bordering such waterways because of arroyo formation, coalescence, widening, and aggradation. When European settlers first arrived, most waterways in the valleys of the Southwest were scarcely if at all incised. Alluvial water tables were relatively high, and many waterways in Arizona had frequent marshes and cienegas.

The most recent cycle of arroyo downcutting in the Southwest, from Southern Arizona to central Utah, took place from approximately 1862 through 1909. The formation of arroyos transformed many valley floors formerly covered by grass and sedge and occasional clumps of trees and bushes into desiccated alluvial terraces. At least six episodes of arroyo formation occurred in prehistoric times. Data from tributaries of the San Pedro River have been crucial in understanding these prehistoric episodes.

Webb and Hereford (2010) provided a six step conceptual model for the alluvial cycle in Southern Utah and Arizona. During stage zero, shallow waterways flowed through alluvial valleys and had near them willows and emergent aquatic species. Groundwater levels were relatively high. Cottonwoods or other riparian trees were locally abundant but did not form extensive gallery forests along the waterways. Stage one was the initial downcutting and subsequent coalescence of discontinuously entrenched mainstream channel segments. It took place between 1862 and 1909 and was driven by floods associated with regional storms or extreme events. The second stage was the widening of arroyos and occurred approximately from 1910 to 1940. The accompanying channel widening removed many plants that ha I d survived the drop in water levels. The third stage occurred from approximately 1940 to 1975 and consisted of aggradation. The aggradation resulted in some narrowing of channels and in alluvial fill producing low terraces or floodplains within the arroyos. The occurrence of scouring floods along the low terraces provided habitats suitable for the establishment of riparian gallery trees such as cottonwoods, willows, tamarisk, and Russian olive. The fourth stage occurred from approximately 1976 to 1995 and consisted of the widening and shifting of course of channels in most arroyos. Stage five occurred from approximately 1996 to 2006. Channels narrowed and there was renewed aggradation of low floodplains, with the magnitude of changes varying regionally.

Researchers agree that flowing water moves sediments and that flowing water, especially that of large floods, is the common denominator for all arroyo formation. Many

researchers have argued that increased precipitation and associated floods on a regional basis produced the most recent or historic episode of arroyo formation and at least some of the prehistoric episodes. Anthropogenic factors have played a role in the most recent episode of arroyo formation. Severe overgrazing of the early 1890s reduced large expanses of former grassland to denuded soil that was susceptible to erosion. Trampling by livestock may have concentrated the drainage of waters and further promoted erosion. In some places, human activities such as the digging of irrigation ditches concentrated floodwaters and caused the erosion of arroyos. Agriculture probably also played a role in recent arroyo formation. Beavers may have helped to create and maintain wetlands and helped to regulate the volume and flow of sediment and water downstream. However, the removal of these animals by itself did not cause arroyo formation. Timber cutting may have resulted in additional erosion that facilitated arroyo downcutting. The reason for the lack of agreement among scientists as to the cause of arroyo formation is that many workers have attempted to oversimplify the great complexity found in nature. There is no reason why there must be a single explanation for arroyo formation. Multiple different causes probably operated on major waterways to promote the most recent episode of arroyo formation.

Woody riparian vegetation greatly increased along most Southwestern waterways after the 1940s because of progression of the alluvial cycle. The lowering of water tables that resulted from arroyo formation facilitated the establishment of trees by dewatering the upper few feet of the previously saturated alluvial aquifer. The deposition of the new floodplains as low terraces along entrenched waterways provided potential habitat for woody vegetation. Scouring floods produced open, moist substrates along the new floodplains and thereby provided the habitat required for the establishment of seedlings of Fremont cottonwood, Gooding's willow, and other trees.

Prior to the most recent episode of arroyo downcutting, the Upper San Pedro River had perennial waterflow throughout its length, was mostly unentrenched, and had a much larger area prone to flooding than today. The river had many marshes and cienegas. Beginning in the late 1870s, large floods along the river started the process of arroyo downcutting, coalescence, and widening. This process continued until the overall geometry of the river stabilized by 1941.

Extensive stretches of continuous riparian gallery forest were absent along the main stem of the Upper San Pedro River before the most recent episode of arroyo production. Fremont cottonwood and Gooding’s willow occurred in local areas along the Upper San Pedro River before the 20th century but did not form the continuous gallery forest currently extending along much of it. Before 1900, the river had a lower energy flood regime because floods and sediment inputs were attenuated by dense growths of riparian grasses and marshy plants in the wide floodplain. There thus were fewer opportunities for the scouring types of floods that disturbance dependent tree species such as Fremont cottonwood and Goodding's willow require. The very large floods associated with turn-of-the-century arroyo cutting removed most of the vegetation from the river channel, including cottonwood and willow trees. Scouring floods along the widening floodplains produced bare substrates suitable for the establishment of cottonwoods and willows. During the 1940s, these trees occurred along the river but apparently usually only on one side at a time because of shifts in river positions. After 1960, climatic fluctuations associated with frequent El Niño conditions created a pattern of floods more favorable to germination and establishment of Fremont cottonwood, Goodding's willow, and other native trees. The currently extensive gallery forests along the mainstream of the Upper San Pedro River are thus a relatively recent phenomenon, mostly of post-1960 origin.

The San Pedro River and other southwestern waterways have a lifecycle somewhat analogous to the mythological Phoenix bird. However, these waterways are liquid phoenixes. Each riparian habitat stage in time gives way to another habitat stage whereby the waterways continually replenish themselves through the changes engendered by the alluvial cycle. Water is the lifeblood that permits the existence of the current assortment of riparian plants. It also is the driving force behind the naturally occurring alluvial cycle and the natural succession of riparian habitats. If humans refrain from removing water from the San Pedro River Valley, the river habitat will continue to follow its repeated progression through alluvial cycles. The river will remain a dynamic and ever-changing liquid Phoenix.

"*Everything changes and nothing remains still .... and ... you cannot step twice into the same stream*", Heraclitus.

Introduction

In the introduction to the 2009 book "Ecology and Conservation of the San Pedro River", Stromberg and Tellman (2009) observed, "Dryland rivers have some of the most variable flow regimes in the world, as wet periods alternate with dry periods, river channels widen and contract, water levels peak and recede, and vegetation waxes and wanes." This literature review summarizes major riparian habitat changes and the causes of such changes along the Upper San Pedro River in Southeastern Arizona and in general terms along other Southwestern waterways. The area of the San Pedro River here discussed extends northward from the US Mexican border near Palominas for approximately 60 river miles before leaving the Upper San Pedro River basin at The Narrows north of Benson (Christiana et al. (2005). The habitat changes resulted from a regional alluvial cycle progression that produced profound modifications in riparian vegetation and habitats. **The alluvial cycle is here defined to include all significant changes that occurred in the Southwestern waterways and in the riparian habitats bordering such waterways because of the formation of arroyos, coalescing and widening of them, and subsequent narrowing and aggradation.** (Not all workers use the term "alluvial cycle" to denote the above events. Some researchers use "arroyo formation", "arroyo downcutting" "gully formation" or other terms to denote the formation of arroyos and then may discuss other topics such as changes in habitats resulting from arroyo formation.) Because the massive habitat changes along the San Pedro River resulted from an alluvial cycle that operated throughout the Southwest, a discussion of regional changes is necessary to understand the changes that occurred along the San Pedro River.

The alluvial cycle in the Southwestern United States

Arroyo formation, coalescence, and widening, narrowing, and subsequent aggradation are major components of an alluvial cycle. An arroyo is a nearly vertically walled, nearly flat-floored stream channel that typically forms in fine, easily eroded material (Antevs, 1952; Vogt, 2003). Arroyos can be as much as 65 feet deep, more than 165 feet wide, and hundreds of kilometers long. Arroyos or deeply entrenched channels occur in many alluvial basins in arid and semi arid areas of the Southwestern United States (Allen et al., 2003; Antevs, 1952; Cooke and Reeves, 1976; Harden, 2007; Waters and Haynes, 2001; Webb and Hereford, 2010; Webb et al., 2007). (Examples of papers discussing arroyos in smaller Southwestern areas include: Aby et al., 2004; Alford, 1982; Arnold et al., 2007; Balling and Wells, 1990; Gellis, 1991; Hall, 1990; Hastings, 1959; Hereford, 1993, 2002; Hereford and Betancourt, 2009; Huckleberry, 1996; Huckleberry and Duff, 2008; Huckleberry et al., 2009; Leopold, 1976; Malde and Scott, 1977; Mann and Meltzer, 2007; Pazzaglia, 2005; Pederson, 2000; Vogt, 2003).

Historic regional formation of arroyos

Historical records such as diaries of 19th century explorers demonstrated that most waterways in the valleys of the Southwest were scarcely if it all incised by riparian channels before the present cycle of entrenchment began in approximately the latter half of the 19th century (Hastings, 1959; Malde and Scott, 1977). There were however scattered local washes and arroyos as indicated by the records of Bartlett (1854) for southern Arizona.

The most recent cycle of arroyo formation in the Southwest, from Southern Arizona to central Utah, took place from approximately 1860 into the 1920s (Bryan, 1925; Cooke and Reeves, 1976; Hastings, 1959; Hereford, 2002; Malde and Scott, 1977; Turner et al., 2003; Vogt, 2003). The formation of arroyos along many permanent and ephemeral waterways transformed the landscapes of valleys in the Southwestern United States. Military expeditions and settlers watched as shallow waterways rapidly transformed into deeply entrenched channels with nearly vertical banks (Waters and Haynes, 2001). The formation of arroyos transformed valley floors formerly covered by grass and sedge and occasional clumps of trees and bushes into desiccated alluvial terraces that have been diminished by periodic losses to encroaching arroyos (Cooke and Reeves, 1976). Arroyo cutting in many valleys removed substantial portions of the floodplain, often exceeding 25% (Cooke and Reeves, 1976).

The formation of arroyos produced significant hydrological changes (Cooke and Reeves, 1976). Before such formation, the valley bottoms provided inefficient and hydraulically rough channels that retarded and spread floods, promoted infiltration, and moderated peak discharges. The alluvial fills in the valleys provided important water-storage and flow-regulatory functions by absorbing runoff and supplying a source of water for riparian vegetation and for base flow during dry periods. Waterways in southeastern Arizona had a much wider distribution of cienegas and riparian marshes than is found today (Hendrickson and Minckley, 1984). The downcutting of arroyos resulted in narrow, deep, and relatively smooth drains that efficiently removed water from drainage systems and started the rapid draining of alluvial deposits. Waterflow became relatively more "peaked" and of shorter duration. Increasingly xeric plant communities replaced formerly dense grass cover and lush strands of riparian vegetation that had been dependent either on overflow of water or unreliable supplies of near-surface water.

There were significant adverse impacts to humans from arroyo formation (Cooke and Reeves, 1976). The expanding arroyos destroyed cropland. The lowering of water tables and desiccation of newly formed terraces greatly reduced crop productivity and caused new costly problems, such as the need to deepen canals. The decrease in suitably watered arable land in valley bottoms seriously restricted agriculture. The increasing fluctuation of and decreasing reliability of water sources and the difficulties of transferring water to fields drove out some farmers or increased their emphasis on livestock. However, livestock production also suffered. Before arroyo formation, valley floors often contained cienegas that were nourished by high water tables and provided the best and most dependable forage and source of water for livestock during the dry season. Arroyo floods frequently caused damage to railroads, roads, bridges, landfills, and other structures. However, in some places with highly capitalized irrigation agriculture that was based on well water, the arroyos sometimes alleviated flooding by providing low-cost storm drains. Arroyo downcutting and the 19th century drought ended agricultural activities that were supported by surface water diversion in the Tucson region (Webb et al., 2007).

Prehistoric episodes of arroyo formation

A brief explanation of "^{14}C B.P" is necessary. ^{14}C is a rare isotope of carbon present in the atmosphere. Plants fix atmospheric carbon during photosynthesis, so the level of ^{14}C in plants and animals when they die approximately equals the level of ^{14}C in the atmosphere at that time. However, ^{14}C in dead organic material decreases from radioactive decay, allowing the date of death to be estimated. ^{14}C B.P means years before present estimated by radiocarbon dating. The raw numbers of radiocarbon dating do not provide a conventional calendar date for two reasons. First, "present" is defined as 1950 Common Era. Secondly, the amount of ^{14}C in the atmosphere varies over time. Scientists use a variety of methods to calibrate ^{14}C dates and obtain calendar dates. Calibration is done based on comparison of radiocarbon dates of samples that can be dated independently by other methods such as examination of tree growth rings (dendrochronology), deep ocean sediment cores, lake sediment varves (annual layer of sediment or sedimentary rock), coral samples, and speleothems (cave deposits). Many scientists prefer to present uncalibrated data because calibration methods are constantly being improved. For our purposes, the exact conventional calendar dating of prehistoric episodes of arroyos downcutting is not important. The crucial information is that episodes of arroyo formation occurred during prehistoric times.

At least six episodes of arroyo formation occurred in prehistoric times. Waters and Haynes (2001) studied stratigraphic records of the Santa Cruz River, tributaries of the San Pedro River, and Whitewater Draw in the Sulfur Springs Valley. Except possibly at the Lehner site, arroyo cutting was absent from about 15,000 to 18,000 ^{14}C B.P. During this period, woodlands covered the floors of desert basins, and conditions were unsuitable for arroyo formation. Arroyo cutting occurred sometime between about 5600 and 8000 ^{14}C B.P. on the Santa Cruz River floodplain, approximately 7500 ^{14}C B.P. along the San Pedro River, and about 6700 ^{14}C B.P. along Whitewater Draw. The frequency of arroyo cutting increased greatly after about 4000 ^{14}C B.P.. Five subsequent prehistoric episodes of synchronous channel entrenchment occurred along Curry Draw and other low order streams in the San Pedro River Valley and on the floodplain of the Santa Cruz River. Entrenchments occurred near 4000 ^{14}C B.P. in the San Pedro and Santa Cruz valleys, at about 2600 and 2500 ^{14}C B.P. in the San Pedro and Santa Cruz valleys respectively, at approximately 1900 and 2000 ^{14}C B.P. in the San Pedro and Santa Cruz valleys respectively, near 1000 ^{14}C B.P. in the Santa Cruz and San Pedro valleys, and at about 600 and 500 ^{14}C B.P. in the San Pedro and Santa Cruz valleys respectively.

After entrenchment and coalescence of arroyos, river channels widened and then over time began to undergo aggradation or the filling with sediments. Eventually rivers returned to being shallow streams flowing across landscapes without significant entrenchments in most areas. Arroyo formation would then initiate another alluvial cycle (Mann and Meltzer, 2007; Webb and Hereford, 2010; Webb et al., 2007).

A conceptual model for arroyo formation

Webb and Hereford (2010) provided a six step conceptual model (Fig. 1) for the alluvial cycle in Southern Utah and Arizona. The model described the historic synchronous downcutting of many waterways on a regional basis and did not treat the isolated arroyo production that has occurred since the 1940s. They used data from repeat photography to construct the model. Repeat photography is the technique by which researchers analyze series of historic photographs from individual sites to determine changes in landscapes and vegetation over time. This technique historically has been used successfully to study landscape changes in the Southwestern United States. The six-step model is a generalized concept, and many exceptions to it occurred, especially in those waterways where stage four was minor. The model is based upon analyses of data for the most recent or historic episode of arroyo formation. Prehistoric episodes have consisted of stage zero and then of arroyo downcutting, widening and coalescing, and subsequent channel narrowing and aggradation. We do not currently know the exact details of the stages of prehistoric alluvial cycles. Some of them might for example have skipped the channel widening and adjustment of stage four. During some prehistoric episodes of alluvial cycles, stages 3-5 might have been interrupted by renewed channel widening and deepening. We do know that for each episode of the alluvial cycle, most sections of southwestern rivers filled in and eventually reverted to stage 0, thereby concluding an alluvial cycle. In a few places, the aggradation or filling in was not complete, and in those localized areas, riparian terraces remained even after most other areas of a waterway had filled in and reverted to stage zero. (As noted below, terraces from prehistoric episodes of arroyo formation were present in a few places along the San Pedro River when Europeans first visited it.)

Stage zero was the conditions before arroyo formation. Shallow waterways flowed through alluvial valleys and had near them willows and emergent aquatic species. Groundwater levels were relatively high. Cottonwoods or other riparian trees were locally abundant but did not form extensive gallery forests along the waterways. Figure 23A is an example of stage 0. It shows the Babocomari River just to the west of its junction with the San Pedro River. The former river is composed of a marshy area without trees.

Stage one consisted of the initial downcutting and subsequent coalescence of discontinuously entrenched mainstream channel segments. The downcutting produced deep, narrow channels (arroyos) that either occurred during a single event or during a series of floods associated with regional storms or extreme events. Stage one took place between 1862 and 1909, with most of the downcutting beginning in the late 1870s through the mid-1890s. The earliest date of initial downcutting was 1862 at the Santa Clara River just upstream from St. George, Utah. The incision related to an unusually intense and widespread storm during the winter of 1861-1862. The latest date of initiation of downcutting was 1910, at Polacca Wash on the Navajo Indian Reservation in Northern Arizona. In 1935, downcutting began at Bull Creek, a small tributary of the Fremont River. However, that unusually late date was probably related to upstream headcut propagation from the mainstream river that began downcutting and widening in 1896. (A headcut is an active erosion feature comprising an abrupt vertical drop in the bed of a stream channel. It often resembles a small intermittent waterfall, with a deep pool at the base resulting from the turbulent, high energy, waterfall produced during high flows. Headcuts are transient and often move rapidly upstream during times of high erosion rates. [NC, 2005.]) The result of initial downcutting was the production of deep and narrow channels. The previously high alluvial aquifers drained through the newly eroded banks. The resulting reduction in level of the aquifer further destabilized the floodplains and probably produced collapse of banks and facilitated additional channel widening. Figure 22A is an example of stage one, showing a narrowly entrenched San Pedro River.

Changes in precipitation patterns occurred both before and during the initiation of downcutting. Studies of the Upper Virgin River basin showed that two or three decades of the driest climate since 1700 preceded initiation of arroyo downcutting. The effects of this drought on vegetation are unknown. However, examination of numerous landscape photographs taken as early as 1863 and compared with photographs taken approximately 1900 provided little evidence of changes in hillslope vegetation cover. However, riparian vegetation changed substantially during and after arroyo cutting. A regional severe drought occurred from 1891 through 1904 and preceded the early-20th century pluvial. The effect of this drought on stream channels is not well known. The magnitude and frequency of floods increased beginning in the late 1800s and was largely coincident with the start of arroyo downcutting. A corresponding increase in the frequency and intensity of El Niño Southern Oscillation events that peaked in the early 1900s apparently caused the increased flood frequency.

The initiation of downcutting in the region began during the unusually heavy precipitation during the winter of 1861-1862. In Southwestern Utah, possibly also over most of the Southern Colorado plateau and much of the Western United States, there was rain almost continuously for 40-45 days from late December 1861 into February 1862, a rainfall pattern not since repeated. This heavy precipitation was the forerunner of a period of frequent large floods from 1910 into the early 1940s. Additionally, climate records show that warm season rainfall was unusually high on the Southern Colorado Plateau from the beginning of global warming following the Little Ice Age (ca. early 1400s to late 1800s [Ramanujan, 2005]) until the early 1940s.

The second stage consisted of the widening of arroyos and occurred approximately from 1910 to 1940. Repeated flooding during this stage produced considerable erosion of channels, with the erosion mostly widening them and producing modest or little increase in depth. The channel widening removed many plants that had survived the drop in water levels. Photographs taken during stage two generally show wide, mostly flat-floored waterway channels almost completely devoid of vegetation. Figure 15A is an example of stage two.

The third stage occurred from approximately 1940 to 1975 and consisted of aggradation. The aggradation resulted in some narrowing of channels and in alluvial fill producing low terraces or floodplains within the arroyos. The occurrence of scouring floods along the low terraces provided habitats suitable for the establishment of riparian gallery trees such as cottonwoods, willows, tamarisk, and Russian olive. This aggradation and the spread of riparian vegetation were the most profound events affecting the waterways since the initial downcutting and widening. Figure 19A is an example of stage three. The midcentury drought occurred throughout the Southwest, with some regional variation, from the mid-1940s through 1975 to 1978. In most of the region, the drought was most severe from approximately 1951 through 1955. Relatively wet El Niño conditions interrupted the drought, especially in 1952, 1957-1958, 1963, 1969, and in 1973. The generally infrequent occurrence of major floods during the drought favored the establishment of vegetation and sediment accumulation on floodplains in most waterways.

The fourth stage was from approximately 1976 to 1995 and consisted of the widening and shifting of course of channels in most arroyos. Increased precipitation from approximately 1976 through 1996 largely coincided with the channel adjustments of stage four. In Southern Arizona, floods of 100-year magnitude occurred in 1977. Figure 15C is an example of channel shifting that resulted from stage four.

Stage five occurred from approximately 1996 to 2006. Channels narrowed and there was renewed aggradation of low floodplains, with the magnitude of changes varying regionally. Drought conditions mostly prevailed from 1996 through 2007 in the Southwestern United States, with interruptions by high winter rainfall during El Niño conditions in 1997-1998 and 2004-2005. During stage five, there were few large floods across the Southwest and infrequent runoff, most of which took place during local summer thunderstorms. The background portion of Fig. 15D may be an example of channel narrowing because of stage five.

Current arroyos presumably will fill-in over time, as they did in prehistoric conditions (Waters and Haynes, 2001).

Arroyos can form rapidly. Baer (1985) documented the formation and growth of a new arroyo in Utah. Over an observation period of 115.5 hours, the channel cut headward 1210 feet, or an average of 10.5 feet per hour. Rates of headward erosion of the arroyo varied from 4.7 to 21 feet per hour. Data from the recent episode of arroyo downcutting show that such downcutting, channel widening and coalescing of arroyos can occur within the span of only a few decades (Webb and Hereford, 2010). Studies of alluvial valley fills indicate that episodes of arroyo maintenance and subsequent aggradation can each last for many centuries (Mann and Meltzer, 2007).

The postulated increase of riparian woody vegetation in the latter stages of Webb and Hereford's (2010) model should not be interpreted as a suggestion that such vegetation was absent from Southwestern waterways before entrenchment. As noted below, such woody plants were locally abundant in some places along the San Pedro River before entrenchment. Webb and Herefords (2010) cited several examples of the presence of woody riparian vegetation along waterways before or just after European settlement. Extensive stands of coyote willow occurred along waterways such as the Escalante River, Kanab Creek, Havasu Creek, and the banks of the Green, Colorado, and San Juan Rivers. Aravaipa Canyon in southern Arizona had dense groves of cottonwood and other riparian trees in 1867. Havasu Canyon in 1885 had dense groves of cottonwood, Arizona ash, and other riparian trees. Additional examples of woody riparian pre-entrenchment vegetation could be cited. However, as documented below, the overall result of arroyo formation was a significant increase in woody riparian vegetation.

Possible causes of arroyo formation

Scientists have extensively debated hypotheses about the causes of arroyo formation (e.g. in part, Balling and Wells, 1990; Cooke and Reeves, 1976; Graf, 1983; Hastings, 1959; Hereford, 2002; Hereford and Betancourt, 2009; Sayre, 1999; Vogt, 2003; Waters and Haynes, 2001; Webb, 1985; Webb et al., 2007). Some of the hypotheses are summarized below. The observations of a geologist who watched an arroyo form in Utah are then summarized. A subsequent discussion section integrates elements of the competing hypotheses and information from the observations by the geologist to explain historic arroyo formation.

Changes in precipitation

Webb and Hereford (2010) noted that climatic explanations for arroyo formation have included periodic drought that reduced vegetation cover, wet conditions with regional storms and floods, fluctuations in groundwater tables related to drought, and various combinations of these factors. Some authors have discussed the possibility that drought reduced vegetation cover and facilitated past episodes of prehistoric arroyo formation (Antevs, 1962; Tuan, 1966). Data are insufficient to evaluate this hypothesis (Tuan, 1966; R. Webb, pers. obs.). However, there is considerable evidence to indicate that in the past climate became dryer in the Southwest, and vegetation in many areas became more xeric adapted. Moreover, there is considerable evidence that arroyo formation has occurred during episodes of unusually heavy precipitation. The above section discussing the conceptual model of Webb and Hereford (2010) provided examples of the correlation of arroyo downcutting and heavy precipitation.

Tuan (1966) provided additional examples of historic arroyo formation that coincided with unusually heavy precipitation. Downcutting in Kanab Creek in southern Utah began with a flood on July 29, 1883 that was followed by additional floods in 1884 and 1885 produced by the melting of unusually heavy snows. During these three years, the floods cut a gully 60 feet deep by about 70 feet wide and 15 miles long. During a protracted period of torrential storms in the spring of 1884, huge gullies were cut into Mountain Meadow in Southwestern Utah. An especially striking downcutting of an arroyo during floods occurred along the former main street of Silver City, New Mexico. In the middle of the 19th century, the main street served as a drainage channel. The channel began to deepen in 1887, and the inhabitants constructed bridges for crossing the street and fabricated a wooden device to prevent further headward cutting. In 1892, a flood carried away the wooden device. Major downcutting of an arroyo began during a six inch of rain of July 21, 1895. In August 1903, there were two more disastrous floods on successive afternoons. By 1917, the arroyo was more than 100 feet wide and 37 feet deep. Tuan concluded that arroyo formation took place during heavy rains and floods. However, the author also concluded that arroyo downcutting was not necessarily correlated with changes in annual precipitation. That is, the concentration of annual precipitation into short periods of time, as opposed to more uniform distribution of precipitation throughout a given year, can cause floods that produce arroyo downcutting. Additional examples of historic arroyo downcutting associated with floods are found below in the sections on drainage-concentration by humans, and arroyo formation along the Upper San Pedro River. Arroyo downcutting can of course also occur during a year of unusually heavy precipitation as shown in the section below that summarizes observations by a geologist of formation an arroyo in Utah.

Waters and Haynes (2001) argued that broad climatic and biotic changes in the American Southwest coincided with the arroyo cutting that occurred sometime between 5600 and 8000 ^{14}C B.P. on the Santa Cruz River floodplain, approximately 7500 ^{14}C B.P. along the San Pedro River, and 6700 ^{14}C B.P. along Whitewater Draw. Higher temperatures and less effective moisture conditions replaced previously cooler temperatures and more effective moisture around 8000 ^{14}C B.P. Water tables dropped, and desert scrub replaced the xeric juniper scrub that previously covering the floors of desert basins. These changes apparently made the valley floors more susceptible to erosion than when woodlands covered them and water tables were higher. There is no evidence of a wet period between about 5600 to 8000 ^{14}C B.P. that might have caused flooding. However, Waters and Haynes (2001) concluded that flooding across the very erodible landscape triggered channel entrenchment. The authors also suggested that the beginning of arroyo cutting approximately 4000 ^{14}C B.P. in both the San Pedro and Santa Cruz valleys and the correlation of the subsequent episodes of prehistoric arroyo formation in the spatially separated valleys with watersheds of significantly different size strongly suggested climatic origin for arroyo cutting. The period of repeated arroyo cutting and filling that started at about 4000 ^{14}C B.P. coincided with a major change in vegetation and climate in the American southwest (Waters and Haynes, 2001). By about 4000 ^{14}C B.P. the floors of desert valleys of the Southwest had a fully modern scrub vegetation community. At approximately 4000 ^{14}C B.P. the current climate regime began and was characterized by lower temperatures than before and more effective moisture compared to the middle Holocene. There were numerous wet and dry episodes.

Three of the prehistoric arroyo cutting episodes along the Santa Cruz River and the tributaries of the San Pedro River Valley corresponded with wet periods as documented by pollen, pack rat middens, and geological records at about 4000, 1000, and 500 ^{14}C B.P. The poorly documented paleoenvironmental records for about 2000-2500 ^{14}C B.P. prevented correlation of arroyo entrenchment with a particular wet period. However, evidence from lakes along the Mogollon Rim showed that desiccated lake basins filled with water between approximately 3000 and 2000 ^{14}C B.P., demonstrating that precipitation increased during that time.

Changes in the El Niño-Southern Oscillation (ENSO) pattern may have been related to the triggering of arroyo cutting in the late Holocene (Waters and Haynes, 2001). By about late 4500 ^{14}C B.P., El Niño events were becoming more frequent and reached their current periodicity and strength. These El Niño events produced periods of extended heavy rainfall, resulting in major flooding within watersheds of Southern Arizona (Ely, 1997; Ely, et al., 1993).

Waters and Haynes (2001) concluded that the synchronous arroyo-cutting events that began approximately 4000 ^{14}C B.P. appeared to be the result of cycles between dry and wet climate. Floods that occurred during a period of increased precipitation following a dry period would trigger an episode of arroyo cutting. The authors noted that arroyo cutting in the Zuni Valley of New Mexico in 1905 began with the combination of extended drought that was followed by several years of increased rainfall that produced major floods. They similarly pointed out that in the Colorado Plateau of Northern Arizona other authors have linked late Holocene and historic arroyo cutting and filling with cycles of dry and wet climate. Moreover, they noted that like prehistoric arroyo cutting, historic channel entrenchment coincided with periods of increased El Niño activity that generated major floods in Southern Arizona.

Mann and Meltzer (2007) studied the alluvial histories of eight small watersheds in uplands of northeastern New Mexico. They documented nine periods of valley aggradation separated by entrenchment episodes over about the past 12,000 ^{14}C B.P. These alluvial cycles occurred in rough synchrony within the different drainages. Parts of some of the cycles coincided with well-known climatic fluctuations. The authors concluded that changes in precipitation tied to the strength of the North American monsoon system probably drove the cycles of aggradation and incision.

Hereford (2002) discussed possible causes of arroyo cycles in the Paria River basin in Utah and Northern Arizona. He grouped causes suggested by other researchers into four main models. The first two models were largely independent of climate while the latter two were caused primarily by climate. The first model regarded arroyo formation as a complex response to an intrinsic series of geomorphic thresholds. This model assumed that arroyo formation was linked to temporally random processes that were coupled with intrinsic characteristics of riparian basins. Hereford concluded these processes might have been important in small basins or over short time scales but could not be reconciled with the ability to regionally map and correlate generally synchronous widespread arroyo formation over the Southwest. The second model assumed that the most recent historic episode of arroyo cutting resulted from settlement and overgrazing that reduced plant cover and facilitated erosion. This model, however, failed to explain prehistoric arroyo cutting, did not address the cycles of aggradation, and was inconsistent with demonstrated relationships of climate to historic erosion. In addition, overgrazing may not have substantially altered hill slope and alluvial valley hydrology because the net effect was replacement of parts of one plant community by another rather than wholesale destruction of plant cover. The third model postulated that rising (wet) or falling (dry) base levels of aquifers resulted in aggradation or erosion respectively. However, this model was inconsistent both with: historic arroyo downcutting that occurred during episodes of relatively wet conditions with frequent and large floods; and with modern aggradation that occurred during relatively dry climate and infrequent large floods. The fourth model postulated that erosion occurred during wet conditions when streams were able to carry heavy sediment loads and that aggradation occurred during dryer climates. This model explained both prehistoric and historic episodes of arroyo downcutting and aggradation.

Arroyo formation requires the presence of a large volume of moving water that erodes the landscape and moves sediments. As noted above, several of the prehistoric episodes of arroyo downcutting were correlated with increased precipitation. The most recent episode of arroyo formation occurred during historic times, and both historic accounts and climatic data indicate that historic arroyo downcutting occurred during a time of unusually large storms of regional extent that caused some extraordinary floods (Cooke and Reeves, 1976; Graf, 1983; Webb, 1985; Webb et al., 2007; Webb and Hereford, 2010). The historic downcutting was a series of discrete events, with several such events required to coalesce arroyos over long alluvial valleys (Webb et al., 2007). The task for scientists is to continue to investigate the relative importance of other factors, such as those discussed below, in both prehistoric and historic arroyo formation.

Overgrazing

One of the first hypotheses was that overgrazing caused arroyo downcutting (Bahre, 1991; Cooke and Reeves, 1976; Webb et al., 2007). The primary evidence was that overgrazing seemed to be temporally related to downcutting.

Sayre (1999) provided a history of cattle in southern Arizona. In 1540, Coronado brought the first cattle into Arizona, but these animals were consumed as food or otherwise perished without establishing breeding populations. Padre Eusebio Kino brought the first enduring herds into Arizona and dispersed cattle and other livestock to the missions and *visitas* (visiting stations of the '*cabecera*' or primary mission) he founded in present-day northern Sonora and southern Arizona between 1687 and 1710. Cattle raising subsequently expanded or contracted until about 1873 depending on the condition of relations with the Indians, especially the Apaches. For approximately 80 years after Kino’s death in 1711, the Indians held the upper hand. Spanish settlement was mostly limited to the Santa Cruz River, with concentrations around the Presidio at Tubac and missions at Tumacacori and Tucson. A visiting Jesuit reported in 1764 that nearly 300 ranches and estancias in Sonora (which then included present-day southern Arizona) had been abandoned in the preceding seven years and that thousands of heads of livestock were lost to the Indians. Relatively peaceful relations with the Indians from 1790 into the 1820s allowed several secular cattle operations to become established in favorable locations in the Santa Cruz, Sonoita, San Pedro, and Babocomari Valleys. Peace broke down in the decades after Mexican independence, and ranchers abandoned the herds. The cattle reverted to a feral stage on the range, and Indians and others hunted them as game. US military parties in the 1840s and 1850s found the remnants of these herds, mostly bulls, to be extremely wild and dangerous. The Indian threat prevented the widespread establishment of Spanish and Mexican livestock production in southern Arizona until the cattle boom began in the 1870s. Sayre reported that while scholars have debated the size of Spanish and Mexican cattle herds, the consensus is that such herds did little or no lasting damage to southern Arizona ecosystems.

Hereford (1993) provided the following arguments against overgrazing having been an important factor in entrenchment of the San Pedro River. He reported that cattle were introduced into the valley in 1697, if not a decade earlier, during the Spanish-Mexican phase of the cattle industry. Subsequently, people settled the valley and began cattle ranching during the period 1820-1831 when petitions were filed by Mexican Nationals for land grants. Apache attacks soon forced abandonment of the ranches. The livestock subsequently multiplied successfully without human intervention. Hereford cited the observations of cattle by Cooke and Bartlett that are summarized below. He also referred to an estimate that as many as 100,000 animals grazed the valley and adjacent areas, based on reports of early explorers and assuming that the ranchers abandoned substantial numbers of cattle that reproduced successfully. He asserted that large numbers of feral livestock and evidence of grazing were probably typical of the Upper San Pedro River Valley in the early to mid 1800s. Hereford then concluded that grazing preceded entrenchment of the river by more than 40 years, casting doubt upon the importance of grazing as a factor in entrenchment.

Other workers cast doubt upon Hereford's arguments. Turner et al. (2003) reported that Apache raids halted cattle raising efforts in the 1820s and 1830s and that the cattle raising during these times did not attain the proportions of the 1880s when arroyo cutting and shrub invasion began. They noted that visitors to Southeastern Arizona in the 1840s and 1850s did find evidence of former cattle ranching and did see herds of cattle. However, they concluded that despite many early observations of large numbers of cattle, the numbers were probably exaggerated and ultimately produced the myth of great herds. The authors reported that any large herds were probably gone by 1854 because records kept that year by cowboys passing through Southern Arizona on a large Texas Trail Drive indicated that no signs of wild cattle were seen. Moreover, the authors noted that centrifugal windmills did not appear before the 1870s and before that, livestock would have been clustered around natural water sources. Visitors may have noted the locally dense herds near natural water and extrapolated such numbers across the vast adjacent areas without natural water.

The key question as regards cattle and the San Pedro River Valley in the early 1800s is not whether or not they were present but whether or not they overgrazed the range there. Several accounts suggested at least moderately abundant cattle in local areas of southern Arizona between 1846 (time of the Mormon Battalion) and the Gadsden Purchase of 1853. However, these accounts do not provide a basis for concluding that the rangeland was then overgrazed. Lieutenant Colonel Philip St. George Cooke led the Mormon Battalion through southeastern Arizona in 1846 and reported (Bahre, 1991) that wild cattle attacked it at the junction of Babocomari Creek and the San Pedro River. He also reported, "There is not on the open prairies of Clay County, Missouri, so many traces of the passage of cattle and horses as we see every day."

In 1851, John Russell Bartlett, Commissioner to the United States-Mexican Boundary Survey, entered southern Arizona along with other members of the boundary survey (Bartlett, 1854). His report showed that cattle were present in southern Arizona but did not indicate that overgrazing was occurring. His travels took him into the San Bernardino Valley, located east of current day Douglas in southeastern Arizona. Bartlett first viewed the valley from a high hill and characterized it as "the rich valley of San Bernardino" and recorded, "Here was stretched out before us a level patch of green, resembling a luxuriant meadow." He visited the ruins of the former San Bernardino ranch and reported that vast herds of cattle were raised there before Apache attacks caused abandonment of ranching approximate 20 years previously. Bartlett reported that cattle that had strayed away had greatly multiplied since and roamed over the plains and valleys and had produced cattle trails, some of which were fresh. He encountered small herds, comprising up to six cattle, and each led by a bull. At one campsite in the San Bernardino Valley Bartlett and his party used dried cattle dung as fuel for a campfire. The bellowing of bulls and the incessant yelping of wolves occasionally disturbed the sleep of him and his companions. According to Bartlett, Colonel Cooke in his march to California supplied his whole command with beef from these cattle, and travelers journeying to California also used this source of meat. Bartlett reported that the valley of the Babocomari River also contained an abandoned ranch that had not less than 40,000 head of cattle as well as a large number of horses and mules when Apache attacks forced its abandonment. He reported that many of the cattle had remained and spread themselves over the nearby hills and valleys and given rise to many herds that then ranged along the entire length of the San Pedro River and its tributaries. Additionally, Bartlett reported that a party of 30 to 40 Mexicans was camped at the junction of Babocomari River and the San Pedro River to hunt wild cattle. While Bartlett reported that one place in the San Pedro River Valley (near St. David) had abundant mesquite but sparse grass (probably a mesquite bosque), he also found that abundant grass was present in another place near the river alongside springs – probably in a cienega. Bartlett also reported abundant grass in other areas of southern Arizona. If the rangeland of southern Arizona had been seriously overgrazed in 1851, the cattle would have previously eaten the abundant grass near springs and elsewhere. While Bartlett reported cattle in several areas, his report does not indicate that large numbers were present in most regions he visited. On several occasions, Bartlett reported that his party was running low on fresh meat and referred to taking sheep along to provide meat. If cattle had been generally abundant, Bartlett's party would have hunted them and not needed to bring sheep for meat.

Bahre (1991) also cast doubt upon the idea of significant cattle herds in the 1820s and 1830s. He noted that there were no windmills or stock tanks and that it was difficult to believe that grass and other suitable plants adjacent to major sources of perennial water could have supported high numbers of cattle. Moreover, he concluded that there was no evidence of overgrazing during the 1820s and 1830s as suggested by the journals of travelers from 1850 to 1880 who emphasized the presence of largely pristine vegetation ideal for cattle.

Evidence against the overgrazing of the San Pedro River Valley before 1859 comes from a talk given by S. Mowry in 1859 to the American Geographical Statistical Society (Mowry, 1859). He described the valley as, "par excellence, the agricultural district south of the Gila. The valley is wide, very rich . . .." His paper had no mention of overgrazing in the valley or elsewhere in Arizona and Sonora.

Intensive cattle ranching and overstocking of Arizona ranges began with the 1881 arrival of the Southern Pacific that provided a means of transporting cattle to market (Bahre, 1991; Sayre, 1999). Additionally, the spread of windmills and the elimination of the Apache threat opened up southeastern Arizona to ranching. The Southern Pacific advertised for settlers in

1881, and soon afterwards, ranchers began moving their herds from overgrazed areas in Texas, New Mexico, and the Mexican states of Durango, Chihuahua, and Sonora. The transformation of the rangelands was so rapid that by 1884 a pioneer rancher in the San Rafael Valley complained that every running stream and permanent spring has been claimed and adjacent ranches stocked with cattle. In 1870, there had been fewer than approximately 40,000 cattle in Arizona, with slightly over a third of them in the Gadsden Purchase area. Twenty-one years later, there were approximately 1.5 million, with about 400,000 of them grazing in southeastern Arizona. American settlers had little experience with arid ecosystems and optimistically noted the perennial grasses that blanketed the broad valley floors because of several years of good rain. The settlers did not realize that Arizona would have years with much less precipitation. The years of plentiful rainfall produced an optimistic determination to not sell cattle during dry years.

Bahre (1991) summarized the results of drought. The year 1890 had less than normal rainfall, and summer rains were almost absent in 1891 and 1892. During the first months of 1893, the combined effects of drought and overgrazing caused the death of 50 to 75% of the livestock, mostly in southeastern Arizona. Summer rains in July 1893 rescued the cattle industry from complete ruin, but overstocking and overgrazing continued. Major changes in the landscape occurred after 1893, with many areas becoming almost completely denuded of grass cover, and the topsoil eroding and cienegas being destroyed. The degraded range conditions were substantiated in a government publication with pictures of southeastern Arizona and in the Roskruge Photograph Collection at the Arizona Historical Society, and Tucson. The pictures showed hundreds of square miles of rangeland that were denuded of cover. The grasses, even the sacaton in the bottomlands, were grazed to the ground. Hills were covered with cattle trails and erosion was rampant.

Bahre and Bradbury (1978) further documented the effects of overgrazing. In 1891, a University of Arizona botanist reported that southeastern Arizona ranges were so depleted that it was difficult to find suitable grass specimens for study. He further noted that cattle then had to depend on oaks and shrubs for browse. Photographs taken in 1892 of the U.S.-Mexican Border Monument 105 in southern Arizona showed almost total destruction of the grass cover over vast areas of land.

In 1901, D. A. Griffiths, chief botanist in charge of grass and forage investigations for the Arizona Experiment Station in Tucson, concluded that the rangelands of southern Arizona were more degraded than any others he had seen in the western United States (Bahre, 1991). He sent a questionnaire about range conditions to several pioneer ranchers. The answers of H. C. Hooker, proprietor of the Sierra Bonita Branch, and C. H. Bayless, owner of a large ranch near Oracle, provided information about conditions in the San Pedro River Valley.

Hooker reported that as of 1870 the valley had an abundance of willow, cottonwood, sycamore, and mesquite timber, large areas of sacaton and grama grasses, sagebrush, and underbrush of many kinds. The riverbed was shallow and grassy and its banks had a luxuriant growth of vegetation. He reported that conditions were quite different in 1901. The river was deep with washed out banks, trees and underbrush were gone, the sacaton had been cut by the plow and grub hoe, thousands of horses and cattle had grazed the mesa, and people had farmed the valley. There were many cattle and horse trails and paths to the mountains. Fire had destroyed much of the shrubbery and grass. Rains would sweep away much of the earth loosened by the feet of animals and in this way many waterways had been cut from the hills to the riverbed. There was little or nothing to stop large currents of water from reaching the riverbed with such force as to cut large channels and destroy much of the land under cultivation, resulting in the river being 10 to 40 feet below its former banks. Hooker reported that the unproductive condition of the range in the valley was principally because of overstocking of cattle. During drought, the livestock ate and destroyed even the roots of plants, and if not so destroyed, the roots would have grown out again with winter moisture.

Bayless reported that as of approximately 1889 the valley was a narrow strip of subirrigated and very fertile lands. Beaver dams checked the flow of water and prevented the cutting of a channel. He concluded that the extermination of the beavers along with less grass on the hillsides resulted in greater erosion so that within four or five years a channel varying in depth from 3 to 20 feet was cut almost the whole length of the river. He reported that as of 1901 the deep channel, in addition to curtailing the area of good land, had drained the bottoms, leaving the native grass without any chance to recover from the effects of overgrazing. Bayless concluded that the valley lands as of 1901 were unproductive due entirely to overstocking. He reported that the valley still received the same average amount of rainfall and sunshine necessary for plant growth and that droughts were not more frequent in 1901 than in the past. However, the earth had been stripped of all grass covering. When rain fell on the bare ground, water washed away in destructive volumes and bore with it all the lighter and richer particles of soil. The remaining sand and rocks were not adequate for native vegetation to thrive as previously. Cattle had trampled the roots of the grass, and there were no roots or seeds to provide for regeneration of native plants. Bayless reported that as of approximately 1889, 40,000 cattle grew fat "along a certain portion of the San Pedro Valley" where now 3000 were unable to find sufficient forage for proper growth and development. He noted that few of the former cattle were sold or removed from the range. Ranchers simply left them there until the pasture was destroyed and the livestock perished from starvation.

Hendrickson and Minckley (1984) suggested that concentrations of cattle along waterways in southeastern Arizona in 1891-1893 must have produced remarkable damage to riparian communities. They concluded that cattle must have destructively grazed and trampled cienegas. Such natural features were located at places with the most permanent water supplies and supported lush plant communities made up of species palatable to cattle. The activities of cattle in present-day cienegas fragment the sponge-like surface deposits and promote drying of part of the cienegas. Such damage presumably also occurred during the times of overgrazing.

Turner et al. (2003) summarized information about the overstocking of ranges. Ranchers became so concerned about overstocking of cattle in the San Pedro River Valley that in 1885 the Tres Alamos Association passed a resolution stating that the ranges were "already stocked to their full capacity" and demanding that the influx be controlled. In 1886, the Tombstone Stock Grower’s Association reported that, "a crisis is fast approaching", and that the San Pedro River Valley ranges have been stocked to the extreme limit of their capacity, leaving no surplus grass. However, ranchers continue to increase their herds throughout the rangelands of Arizona. The *Southwestern Stockman* reported in 1891, "the malady of overcrowding is with us in an aggravated form" and reported that disaster had been averted that summer only by the "phenomenal" late rains. An official assessment roll for 1891 showed 720,940 cattle in Arizona, and the governor wrote that there were "closer to 1,500,000." The summer rains of 1891 were considerably below normal, and in the arid fore-summer of 1892, livestock began to die. The summer rains of 1892 were also below normal and by the late spring of 1893, the losses of livestock were "staggering."

Sheridan (1995) described the massive die off of cattle. The losses were greatest in southern Arizona, where 50 to 75% of them died. Judge J. C. Hancock reported that San Simon Creek was littered with the bodies of cattle and that the cowboys strained their drinking water through burlap sacks to filter out the maggots. Rancher Edward Land recalled, "Dead cattle laid everywhere. You could actually throw a rock from one carcass to another."

The drought apparently only temporarily interrupted grazing pressures in Arizona (Brown, 2009). After the drought, the number of livestock was still large and continued to expand as new water sources and lands were developed. By the time of statehood in 1912 and estimated 915,000 head of cattle and 1,260,000 sheep were in Arizona, with larger numbers of both species to come. Overgrazing continued even in 1900 (Bahre, 1991). However, it was at lower levels than during the 1880s and 1890s. By 1900, the large ranches in southeastern Arizona had begun to buy up smaller ranches. This consolidation -- along with the Stock Raising Act of 1916 that expanded the size of ranching homesteads -- led to the death of the open range. In 1906, the U.S. Forest Service placed grazing control on its lands. However, it was not until 1934, with the passage of the Taylor Grazing Act, that there was an effort to stop injury to other public lands and to stabilize the livestock industry dependent upon public ranges. The effects of grazing made thus have influenced arroyo formation during most of the period when arroyos cut into riparian floodplains.

The descriptions by Hooker and Bayless provided eyewitness accounts of the interaction between cattle damage to the environment and the formation of arroyos during floods. The prehistoric episodes of arroyo downcutting demonstrate that arroyo formation can occur in the absence of environmental damage by livestock. The downcutting of the San Pedro River and of others Southwestern Rivers probably would have occurred at some stage during the series of floods from approximately 1910 to 1940. However, it is very difficult to believe that the environmental damage caused by livestock did not play an important role in facilitating such downcutting. The denuded state of rangeland and the presence there of cattle trails may have resulted in formation of some arroyos that would not have otherwise formed.

Denevan (1967) did an analysis that weakened the argument that livestock grazing was essential for historic arroyo formation but that suggested that the effects of overgrazing or part of a complex set of factors promoting historic arroyo downcutting. During control by Mexico, the ranges of New Mexico were heavily stocked with sheep, possibly three million head in the 1820s. However, there was little or no production of arroyos. Additionally, modern production of arroyos occurred in some areas of New Mexico where there apparently was little or no grazing. Denevan concluded that for New Mexico the 19th century pattern was sequentially: (1) higher than average rainfall and high livestock numbers, with little or no arroyo production; (2) drought and low livestock numbers, with little or no production of arroyos; (3) high intensity rainfall, low livestock numbers, and little or no arroyo production; and (4) drought that was followed by several years of heavier than average summer storms, high livestock numbers, probably a weak and reduced vegetation cover, and intensive arroyo production. The overall pattern for New Mexico thus supported the importance of summer floods for arroyo production but also gave some support to the possible importance of impoverished vegetation in facilitating arroyo production.

McFadden and McAuliffe (1997) studied the causes of arroyo formation in the southern part of Antelope Mesa in northeastern Arizona. They concluded that unusually heavy livestock grazing for over 120 years in this arid region may have accelerated valley floor erosion and nearby arroyo formation. However, the authors concluded that the landscapes were associated with highly erodible materials that were highly sensitive to even minor climatic changes and that climatic changes during the last one or two centuries largely overwhelmed the effects of grazing in almost every part of the study area.

Drainage-concentration by humans

Cooke and Reeves (1976) described a "drainage-concentration" hypothesis to explain the formation of some arroyos. According to this hypothesis, specific valley floor changes, such as the cutting of ditches and canals, the creation of roads, and the building of embankments, provided the loci for the initiation of many arroyos. Such structures concentrated drainage water into specific areas and thereby promoted erosion. The authors suggested that such changes by themselves were adequate to promote entrenchment and that recourse to other environmental changes was unnecessary in most areas. They noted however that other changes did occur and that they may have promoted arroyo initiation and development. The authors discussed evidence suggesting that the hypothesis explained formation of some arroyos in the San Simon Valley, at Tucson, at San Xavier del Bac, on the Santa Cruz Plains, and in Avra Valley.

According to Cooke and Reeves (1976), historical records suggest that human activities caused or at least served as the loci for the formation of arroyos in the San Simon Valley from the Gila River south to San Simon. The first entrenchment apparently began approximately in 1883 when settlers near Solomonville became distressed by debris deposited on their land during floods following heavy rains. These people therefore excavated a channel approximately 4 feet deep and 20 feet wide to concentrate waterflow from the San Simon Valley and discharge it more efficiently into the Gila River. Funneling levees were also reportedly built upstream of the canal to promote drainage concentration. Newspaper accounts reported that the channel was severely eroded in the floods of 1890 that produced a flow of water over a mile wide and cut a swath to the Gila River.

Subsequent arroyo formation apparently occurred along the route of a former wagon road. Data from surveyor's notebooks indicate that between 1875 and 1885 there was no arroyo at least as far south as T.11 S., R.29 E. Excessive channel erosion apparently began during heavy rains in 1905-1906 that followed the severe drought of 1902-1905. Heavy rains in 1916, that also followed an extended drought, caused further entrenchment. By the 1930s, the arroyo was apparently over 200 feet wide in some places and up to 30 feet deep, and generally was approximately 9 feet deep and 75 to 90 feet wide. The authors speculated that: the road concentrated the flow of water; traffic stripped away vegetation and thereby reduced surface roughness; traffic destroyed soil structure, created ruts, reduced infiltration capacity, and promoted runoff; and vegetation removal and traffic together made exposed sediment more vulnerable to erosion. Cooke and Reeves (1976) concluded that because the road acted as the line along which most entrenchment occurred, there was no reason to speculate that entrenchment proceeded by headward erosion from the flood control channel near Solomonville.

A third possible human cause of entrenchment in the valley was the extension of a railroad through the area in 1884. For more than 20 miles, the railroad closely followed the valley floor along a way that reflected a compromise between the undesirable dissected alluvial plains and the flood prone valley flats. It was largely built on low embankments across the flood zone. In some stretches, the unintentional effect of the railroad embankment could have been to concentrate flow and to promote erosion. In several places, the railroad embankments could have reduced flood width by as much as 40%.

Cooke and Reeves (1976) noted that discussions by other authors of soil erosion in the San Simon Valley identified three main causes: overgrazing by cattle that caused vegetation depletion and increased runoff; heavy rains that followed the droughts in the early part of the 20th century; and undesirable homesteading and dry farming. They asserted that these phenomena might have contributed to general soil erosion but that it was not clear that they were individually or collectively responsible for arroyo initiation. Cooke and Reeves concluded that new features created along the valley floor, such as canals, embankments, and roads, were equally if not more important and that at minimum such new features determined the location of arroyo formation.

The current arroyo in Tucson developed along a ditch dug by Sam Hughes in the floodplain of the Santa Cruz River (Betancourt, 1990; Hastings, 1959; and Webb et al., 2007). The river there had no well-defined channel before 1890, and during floods, it spread out in a shallow sheet across the fields and lowlands. In the 1860s, farmers dug infiltration ditches in the Tucson region. They excavated the ditches in the floodplain to intercept the shallow water table and thereby provide a regular water supply. The ditches headed upstream in the floodplain and were deepest at their headings, and apparently, no attempts were made to protect the headings from erosion. Sam Hughes dug one such ditch. Starting around 1878, the river began downcutting into its floodplain in the Tucson region along the former irrigation canal of Sam Hughes, and the headcut propagated upstream. Reports in the Arizona Daily Star in August 1890 documented the rapidity of formation of arroyo segments. August 5: the flood on August 4 washed a deep cut across the hospital road, making it impassable. August 5: the Santa Cruz River began cutting a segment of its present channel along a ditch that had been dug by a farmer for irrigation purposes. August 7: the arroyo made by the overflow of the Santa Cruz River was a mile and a half long and about 100 to 200 yards wide. August 8: more than 50 acres of farmland in the Santa Cruz bottom was rendered worthless by being washed out to form an arroyo. August 9: the single channel that was being washed out through the fields of the Santa Cruz by the floods produced considerable damage. The danger was greatly increased by the arroyo forking at its head so that there were several channels being cut by the flood, with all of them running into the main arroyo. August 13: the Santa Cruz continued to wash out a channel, with the head of it now opposite town. By 1912, numerous floods had extended the arroyo to a length of 18 miles (Cooke and Reeves, 1976). Various other arroyos formed along the river at unknown dates, but probably extending into the 1930s, and coalesced to form the current arroyo extending from Tucson to the headwaters in southern Arizona (Webb et al., 2007).

People at San Xavier del Bac constructed two infiltration ditches. Over time, heavy floods converted the ditches into two arroyos (Cooke and Reeves, 1976).

Humans constructed a canal that developed into an arroyo on the Santa Cruz Plains (Cooke and Reeves, 1976). The intention was to use dikes, brush dams, and embankments to concentrate floodwater from the Santa Cruz River into the canal and then transfer the water along the canal to a reservoir that would provide irrigation water near Toltec. Plans for the canal and reservoir were drawn up in 1909, and the structures were completed in 1910. A major flood in 1914 destroyed the dam at the reservoir, damaged the canal, and eroded it to a depth of approximately 12 feet. Since then, floods have followed the course of the former canal and converted it into an arroyo that has become sinuous, deeper, and wider. Well water has provided irrigation in the district since 1916.

The occurrence of an arroyo in Avra Valley is clearly the result of human activities (Cooke and Reeves, 1976). When the land was subdivided in the 1950s for irrigation, dikes were constructed to protect the fields from occasional flooding by diverting floodwater into flood channels. One of the channels was in the southern part of the area and was nearest to the major floods that came down the valley. It was too small to accommodate large floods, such as that of 1962, and has been eroded into an arroyo.

The entrenchment of Curry Draw in the San Pedro River Valley apparently occurred along the ruts of a wagon road in 1916 (Hereford and Betancourt, 2009). This entrenchment further supports the drainage-concentration hypothesis.

Analysis of photographs of the Babocomari River near its junction with the San Pedro River suggests that arroyo formation started along an irrigation canal that had been dug along the Babocomari River in that area. An approximately 1890 photograph (Fig. 23 A) showed a marshy landscape that gently sloped downward toward the San Pedro River. The foreground had an irrigation canal that followed the north bank of the river and that probably was the old Ramon Escude irrigation ditch (Bahre, 1991). The ditch was close to the hill from which the photograph was taken. A subsequent 1962 photograph (Fig. 23B) was taken approximately 100 feet northwest of the old one because the entrenchment of Babocomari River had cut deeply into the hill from which the first photograph was taken. The initial entrenchment of the river apparently followed the line of the irrigation canal. The dike at the left of the photograph was part of a project to divert the creek into a new channel, visible at the center and approximately on line with the water in Fig. 23A. The 1994 photograph of Fig. 23C showed that many of the tall trees found in 1962 were still present.

Agriculture

Webb, et al. (2007) summarized information about agricultural clearing. The clearing of floodplain vegetation for agriculture had notable effects upon riparian vegetation. However, the extent of such clearing, with some notable exceptions, was relatively small by the start of the 20th century. Early 20th century photographs documented clearing along the Santa Cruz

River at Tucson, apparently dating to presettlement use by the Tohono O'odham. The cleared fields were small compared with the total riparian area in the photographs. Old photographs and lithographs made from old photographs of Moenkopi Wash and Havasu Creek, respectively, showed agricultural clearings by the Hopi and Havasupai. There were agricultural clearings near every town along the watercourse, but such fields supplied mostly local produce rather than commercial crops grown for long-distance transport.

Clearing of bottomland vegetation in Southern Utah along the major rivers affected areas dominated by saltbush, greasewood, and big sagebrush. Cottonwood along the alluvial reaches of the San Juan River were not cut to clear land for agriculture because the floodplains on which the cottonwood grew were subject to inundation and scour. However, cottonwood was locally cut to provide timber for bank stabilization structures. Cottonwood trees were otherwise treasured for the shade they provided in an otherwise treeless desert.

During the second half of the 20th century, agriculture on or adjacent to floodplains increased because of increased construction of water-diversion structures along the Lower Colorado River or the construction of well fields on floodplains removed from waterways. For example, the construction of irrigation canals facilitated extensive agricultural development of the middle and lower reaches of the Gila River and of the Lower Colorado River. Much of the cleared land formerly had mesquite bosques or arrowweed. However, repeat photography near Dome, Arizona showed that agricultural clearing there removed mature cottonwood. The land cleared for agriculture along the middle portion of the San Pedro River increased, mostly at the expense of mesquite. There was extensive agricultural development in the broad valleys of Southern Arizona and the Lower Colorado River, but most such development was at the expense of xerophytic vegetation. In places where agriculture encroached on floodplains, mesquite was the most affected.

It seems reasonable to conclude that agriculture facilitated historic arroyo formation. Floods eroded several agricultural canals and converted them into arroyos. The disturbance of soils for agriculture purposes and the construction of dirt roads associated with agriculture probably made soils more susceptible to erosion. In 1982, the Arizona Daily Star reported (Bahre, 1991), "the vast plain of gramma [sic] grass west of Tucson is being dug out by the roots, thus totally destroying the hope of the grass starting where it has been cut out. Many tons have been dug out by the roots and brought to the city for sale." Except for the few observed erosions of arroyos along human constructed ditches and other structures as cited above, it is difficult to determine precisely the affects of agriculture on the most recent episode of arroyo downcutting. Turner et al. (2003) noted that the heterogeneous history of the southern Arizona and northwestern Mexico makes it difficult to link settlement and cultural factors with historic arroyo downcutting that occurred synchronously over a broad region.

Elimination of beaver

Webb et al. (2007) summarized information about beavers. These animals were formerly widespread throughout the Southwest and probably had profound effects upon the prehistoric distribution of riparian vegetation. They culled woody riparian vegetation, such as cottonwood, willow, tamarisk, and adjacent woody plants such as mesquite. The ponds impounded by their dams could kill trees within a year. Their low numbers in the middle of the 20th century might have been a factor in the growth of riparian gallery forests. Along some waterways, such as the Upper San Pedro River, the high water tables in alluvial aquifers before arroyo entrenchment may have been partly due to the small dams built by thriving beaver populations.

Beavers are keystone species for small-order streams and may have played a role in helping to maintain wet conditions along the river and in providing suitable habitats for large fish (Ohmart, 1996). The activities of beavers helped to create and maintain wetlands, influence the timing, rate, and volume of water and sediment movement downstream, and create pools and backwaters providing habitats for fish. The beaver dam control of stream gradient could have slowed water flow and increased saturation of the alluvium (Webb, et. al., 2007).

As noted above, the rancher Bayless was of the opinion that the removal of beaver helped produce arroyo downcutting along the San Pedro River. Turner et al. (2003) argued against the view that extirpation of beavers may have resulted in downcutting of southwestern stream channels. They regarded such views as unlikely because in many areas beaver (other than the San Pedro River) populations rebounded by the 1850s, well before arroyo downcutting began. As noted elsewhere in this paper, the very large floods associated with turn-of-the-century arroyo cutting and channel incision removed most of the vegetation from the river channel, including cottonwood and willow trees. Beaver dams would have provided little impediment to such massive floods. I believe that the aggradation of the San Pedro River since the 1940s in the absence of beavers, until reintroduction in 1999-2001, strongly argues against them as necessary to prevent downcutting of waterway channels.

Excessive cutting of timber

Bahre (1991) documented the cutting of wood in Southeastern Arizona during the late 19th century. The primary cooking fuels were juniper, oak, and mesquite, but people also used pine and various shrubs. The mining industry primarily utilized mesquite, oak, pinyon juniper, and some shrubs for fuel. People harvested mesquite and oak to make charcoal that was used for several purposes, ranging from blowing in smelting furnaces to heating laundering irons. They used various woods to kiln firebricks, especially willow and cottonwood, and fed livestock with the leaves of willow and the bark of cottonwood.

A major cause of fuelwood cutting was the enormous need for fuel in the mining industry (Bahre, 1991). Cordwood was the major fuel of mines in Southeastern Arizona until the 1890s except for the English and Colorado coke used in the blast furnaces. People burned wood to heat the boilers and steam engines at virtually every step in mining, such as running stamp mills, pumps, hoists, ore crushers, dryers, amalgamation pans, settlers, and converters. They also used wood to roast ores, to retort amalgam, and to heat all heating and cooking needs. Wood fueled all the steam engines in mining areas from those running trains to those making ice.

Tombstone and its woodshed (the area within a 25-mile radius of the town that served as the primary source of fuelwood) provided an example of the large amount of wood cut for mining operations (Bahre, 1991). The town was possibly the second largest city in Arizona in 1885, with a reported 15,000 inhabitants. During the Tombstone Bonanza years of ore production, 1879-1886, miners took approximately $232 million (converted into current prices) of ore from the district mines. Through this same interval, people used an estimated 31,000 cords of fuelwood for heating and cooking in Tombstone and an estimated 47,260 cords of wood for the stamp mills. (A cord was 128 $ft.^3$ of tightly stacked wood, most often measuring four feet by four feet by eight feet.) People obtained wood from the mesquite thickets along the San Pedro and the Babocomari Rivers, and from the evergreen woodlands of the Huachuca and Whetstone Mountains to the west and the Dragoon Mountains to the east. (If the total estimated amount of fuelwood was placed into a single stack, it would have been 119 miles long by 2 feet wide and 8 feet high.)

By the early 20th century, people had cleared the mountains near Tombstone and Bisbee for fuelwood (Tellman and Hadley, 2006). The stripping of all timber from hills around Bisbee resulted in floods in 1882 (Bahre, 1991). People also removed considerable timber from the Huachuca and Chiricahua Mountains until approximately 1900 (Tellman and Hadley, 2006). Settlers in Arizona also removed large amounts of timber from ponderosa pine and mixed conifer forests for construction and mining purposes, but there are no reliable estimates of the total amount harvested (Bahre, 1991).

Wood harvesting was intensive in Southeastern Arizona in the late 19th century but began to rapidly decrease after the Southern Pacific arrived in Arizona in 1881 (Bahre, 1991). There are no firm estimates for the amount of wood removed, but Bahre (1991) summarized historical records that suggested people stripped the wood from large areas. The Arizona Daily Star reported in 1882 that cordwood had become scarce in Southeastern Arizona and that coal from outside the area must be obtained to replace the former fuelwood. In 1884, the same paper reported, "timber depredations in southern Arizona are becoming so extensive that there is just cause for alarm. Even the palo verde trees are being stripped from the mesa lands." In the same year, the paper also commented on "the wholesale destruction which is being made of the timber on government lands" and reported that "The mesa tracts of southern Pima and eastern Cochise counties are being literally stripped of trees, so that shelter of stock will soon be unknown in these sections." The cutting of wood for fuel had a major impact on riparian forests, mesquite thickets, and evergreen woodlands that were near most of Southeastern Arizona's major cities and mining centers. For example, in 1892, fuelwood had become so scarce near Tucson that woodcutters had to go as far as 20 or 30 miles away and even then brought back roots and stumps that were dug out and cut up into stove size. By 1905, every tree over 7 inches in diameter had reportedly been cut up and used for fuel within a 10-mile radius of Tucson. Bahre (1991) suggested that the scarcity of willows and cottonwoods in photographs of riparian areas taken in the 1880s and 1890s might have been partly due to their having been used as retort fuel, to kiln bricks, or to start mesquite and oak fires in the fireboxes of steam engines.

Webb et al. (2007) argued that the harvesting of wood did not produce widespread impacts on riparian species such as cottonwoods and willows. (For that analysis, they did not treat mesquite as a riparian species and in fact noted that it was the firewood of choice.) They reported that photographs, land-use histories, and anecdotal observations provided no evidence that humans caused widespread elimination of woody riparian vegetation at the time of settlement. Settlers did however use small amounts of riparian wood in construction; lintels above doors and windows may have been cottonwood. The only explicit documentation of systematic woodcutting within the riparian zone was along the lower Gila and Colorado rivers where wood was cut to power steamboats and smelters and to provide building material for the expanding town of Yuma. When settlers had access to an alternate source of higher quality wood, such as oak and pine in Southern Arizona Mountains, they used such better quality material. Woodcutting did occur locally on the floodplains, but the extent of such cutting and its impact on the riparian zone is unknown. Turner et al. (2003) concluded that riparian species, especially cottonwood, were largely avoided for fuelwood because they did not burn as hotly as did other available woods.

The historical records cited above indicate that people stripped wood from large areas within southeastern Arizona. There are no authoritative studies about the impact of such removal on riparian habitats. However, it is logical to conclude that clear cutting of timber from large areas increased runoff into adjacent waterways during floods. For example, the clearing of wood from hills near Tombstone and Bisbee must have greatly increased flood runoff into the San Pedro River. Such presumed increased runoff probably facilitated arroyo formation. The extensive harvesting of mesquite near waterways, including the digging up of its roots, may have made the ground near waterways more susceptible to erosion and arroyo formation.

Observations by a geologist of formation of an arroyo in Utah

Baer (1985) observed an arroyo form along Chriss Creek in Utah in 1983. The 1983 water year in Utah was the wettest since precipitation records had been kept. Sometime in late May to early June of 1983, rapid headward erosion began at the intersection of a shallow and low gradient intermittent waterway with a steep arroyo. In June 1983, Baer found that a waterfall had developed over the 17 to 20 foot elevation difference between the low gradient waterway and the steep arroyo. The newly developing arroyo differed markedly in shape and size from the upstream channel. Waterflow of approximately 55 $ft.^3$ per second was eroding the streambed rapidly.

Erosion of the soil occurred in such a manner that plants offered little impedance to the advancing erosion. The waterfall developed a 10 to 14 foot wide plunge pool at its base where the whirling water undercut both banks as well as upstream. The major contributor to erosion volume was the caving of banks. Blocks fell from the banks at a rate as high as one every three minutes. Some blocks were 16 feet long, 13 feet high, and 3 feet deep. The area was covered with sagebrush with a density of one per thirty square feet and had small patches of grass. The plants provided little resistance to the advancing erosion primarily because such erosion occurred 10 to 12 feet below the root systems of the sagebrush. These root systems primarily served to hold together the blocks before they fell into the stream. The sagebrush crested blocks sometimes served as temporary dams that momentarily blocked the stream. Eventually water spilled over the debris and within a few minutes, there were no traces of the block as the detached sagebrush plants washed downstream. Sometimes the sagebrush plants hung up and created an eddy or small whirlpool in the stream. This allowed the stream to undercut the bank downstream from the waterfall and caused isolated blocks to fall, producing further widening of the new channel.

Discussion about causes of arroyo formation

There is consensus among scientists that flowing water moves sediments. Flowing water, especially that of large floods, is the common denominator for all arroyo formation. Despite many papers about the causes of arroyo formation, there still is no consensus about the factors that produced arroyo formation. Cooke and Reeves (1976) insightfully observed that arroyos could be produced from different initial conditions and in different ways. There is no reason why there must be a single explanation for arroyo formation. Overgrazing promoted some historic arroyo formation but could not have been a factor in prehistoric arroyo downcutting. Anthropogenic activities such as the construction of drainage canals or embankments, agriculture, and the cutting of wood promoted historic arroyo formation. The evidence is especially compelling that the construction of drainage canals and other human activities that concentrated floodwaters resulted in the production of certain arroyos during historic times. However, there is no firm evidence to suggest that human activities caused the multiple prehistoric episodes of arroyo formation. Some data clearly indicate the importance of regional increases in precipitation or the concentration of precipitation into short periods within a year as factors promoting arroyo formation on a regional basis. A few scientists contend that periods of drought preceded and facilitated arroyo formation by reducing the vegetation cover of uplands. Other scientists assert that there is no firm evidence of vegetation reduction before episodes of prehistoric arroyo production. The geologist's observations of the formation of an arroyo in Utah show how heavy precipitation and the pre-existing topographic features of a landscape promoted the production of an arroyo. The above explanations are not contradictory. Multiple different causes probably promoted arroyo formation. Attempts to find a single cause for arroyo formation are analogous to attempts to identify a single factor causing all traffic accidents and are doomed to failure. However, some factor must have coordinated the synchronous prehistoric and historic formation of arroyos across the Southwestern United States. Floods, whether from increased precipitation or the concentration of precipitation into shorter periods within a year, are probably that unifying factor. As listed above, many additional modifying factors influenced where arroyos were cut and how large and long they were. Additional research will help delineate the relative importance of potential causes for the various arroyos currently found in the Southwestern United States.

Regional Changes in riparian woody vegetation

A traditional method of analyzing the environment since European settlement was to use historical sources such as newspaper accounts and the journals or reports of travelers. Considerable analysis of such sources was necessary because some travelers visited different sites within a study region or made such visits during different times of the year. For example, travelers encountering the San Pedro River during monsoon floods had quite a different view of it from those who saw it during May or June. Travelers attempting to cross one place in the river often encountered conditions quite different from those observed elsewhere. Scientists have also deciphered information about former conditions by analyzing the stratigraphic record and data about hydrologic conditions, waterflow, and water usage.

Webb et al. (2007) greatly improved our understanding of the history of riparian vegetation in the Southwestern United States since approximately the 1860s. They analyzed changes in 2724 sets of repeat photographs in conjunction with hydrologic data, previously identified periods of climatic variation, known land uses, flow regulation, and water usage. They also analyzed photographs from aerial photography and satellite imagery for approximately the last quarter of the 20th century until the present.

Yeakley (2008) reviewed the book by Webb et al. (2007) and pointed out limitations. Her strongest reservation was the lack of clarity on the five vegetation change categories (large decrease, decrease, no visible change, increase, and large increase). Landscape photography is unable to measure vegetation mass or density on an areal basis. Repeat photography is necessarily confined to a narrow slice of the landscape. The locations of the original photos are not random because they depend on the access and interests of the original photographers. The timing of the photographs is from the latter 1800s to the present and thereby postdates a strong human influence on the watershed. However, Yeakley concluded that the book is, "a very positive resource for anyone interested in visualizing and better understanding riparian landscape change within most of the major river basins in Utah and Arizona over the past century." Despite the above limitations, repeat photography clearly documents the entrenchment of southwestern waterways and the increase of woody vegetation after entrenchment concluded. Moreover, Webb et al. (2007) synthesize considerable data from other riparian researchers and from historical records such as the journals of early travelers to the Southwest. Many of the conclusions in the book agree with conclusions derived by other authors who used different research methods. For example, the chronology of increase in gallery forests along the San Pedro River agrees with the chronology reached by Stromberg and discussed elsewhere in this paper. The subjective nature of the five different categories for vegetation change does not invalidate the depictions of stages of the alluvial cycle or the chronology of vegetation changes. Every scientific study has limitations.

The analysis by Webb et al. (2007) classified views into five different categories for woody vegetation, large decrease, decrease, no visible change, increase, and large increase. Woody riparian vegetation increased in intensity and biomass in 73% of the repeat photography views, with 49% of views having an increase and 24% having a large increase. There was no change in 15% of the views. Those camera stations with net decreases generally were in reaches inundated by reservoirs or affected by excessive pumping of groundwater or total diversion of surface water. These regions of decrease were concentrated in several places: the Santa Cruz River near Tucson, Arizona; the Middle and Lower Gila River; the Lower Colorado River; and the Mohave River at and downstream from Barstow, California. Along both the San

Pedro and Escalante Rivers, increases in cottonwoods began while livestock still grazed in the riparian zone.

Increases in woody riparian vegetation began after 1940, and the greatest increases occurred in the last third of the 20th century after the 1970s. Gooding's willow increased in 80% of the photographic matches. Fremont cottonwood increased in 69% of the views but notably decreased on larger river reaches at lower elevations, especially along the Gila and Colorado rivers. Tamarisk was present in 1577 matches and increased in 88% of the photographic views. This increase was because it generally was absent or present only in small amounts at the start of the photographic record. Tamarisk seldom occurred alone but rather typically was present along with one or more native species.

The lowering of water tables that resulted from arroyo formation facilitated the establishment of trees. This is because the establishment of most such trees required both dewatering of the upper few feet of the previously saturated alluvial aquifer and disturbance of the substrate that permitted the establishment of seedlings (Webb et al., 2007).

Webb et al. (2007) concluded that the available data do not permit the formation of generalizations about the impacts of grazing on woody riparian vegetation. The presence of grazing animals along riparian areas did not have consistent effects upon riparian vegetation. Such vegetation increased significantly along many waterways despite the presence of grazing animals. For example, woody riparian vegetation increased in places where ranches were continuously present in riparian zones, such as the Mohave River at Victorville. Cottonwood decreased in places never grazed and increased where grazing was heavy. Woody riparian vegetation began increasing along the San Pedro River while cattle were present. The establishment of SPRNCA, with its prohibition of grazing in riparian areas, was after the increase of cottonwood and other native trees. The above comments do not mean that grazing did not have an effect on woody riparian vegetation. Cattle are known to eat cottonwood leaves. Determination of the impact of grazing on woody riparian vegetation needs additional study.

The processes of arroyo downcutting and widening greatly affected riparian vegetation (Webb, et al., 2007). The rapid downcutting quickly lowered the level of aquifers and resulted in the die back or death of woody riparian vegetation. The channel widening removed plants that had survived the drop in water levels. The subsequent development of low terraces above the saturated zone afterward encouraged establishment of woody riparian vegetation. Such vegetation trapped sediments during over bank flows and enhanced the tendency toward arroyo filling. The widespread arroyo downcutting throughout the Southwest apparently resulted in the near disappearance of riparian marshlands or cienegas as major riparian vegetation communities (Hendrickson and Minckley, 1984; Price et al., 2005).

Data about seedling requirements and dispersal of seeds of Fremont cottonwood and Goodding's willow agree with the above concepts as to the probable response of riparian forests to arroyo downcutting and subsequent sedimentation (Dixon, et al., 2009; Friedman and Lee, 2002; Friedman et al., 1995; Scott et al., 1996; Stromberg, 1993; Stromberg, 1998; Stromberg, et al., 2009; Webb et al., 2007). Requirements for seedling establishment are more restrictive than those for adult survivorship. To become established, seedlings require open, moist mineral substrates. Degeneration of the substrates typically requires disturbance by channel migration, channel widening, or over bank deposition. Seedlings die if the substrate dries out faster than they can elongate their roots to reach the capillary fringe of the alluvial aquifer. The female plants of these species each spring produce many seeds. Wind commonly distributes the seeds several miles, but dispersal during floods is probably the most effective way for cottonwood to become established. Large winter or late fall floods can erode and redeposit sediments and create a patchwork of potential seedbeds. Winter floods tend to be of longer duration than those of the summer and may produce more channel movement, vegetation scour, and sediment reworking. After such winter floods, there typically are high flows in the spring and early summer that provide moisture essential to sustain young seedlings.

Fremont cottonwood begins seed dispersal slightly earlier than Goodding's willow, and this difference in time allows the species to partition the riparian habitat. The later dispersing willows tend to become established on surfaces that are slightly lower and closer to the stream channel, because of the streamward contraction of the zone of moist soil exposed by receding floodwaters.

Over time, the areas with cottonwood and willow trees become elevated due to accretions of sediments around the tree bases and to incision of the channel (Stromberg, et al., 2009). Because of floodplain aggradation, the frequency of flood inundation declines, surface soils become drier and contain increased amounts of organic matter, silt, clay, and leaf litter. The depth to groundwater also increases. These effects of elevated surfaces along with the dense canopy prevent the establishment of cottonwood and willow seedlings in their own understory. The forest composition gradually shifts toward species adapted to drier and more stable environments such as mesquite and net-leaf hackberry. Mesquite seedlings are intolerant of saturated soils and intense flood scour. Therefore, within the floodplain of the San Pedro River they tend to be established on aggraded areas that are sometimes in the open and sometimes in the cottonwood understory. Sacaton grassland commonly establishes itself on high surfaces of the San Pedro River floodplains. Its abundance increases with forest age, and this grass becomes the dominant groundcover in the inter-spaces and understory of old cottonwood stands.

Current conditions along the San Pedro River

The San Pedro River originates from tributaries in Northern Sonora, Mexico (Makings, 2005; Stromberg and Rychener, 2010; Stromberg and Tellman, 2009; Tellman and Hadley, 2006). It then flows north to northwesterly through Northern Mexico, across Cochise County in Southeastern Arizona and north through Pima and Pinal Counties to the Gila River. The river has a long and narrow hydrologic basin, and most of its tributaries drain short and relatively steep catchments, oriented perpendicular to the main valley access. The San Pedro River flows through several relatively deep and sediment filled basins bounded by mountain ranges.

Because of a relatively recent historic river entrenchment, the river itself and its floodplain are approximately 7 to 16 feet below adjacent river terraces (Figs. 2-3). Dense stands or galleries of cottonwood and willow trees and other riparian vegetation (Figs. 4-7) flourish along the river where surface or near surface flow is consistently present (Cook et al., 2009; Huckleberry, 1996; Stromberg et al, 2009). Terraces above the river support sacaton grasslands

(Fig. 8), mesquite bosques and savannas (Fig. 9), and active and abandoned agricultural fields (Stromberg and Tellman, 2009; Stromberg et al, 2009). Three cienegas occur along the Babocomari River, a tributary that enters the San Pedro near Fairbank (Hendrickson and Minckley, 1984). The largest cienega on the Upper San Pedro River on the US side of the border is the St. David Cienega (Fig. 10), comprising approximately 74 acres, situated approximately 1200 feet west and 22 feet above the river channel, and fed by artesian springs (Stromberg et al, 2009). A cienega is (Hendrickson and Minckley, 1984) a warm temperate wetland of the Southwest that occurs along small, low energy rivers at middle elevations between approximately 3000 and 6000 feet. Cienegas are typically sustained by groundwater inflow and have a low frequency of scouring floods. Their soils are permanently saturated and rich in organic matter.

The river's floodplain has many secondary flood channels, interspersed gravelly bars and low terraces, and typically is hundreds of feet wide (Cook et al., 2009). The form of the river channel is both braided and meandering, with the low flow channel usually braided and with several branching channels and the high flow channel sinuous in form (Huckleberry, 1996). Abandoned meanders and oxbow lakes occur just south of the bridge crossing the river on State Route 90. The valley floor elevations range (Stromberg and Tellman, 2009) from approximately 4800 feet in the Mexican headwaters to 3300 feet at The Narrows and 1950 feet near its junction with the Gila River. A bedrock constriction, "The Narrows", approximately 10 miles north of Benson divides the San Pedro basin into upper and lower portions.

The climate along the river is hot and dry, and annual rates of potential evapotranspiration far exceed precipitation (Stromberg and Tellman, 2009). The annual growing season for many perennial plant species begins during April through June even though this time of year is typically very dry. Locally heavy precipitation occurs during the monsoon season from approximately July through September. October and November are usually relatively dry and cool, but dissipating tropical storms occasionally produce heavy precipitation during the late summer and fall. A cool rainy season occurs during winter and early spring when more widespread and typically longer duration rains fall, derived from moisture in the Eastern Pacific.

The hydrology of surface water in the San Pedro River basin has a distinctly seasonal regime (Hirschboeck, 2009). Streamflow during the winter-wet season, primarily December through March, is moderate and relatively consistent. During the late spring and early summer dry season of April through June, the streamflow is low. Streamflow is greater and more variable during the summer-wet season of July through September. This seasonal pattern results from wintertime spatial and temporal interplays of latitudinally shifting storm tracks and incursions of moist air during the summer monsoon thunderstorm season.

Upper San Pedro River Conditions before recent arroyo downcutting

Waterflow

From at least the early 1800s until the start of arroyo downcutting in approximately the 1880s, most portions of the upper San Pedro River probably had waterflow throughout the year during times of normal rainfall. Mexican prices charged for land along the Upper San Pedro River suggest waterflow was perennial (Hereford and Betancourt, 2009). An 1825 Mexican law established land-grant units termed *sitios* (approximately 2784 hectares). The price of a dry rangeland sitio was $10 while that for a sitio with water was $60. Mexico made land grants at the price of $60 a sitio from Charleston to just south of Fairbank, between Hereford and the Lehner Ranch and extending north to Lewis Springs, and along the San Pedro straddling the current international boundary.

The accounts of early travelers support the presence of mostly continuous waterflow (Hereford, 1993; Huckleberry, 1996). In December 1846, Major Cooke led the Mormon Battalion along the river from approximately Hereford to Benson (Davis, 1982). Cooke described the San Pedro River as a "fine bold stream." He described fish as abundant and reported that his men caught great numbers of "salmon trout" ranging from 18 inches to 3 feet long. (The fish were probably Colorado pikeminnow. These fish [Stefferud et al., 2009] could attain lengths greater than 6 feet, weights over 90 pounds, and formerly occurred in the San Pedro River upstream to about Fairbank; they were extirpated from the San Pedro River by the late 19th century, possibly because of entrenchment.) During the 1851 US-Mexico boundary survey, John Russel Bartlett recorded (Bartlett, 1854) continuous stream flow in the Upper San Pedro. However, his visit to the river was in September when waterflow would be expected to be continuous. In 1854, Lieutenant John G. Parke led a survey party that reached the San Pedro River on February 25 near the site of present Benson and reported the river flowing with a rapid current (Davis, 1982).

Further support for mostly continuous waterflow between the early 1800s and approximately 1880 comes from the initial abundance of beaver. During the 1820s, trapper James Pattie (Fouty, 1998; Huckleberry, 1996; Pattie, 1831) took 200 beaver skins from the San Pedro River near its junction with the Gila River. His accounts suggested perennial stream flow throughout most of the river. In the late 1800s prior to floodplain entrenchment, European travelers noted the many beaver dams and associated ponds (Tellman and Huckleberry, 2009). The type locality of *Castor canadensis frondator*, formerly considered a valid subspecies, is the San Pedro River at the U.S. and Mexican border. Emory (1957) [Emory was a U.S. Army officer who mapped the U.S.-Mexican border.] viewed the river at the international border and reported, “Though affording no very great quantity of water, this river is backed up into a series of large pools by beaver-dams, and is full of fishes.”However, by 1900 settlers had nearly eliminated the beavers in the San Pedro River during efforts to drain wetlands because the beavers interfered with irrigation systems and their dams caused or were associated with the wetlands (Tellman and Huckleberry, 2009).

Historical records from the 1880s onward suggest that the upper San Pedro River at most places did not have a great water depth or large amount of water, except during times of flood. Rose (2013) reported that on July 25, 1880 several Tombstone residents found that they were unable to take a swim because a dam in the Charleston area had given way. Rose further reported on testimony given during a water rights lawsuit in 1889. The testimony depicts the upper San Pedro River as having a limited amount of water and having places that lacked surface water at times.

The San Pedro River main-channel before the 1880s

Prior to the mid-1800s, the San Pedro River flowed across a mostly unincised surface and had a much larger area prone to flooding than today (Hereford, 1993; Hereford and Betancourt, 2009; Huckleberry et al., 2009; Nichols, 2007; Price et al., 2005; Stromberg et al., 2009). The river was a single meandering channel with many marshes.

Hereford (1993) concluded that the available scanty historical records suggest that the San Pedro River was mostly unentrenched from about 1700 to at least 1878. Journals of Padre Eusebio Kino suggested shallow water tables and a river free of entrenchments in many localities. In 1697, he and Juan Manje traveled the entire length of the river to its junction with the Gila River (Huckleberry, 1996). They described in their journals many Sobaipuri irrigation ditches and meadows along the San Pedro River and the Babocomari River. The approximately 2000 Sobaipuri lived in 14 scattered agricultural-based settlements (Hendrickson and Minckley, 1984). Evidence that the river was unincised and marshy, at least at village sites, comes from mention of extensive ditches for irrigating beans, maize, cotton fields, and squash and statements that houses were made of poles and "reeds." The natives pursued an agricultural lifestyle until they fled from Apache attacks in 1762. Kino's journals also recorded marshy, cienega conditions along both rivers. Journals of a 1716 visit by Velvarde recorded similar conditions. Mexican settlers may have farmed in places along the San Pedro Valley before the Apaches drove them out (Davis, 1982). In May 1852, A. B. Clarke and other travelers followed the Upper San Pedro River for a day and replenished their water supplies from an abandoned irrigation ditch.

A contrary view to that of Hereford (1993) might be the assumption that Native Americans constructed sufficiently lengthy irrigation canals that extended northward from their origins at the river. If sufficiently long, such canals would be able to transport water onto farmlands above the level of the river because the origins of the canals would have been at higher elevations. (Elevations along the river decrease from south to north.)

Historical documents from the 1840s into the early 1880s suggest that the channel of the Upper San Pedro River at most locations was not entrenched until at least the early 1880s (Hereford, 1993). In 1846, the Mormon Battalion of approximately 100 military personnel and their accompanying supply wagons traversed the San Pedro River Valley as noted above (Davis, 1982). The battalion records reported no difficulty in crossing the river with wagons. The accounts of other travelers recorded that in 1859 the San Pedro River had a shallow bed that was almost level with the surrounding terrace, and that in 1875 the river was unentrenched and that a person could stoop and drink water from it at any point. Fish (Colorado pikeminnow) were present in the San Pedro River in sufficient numbers to be caught by early travelers and to be sold commercially in Tombstone, suggesting that the channel and flow conditions were quite different from those at present. An 1878 report noted that the Babocomari River was a clear stream about 20 feet wide and 2 feet deep, and with large cienegas in some places (Hinton, 1878).

A photograph (Fig. 23) taken in approximately 1890 shows conditions before the onset of arroyo cutting for the Babocomari and the San Pedro Rivers near their junction in the Fairbank area. Neither stream had a distinct channel. The Babocomari River was then represented by an irrigation ditch that wound sluggishly through a marshy and grass-filled plain. Trees were absent from the photo except for a grove on a mound that later was the site of the Fairbank railroad station.

Hendrickson and Minckley (1984) inferred from historical records that there were many cienegas and marshes along the Upper San Pedro and Babocomari Rivers before arroyo downcutting.

Localized discontinuous arroyos were present before the most recent episode of arroyo formation. Some visitors described localized steep banks as early as the 1850s (Huckleberry, 1996). On February 25, 1854, Lieutenant John G. Park, leader of a survey party, recorded that near the site of present Benson the river was about 12 feet below the surface of its banks and that such banks were nearly vertical (Davis, 1982). During the 1851 US-Mexico boundary survey, John Russel Bartlett recorded that at a place probably below St. David steep banks were approximately nine feet high and hindered irrigation of adjacent terraces (Bartlett, 1854; Davis, 1982). Mormon settlers encountered an entrenched channel of the river below St. David in 1877 (Hereford and Betancourt, 2009). In 1884, the anthropologist Adolph Bandelier visited the San Pedro and reported that at St. David it ran about 10 to 15 feet deep and about 25 feet wide (Hereford and Betancourt, 2009).Hereford (1993) suggested that accounts of steep banks near St. David and elsewhere did not necessarily indicate that the channel had begun its most recent entrenchment by this early date. He concluded that the accounts indicated the presence of local steep terrace rises near the river because of an earlier prehistoric phase of unrelated entrenchment during a previous episode of the alluvial cycle.

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Vegetation along the San Pedro River before arroyo cutting

Historical accounts and photographs from the 19th century document a complete change in hydrologic and ecological conditions along the river (Webb et al., 2007). James Ohio Pattie viewed the San Pedro River near its junction with the Gila River in March of 1825 and reported that the San Pedro River banks were well timbered with cottonwood and willow. (However, scholars have expressed skepticism about the accuracy of content in Patie. For example, Burt [2004] regarded the book as partly fiction and fact and concluded that the editor, Timothy Flint, might have written much of it. In the introduction to the book, the editor admits that he has been known as "a writer of works of the imagination.") The June 9, 1859 issue of the Tubac Weekly Arizonan (Davis, 1982) published an article by J. H. Wells who had camped about eight miles above the mouth of the San Pedro River. Wells reported that the camp was near the river and under the shade of large and beautiful trees but did not provide information on the number of such trees or the extent of the area occupied by them. Webb et al. (2007) concluded that the only documented 19th century gallery forests along the San Pedro River were near the confluence of it and the Gila River and that these forest were what Pattie observed.

Records from the 1840s to 1860s suggest many areas of the Upper San Pedro River had marshy, mostly treeless conditions (Arias Rojo, 2000; Hereford, 1993; Hereford and Betancourt, 2009; Huckleberry, 1996; Price et al., 2005; Webb et al., 2007). The pre-1850 San Pedro River apparently was mostly shallow and marshy and with the vegetation forming a mosaic of cienegas, sacaton grasslands, and more scattered riparian woodlands of cottonwood, willow, and ash. Before coalesced arroyos developed in the 1880s, groundwater levels along the lower San Pedro River were high enough to sustain marshes along much of its reach. The saturated floodplains and abundant marshy habitats resulted in mortality in Army encampments and settlements. For example, Mormon settlers who established St. David in 1877 were dying of malaria by the next year. In fact, the San Pedro River was infamous for malaria until the 1890s (Bahre and Bradbury, 1978). The floodplains near St. David supported alkali and Wright sacaton grassland with scattered patches of woody vegetation that included isolated and small groves of cottonwood and willow trees. The small dams built by thriving beavers may be a partial explanation for the high water tables in the alluvial aquifers.

Traveler accounts suggest that some portions of the river had trees while others had none. The accounts of the Mormon Battalion for 1846 (Davis, 1982) reported that the initial view of the San Pedro River Valley gave no appearance of the stream other than a few "ash trees" in the midst. However, the Battalion records reported that in the Charleston area each side of the river bottom had a dense thicket of "bramble bush, mostly musket, with which millions of acres are covered." On May 27, 1852 the traveler A. B. Clarke (Davis, 1982) followed the Upper San Pedro River for a day and recorded in his journal that "The road is pretty good down the splendid valley, although in some places rather rough, from thick tufts of grass, that have grown up in it since it has been used. Trees are becoming common on the river; its direction is indicated by them for a long distance. They are principally cottonwoods, with some sycamore, willow and mesquite." During an 1851 visit to the river, probably near St. David, Bartlett (Bartlett, 1854; Davis, 1982) recorded that his party emerged from an arroyo and entered a plain that was thickly overgrown with large mesquite bushes and largely destitute of grass. The party members looked in vain for a line of trees or luxuriant vegetation that might mark the course of the San Pedro River but suddenly found themselves upon its banks. Bartlett reported that the valley of the San Pedro River near their camp was anything but luxuriant. The grass was thin and poor and grew mostly in tufts beneath the mesquite that constituted the only shrubbery and that sometimes was as high as 10 or 12 feet. The party searched for better forage conditions and discovered better grass about three miles further south alongside springs of nearby water (probably a cienega). The party traveled approximately 18 miles due south along the valley through dense mesquite.

Published records (Emory, 1857, 1858) from a border survey in the late 1850s provide information about conditions then in the San Pedro River Valley. The San Pedro River had an uninterrupted stream of water running from the border to the Gila River. The valley consisted of an alluvial belt, variable in width and occasionally marshy. The report characterized the valley as suitable for irrigation and capable of producing large crops of wheat, corn, cotton, and grapes. The valley bottom was flanked by terraced tableland of unequal height, with hard gravelly soil and close growing "gamma grass." The comments about the suitability of the valley for irrigation and crop growing suggested that most of the river was not entrenched.

Rose (2013) examined testimony given during a water rights lawsuit in 1889 and various other historical documents. He concluded that in the 1880s extensive uninterrupted cottonwood forests did not line most of the upper San Pedro River. They were rather isolated individual cottonwoods or small stands of willows and or cottonwoods. They were historical records of wood mills in the Huachuca and Chiricahua Mountains and in the Dragoons that supplied timber for Tombstone and fuelwood for the mills at Charleston. However, there are no historical records of woodcutting along the San Pedro River. The wife of a mining executive recalled her pleasure in the fall of 1880 of finding that Millville had a single very large cottonwood tree.

Edgar Mearns visited the San Pedro River at the US and Mexican border in 1892 and 1893 (Webb et al., 2007). By this time, the arroyo had down cut. He reported a good-sized stream with fish and turtles but no marshes. Trees were limited to the edge of the channel and in addition to Fremont cottonwood included ash, sycamore, box elder, mesquite, black willow, and yew-leaf willow. He did not mention forests, and a photograph that accompanied his text showed scattered trees along the river. The only documented 19th century gallery forests along the river were downstream near the junction of the river with the Gila River. Cochise County court records for 1889 reported about an early suit over water rights and established that a large cienega once extended from approximately current day Benson to the former Tres Alamos (Turner et al., 2003).

In the 19th century, the river corridor between Fairbank and the US Mexican border was either barren or vegetated with alkali sacaton grasslands and scattered and open gallery stands of cottonwood trees and mesquite Webb et al. (2007). Some researchers have suggested woodcutting as an explanation for the open gallery stands. However, no stumps or other evidence of woodcutting are apparent in photographs of the floodplain.

Arroyo formation along the Upper San Pedro River

Stratigraphic analyses of tributaries of the San Pedro River along with similar studies of the Santa Cruz River and Whitewater Draw have provided important information for understanding the history of arroyo formation in the American Southwest (Waters and Haynes, 2001). The tributaries of the San Pedro River contain a stratigraphic record for about the past 40,000 years. The most thoroughly studied stratigraphy within such tributaries is in Curry Draw. The Lehner Ranch Arroyo and other tributaries have also provided important data. After approximately 7500 ^{14}C B.P., cycles of arroyo channel cutting and filling began. The first arroyo cutting was approximately 7500 ^{14}C B.P. and was followed by arroyo cutting at around 4000, 2600, 1900, 1000, and 600 ^{14}C B.P. Thus, six episodes of arroyo cutting are known to have occurred along the San Pedro River before European settlement. The most recent episode of arroyo cutting was within historic times, during the late 19th and early 20th century.

Newspaper accounts and other documents provided a flood history for the late 1800s to early 1900s (Hereford, 1993). In 1881, a dam upstream of Charleston was washed out, and the channel at Charleston widened and deepened. Floods in 1887 later destroyed this dam. Local newspapers recorded damaging floods in July, August, and September of 1887. In August 1890, large floods again caused damage in the Upper San Pedro River Valley. In August 1891, floods extensively damaged farms and the railroad through the upper valley. A large flood in August 1893 threatened Fairbank and cut railroad traffic south from Benson. In August 1894, large floods washed out a dam at St. David and damaged ranches along the river. Extensive flood related damage again was reported in July, August, September, and October of 1896. In 1900, flood weakened bridges delayed trains. Floods in February and August of 1904 and in January and March of 1905 damaged structures and shifted the channel locally.

The scanty and sometimes contradictory historical records suggest that significant channel widening and deepening occurred at various times and localities from the 1880s into the 1920s (Hereford, 1993; Hereford and Betancourt, 2009; Huckleberry, 1996; Turner et al., 2003). Such widening and deepening was associated with periods of unusually heavy rain. Reminiscences by Mary Wood in the Tombstone Epitaph in 1929 provided the first mention of active arroyo cutting. She recalled that an August 1881 flood destroyed a small dam near Millville and resulted in the widening and deepening of the riverbanks. Heavy rains in 1881 caused an overflow of the active river channel and erosion of the terrace on which Charleston was built. Two photographs in Turner et al. (2003) provided information about early entrenchment. An 1880 photograph at Charleston (plate 51a) showed a well-defined channel trench. A short distance away, neither the Babocomari nor the San Pedro Rivers was entrenched in a photograph taken at approximately 1890 (plate 57a). These photographs documented that arroyo formation began with a series of separate arroyos that later coalesced into the current arroyo along the San Pedro River. Recollections by ranchers suggest that neither the river nor tributaries were extensively entrenched upstream of Charleston before the 1910s and that the river channel was narrow and only approximately 1.5 to three feet deep. The approximately 20 miles of river between Fairbank and Hereford was probably entrenched in less than 18 years between the 1910s and 1920s. Further entrenchment of the river occurred during September 1926 floods. These floods were the greatest gauged to date for the river. The river channel at St. David was 59 feet wide in 1918, 151 feet wide in 1922 and widened to 351 feet during the 1926 floods. Webb et al. (2007) concluded that by the mid-1890s an arroyo spanned the length of the San Pedro River. This conclusion however does not mean that additional entrenchment could not have occurred for example between Fairbank and Hereford between the 1910s and 1920s. Huckleberry (1996) concluded that the entrenched channel reached its maximum width in the 1950s and that since then alluvium has been accumulating within the entrenched channel. Hereford (1993) agreed with Huckleberry as to dating of when the river reached its maximum width but concluded that aggradation began after 1937.

Webb and Leake (2006) summarized arroyo formation along the San Pedro River. Starting in the late 1870s, floods along the river started a process of downcutting and created a well-developed arroyo near the confluence with the Gila River by 1883. By 1892, this headcut had extended approximately 200 km upstream along the river. Widening of the channel began, with the overall geometry of the arroyo stabilizing by 1941. Photographs taken in the 1930s depicted a barren channel without stable floodplains within the arroyo walls. After 1941, a summer dominated flood regime facilitated the formation of low floodplains. A combination of mostly native woody species began to extend along these floodplains. During the mid-1960s the seasonality of flooding shifted to a pattern of predominantly fall and winter floods. Woody riparian vegetation increased despite the periodic sizable floods. Because of the arroyo cutting, surfaces that were formerly part of the floodplain became terraces elevated above the surface of the river (Huckleberry et al., 2009).

A 1904 fish survey by Frederic Morton Chamberlain (Minckley, 2009) provided information on the appearance of the river at Fairbank and Charleston in April of that year. Chamberlain reported, without specifying a particular location, that the subsurface water level had dropped approximately 6 feet during the two or three years before 1904. Just below Charleston, the river passed through a short canyon. The channel was 50 to 100 feet wide and had sand or gravel bottom and a few large boulders in some places. There were a few small pools, with the greatest depth being approximately 3 feet. The water was strongly impregnated with alkali and showed considerable alkali deposits. Vegetation was absent along the river, but watercress was abundant in a spring near a dam located below Charleston. At Fairbank, the channel or arroyo was about 100 feet wide and 15 feet deep. The river varied from five to 20 feet wide and from 1 inch to 2 feet deep. There was an 8 to 10 feet high dam across the river below the Southern Pacific railroad bridge. Large fish were absent from both places and Chamberlain reported that they probably were killed by cyanide from ore processing at Charleston when a mine was abandoned. Another factor that may have contributed to the loss of large fish was the problem as of 1885 of people harvesting them with dynamite (Brown, 2009). The process of arroyo formation, the accompanying drop in water table levels, and the associated loss of favorable habitats may by then have eliminated any large remaining fish.

Woody vegetation changes along the San Pedro River as a result of arroyo cutting

The San Pedro River has undergone alluvial cycles like other Southwestern rivers (Huckleberry et al., 2009). Each cycle began with channel downcutting or arroyo formation. The channel then widened because of it swinging laterally and causing bank collapses. The channel widening resulted in the creation of new alluvial surfaces for vegetation growth. The plants helped trap sediment and facilitated the backfilling of the incised channel. The San Pedro River has several times during the Holocene backfilled and reverted to a condition of streamflow across an unincised surface with relatively large areas prone to flooding and with frequent marshes.

Both cottonwoods and willows are obligatory phreatophytes and require groundwater for their survival (Stromberg, et al., 2009). Their abundance and age diversity along the San Pedro River are linked to groundwater availability. While individual cottonwood trees can grow in places where depth to groundwater may be 13 to nearly 20 feet or more, dense, multiple aged stands develop only where the groundwater averages less than approximately ten feet during the dry season and fluctuates by less than approximately three feet annually.

Cottonwood and willow abundance along the San Pedro River is also related to stream flows, and the forest becomes sparser as flows become more intermittent. This correlation probably exists because streamflow permanence is correlated with depth to the water table and degrees of fluctuation in water table height.

The nearly continuous distribution of Fremont cottonwood and Gooding's willow gallery forests along the Upper San Pedro River is a relatively recent development (Stromberg et al., 2009). Such trees occurred along the river before the 20th century but did not form the continuous gallery forest currently extending along much of the river. Before 1900, the river had a lower energy flood regime because floods and sediment inputs were attenuated by dense grasslands in the uplands and by dense growths of riparian grasses and marshy plants in the wide floodplain. There thus were fewer opportunities for the scouring types of floods that disturbance dependent tree species such as Fremont cottonwood and Goodding's willow require. The very large floods associated with turn-of-the-20th-century arroyo cutting and channel incision removed most of the vegetation from the river channel, including cottonwood and willow trees (Stromberg, 1998). The 1926 flood-of-record was especially important in removing riparian vegetation. The change in riparian vegetation along the San Pedro River represented one of the largest increases in woody riparian vegetation in the Southwest (Webb et al., 2007). (Because of the severe overgrazing described above, by approximately the early 1890s – rather than "before 1900" – there probably were no serious vegetation impediments to floods and sediments.)

Cottonwoods and willows became more abundant along the river during the 1920s to early 1940s and subsequently (Hereford, 1993; Stromberg, 1998; Stromberg et al., 2009). The San Pedro floodplain began to widen after a period of entrenchment in the late 1800s and early 1900s. Favorable flood conditions during the 1920s to early 1940s facilitated the establishment of cottonwoods and willows on the widening floodplains. During the 1940s, these trees occurred along the river but apparently usually only on one side at a time because of shifts in river positions.

Most of the San Pedro River cottonwoods and saltcedars date to years with winter (October-March) floods in the post-1960 era (Stromberg, 1998, 2010). After 1960, climatic fluctuations associated with the El Niño Southern Oscillation weather patterns created flood flow patterns more favorable to riparian tree establishment. Increased fall and winter floods favored the germination and growth of tree seedlings while decreased summer thunderstorms favored seedlings survivorship. The greatest establishment of current cottonwoods was during the 1960s with that decadal cohort occupying 24% of the floodplain. Cottonwoods established in the 1970s covered 15% of the floodplain (mostly along the active channel). Trees originating in the 1980s and 1990s covered only small bands at the channel edge or in overflow channels (6% and 4% of the floodplain, respectively). In 1993 the total area occupied by cottonwoods was distributed among decadal cohorts as follows: 1900s-1%; 1910s-0%; 1920s-4%; 1930s-7%; 1940s-11%; 1950s-0%; 1960s-36%; 1970s-24%; 1980s-10%; and 1990s-7% (Stromberg, pers. comm.).

Stromberg et al. (2010) analyzed a time series of aerial photographs from 1955 to 2003. The active channel that was wide in the 1930s decreased substantially during the study period. In contrast, because of the periodic erosion of terrace walls by large floods, the combined floodplain-channel area (post-entrenchment surfaces) increased by 14%. The percent of the post-entrenchment area covered by woody vegetation increased from 25% in 1955 to 62% in 2003. The increase was the result both of expansion of cottonwood-willow forest that increased nearly threefold, and of the increase in shrubland-woodland (primarily saltcedar and mesquite) that approximately doubled in area. Most of the cottonwood-willow forests mapped in 2003 arose from land that was bare ground in 1955. The shrubland-woodland arose mostly from pre-existing shrubland-woodland, bare ground, or grassland. The predominant cover types in the post-entrenchment zone shifted from bare ground and grassland in 1955 to shrubland-woodland and cottonwood-willow forest.

Although floods have been the primary disturbance that shaped the San Pedro River floodplain forests, fire also played a role (Stromberg et al., 2009). During much of the 20th century, reduced grassland cover, abundant livestock, and active fire suppression resulted in reduced fires that allowed for higher survivorship of cottonwoods.

Sacaton grasslands were formerly more abundant in the San Pedro watershed (Stromberg et al., 2009). These grasslands reduced the velocity of flood runoff and thereby reduced erosion rates, trapped sediments that enhanced soil fertility, and increased the infiltration of water that contributed to the occurrence of shallow water tables and perennial waterflow. Mesquite forests or sacaton-mesquite savannas now occur in many sites that were formerly sacaton grasslands. The mesquite increase occurred because of a complicated combination of climatic and human influences in the late 1800s and early 1900s. These influences included extreme flooding following extended drought, channel entrenchment, livestock over grazing, and alteration of fire regimes.

Webb et al. (2007) documented increases in woody riparian vegetation by studying 90 photographs taken along the length of the river from 1880 through 2003 and by examining data from other researchers. For example, photographs of monuments at the US Mexican border that were originally taken in 1892 and matched in 1969 and 1976 showed considerable increases in woody riparian vegetation along the river, primarily in Fremont cottonwood and mesquite. Another set of repeat photographs was at the confluence of the San Pedro River and Babocomari River. The first photographs were taken in 1890, and matching photographs were taken in 1962 and 1994. The photographic sets showed significant increases in woody riparian vegetation at the site.

Examples of repeat photographs included in this paper (Figs. 11-24) document a striking increase in woody riparian vegetation along the San Pedro River. (The photographs discussed below are arranged from south to north. There apparently are slight errors in the elevation associated with some of the photographs because some have a stated elevation slightly higher than stated elevations for more northern sites even though elevation of the river channel decreases from south to north.)

Five repeats sets were from the Palominas Area (Figs. 11-15). The 1953 view of the river in Fig. 11A showed an entrenched river with scattered cottonwood trees in the background. The 1981 view of Fig. 11B showed that cottonwood trees had become much more abundant on both sides of the river. Figures 11C and 11D depicted increasingly greater growth of cottonwood gallery forest along both sides of the river than in the previous two photographs of the site. In Fig. 12, the 1959 view of Fig. 12A showed an entrenched river with groves of cottonwood trees in the background along the right side of the river. The 1981 view of Fig. 12B illustrated that cottonwood gallery forest had grown up along both sides of the river. Such forest was increasingly prominent in Figs. 12C and 12D. Figure 13 provided upstream views of the river from the bridge east of Palominas. The 1939 photograph of Fig. 13A looked over open grassland toward mountains across the border in Mexico. There were scattered cottonwood trees along the right side of the shallowly incised channel, and vertical banks about five feet high showed in the mid-ground at the right. By the 1981 photograph of Fig. 13B small defoliated cottonwood and willows blocked out most of the background. The river channel was deeper, but the floodplain remained relatively free of woody plants. A flood of 22,000 ft^3/s had occurred in 1940, a flood of 16,500 ft^3/s in 1958, and a flood of 14,500 ft^3/s on October 9, 1977 (Webb et al., 2007). Despite such floods riparian vegetation increased since 1939. The 1995 photograph in 13C showed dense gallery forest composed of mostly cottonwoods along both sides of the river. In the 2000 photograph of Fig. 13D, gallery forest of cottonwoods and willows had become dense enough to obscure the view of the river. The 1930 view of the river in Fig. 14A showed an open countryside with scattered cottonwoods or other woody vegetation on both sides of the river. Entrenchment of the river was visible in the background. The photograph taken in 2000 for Fig. 14B showed that gallery forest had developed along the river channel in the background, along the left side of the river, and along part of the right side. The 1930 view of the river in Fig. 15A depicted open countryside and an entrenched river with a grove of trees in the background on the right side. Figure 15B showed that by 1981 the grove of trees on the right side had either grown closer to the camera station or that the camera station had been moved closer to the grove. The 1995 view of Fig. 15C demonstrated that the river channel had shifted and that cottonwoods were by then present on both sides of the river. In the 2000 photograph of Fig. 15 D, dense riparian gallery forest was present in the background along both sides of the river.

Five sets of repeat photographs for the Charleston area illustrate striking increases in riparian forests along the river. Figure 16 depicted the river just south of the Charleston Bridge. The first two photographs were taken from a camera station above the level of the channel while the third photograph was taken from a station along the river channel and looked northward toward the bridge. In the 1942 view of Fig. 16A, the east bank of the river had a dense growth of woody plants that probably were mostly mesquite. By the 1986 photograph of Fig. 16B, gallery forest of cottonwood and willows lined both sides of the river. In the 2009 photograph of Fig. 16C, gallery forest was evident along both sides of the channel. A 1943 photograph of Fig. 17A showed scattered cottonwood trees along the right side of the river. By the 1986 photograph of Fig. 17B, gallery forest was present along both sides of the river. In the 1995 photograph of Fig. 17C, defoliated riparian forest partially obscured the river. Gallery forest in the 2000 photograph of Fig. 17D obscured the view. The 1925 photograph of Fig. 18A depicted a channel devoid of trees. By the 2000 photograph of Fig. 18B, gallery forest lined the left side of the channel and cottonwood was visible to the right of the railroad tracks. Figure 19 depicted a view to the east, with the river flowing from the right to the left. In the 1954 photograph of Fig. 19A, scattered cottonwoods were visible along the far bank. By the 2000 photograph of Fig. 19B, cottonwoods, willows, and scattered tamarisk blocked much of the view.

Three sets of photographs from the Fairbank area document increases in woody vegetation. In the 1930 photograph of Fig. 20A, trees were absent except for some dark shapes in the background that possibly were trees. By the 2000 photograph of Fig. 20B, trees obscured much of the view. In the 1930 photograph of Fig. 21A, the channel was wide and with little low floodplain development. The only riparian vegetation present near the bottom of the channel was low shrubs. Most of the riparian plants were mesquite, although a cottonwood was visible in the left foreground (Webb et al., 2007). By the 2000 view of Fig. 21B, cottonwood blocked any view of the channel. The 1880 photograph of Fig. 22A depicted stage one of the alluvial cycle. The narrowly entrenched San Pedro River lay just to the east of Charleston and had relatively little riparian brush. A single cottonwood tree occurred on its banks. By the 1960 photograph of Fig. 22B, young cottonwoods lined the river. An earthquake in 1887 had leveled Charleston, and the town had disappeared into the new growths of mesquite (Turner et. al, 2003). In the 1994 photograph of Fig. 22C, the cottonwood and willow trees lining the river were larger.

A set of two repeat photographs (Figs. 23-24) from near St. David depict a striking development of gallery forest. In an approximately 1890 photograph (Fig. 23A), the view was from a hill overlooking the west side of the San Pedro River and was from the east to the northeast, with the Dragoon Mountains visible in the background. The river channel (opposite banks indicated by left most arrows) was barely discernible in the mid-ground and had isolated small trees and shrubs along it and flowed through what appeared to be an alkali sacaton grassland. Mesquite dominated the foreground slopes. In a 1962 photograph (Fig. 23B), the river had deeply cut into the hill from which the first photograph was taken. The new camera location was approximately 100 feet northwest of the former. The dike at the left of the photograph was part of a project to divert the river into a new channel, visible at the center and approximately online with the water in the old photograph. Woody vegetation obscured the deeply incised channel of the San Pedro river. The junction of the two waterways was out of the photograph, to the left. The valley floor had dense growths of mesquite, cottonwood, and Gooding willow. In a 1994 photograph (Fig. 23C) a forest of cottonwoods, Gooding willows, and mesquite occupied the valley floor that was predominantly marshy or grass covered in the first photograph.

A set of two repeat photographs from near St. David depict a striking development of gallery forest. In an approximately 1890 photograph (Fig. 23A), the view from a hill was southeast across the junction of Babocomari River (possible eastern bank indicated by lower left most arrow) and the San Pedro River (upper arrow). By 1962 photograph (Fig. 23B), the river had deeply cut into the hill from which the first photograph was taken. The new camera location was approximately 100 feet northwest of the former. The dike at the left of the photograph was part of a project to divert the river into a new channel, visible at the center and approximately online with the water in the old photograph. Woody vegetation obscured the deeply incised channel of the San Pedro river. The junction of the two waterways was out of the photograph, to the left. The valley floor had dense growths of mesquite, cottonwood, and Gooding willow. In a 1994 photograph (Fig. 23C) a forest of cottonwoods, Gooding willows, and mesquite occupied the valley floor that was predominantly marshy or grass covered in the first photograph.

A 1890 photograph (Fig. 24A), provides a view from a hill overlooking the west side of the San Pedro River and was from the east to the northeast, with the Dragoon Mountains visible in the background (Webb et al., 2007). The river channel (opposite banks indicated by arrows) was barely discernible in the mid-ground and had isolated small trees and shrubs along it and flowed through what appeared to be an alkali sacaton grassland. Mesquite dominated the foreground slopes. In the 2003 photograph of Fig. 24B, the camera station was lower because of blading of the hilltop. The gallery forests along the river channel had become striking in appearance, greatly increasing in size, density, and species composition (Webb et al., 2007). Cottonwood was the dominant tree with interspersed Gooding's willow, ash, fourwing saltbush, and tamarisk. The foreground vegetation had also increased and included mesquite, catclaw, greythorn, crucifixion thorn, Lehmann's lovegrass, and tumbleweed.

In summary, woody riparian vegetation began expanding after channel widening ceased in the 1940s. This expansion was unchecked from approximately 1960 to the present. Particular increases in woody vegetation in the late 1970s and early 1980s were associated with winter floods that enhanced the potential for germination and the establishment of trees such as cottonwoods.

Conclusions

The San Pedro River and other southwestern waterways have a lifecycle somewhat analogous to the mythological Phoenix bird. However, these waterways are liquid phoenixes. Each riparian habitat stage in time gives way to another habitat stage whereby the waterways continually replenish themselves through the changes engendered by the alluvial cycle. During one habitat cycle, the waterways are shallowly incised, with many marshes and cienegas along them, sometimes with many large fishes in them, and with riparian trees such as cottonwood and willows locally abundant in some places but not forming extensive gallery forests. The riparian trees are then only locally abundant because most places have water tables too high for such trees and there are relatively few scouring floods that prepare the substrate for the establishment of tree seedlings. This habitat cycle may persist for many years. Ultimately, it gives way to episodes of arroyo formation, widening and coalescing. These entrenchment episodes can occur relatively rapidly, over a period of a few decades. For a short time, riparian vegetation along waterways is reduced because of the scouring effect of floods during the entrenchment episodes. Alluvial water tables drop relatively rapidly during entrenchment because water drains away through the newly entrenched channels. This natural lowering of water tables is one of the prerequisites for future establishment of extensive stretches of riparian woodland gallery forest. When the scouring floods become less common and less severe, waterway channels begin to narrow, and aggradation or the deposit of sediment begins to occur. The aggradation provides suitable habitats for riparian woodlands. Over a period of just a few decades, riparian trees such as cottonwoods and willows may form extensive gallery forests along waterways with perennial water. Waterways continue to fill in over hundreds of years, the water table level of alluvial aquifers naturally rises as waterways fill in, and habitats gradually shift back to the initial conditions of shallowly incised channels with many marshes and cienegas.

There were at least seven episodes of arroyo formation in the Southwestern United States. Six of them were prehistoric. The most recent episode occurred from approximately

1860 into the 1920s. There is consensus among scientists that flowing water moves sediments and that downcutting occurred during floods. Flowing water, especially that of large floods, is the common denominator for all arroyo formation.

Scientists disagree about the other causes of the most recent episode of arroyo formation. The reason for such disagreement is probably that many workers have attempted to oversimplify the great complexity found in nature. There is no reason why there must be a single explanation for arroyo formation. Overgrazing promoted some arroyo formation. In some places, human activities such as the construction of drainage canals or embankments resulted in a concentration of floodwaters that promoted arroyo formation. Other human activities such as the cutting of trees and clearing of land for agriculture may have facilitated arroyo formation. There is no firm evidence to indicate that human activities caused the multiple prehistoric episodes of arroyo formation. Many researchers believe that regional increases in precipitation were a crucial factor promoting synchronous regional arroyo formation. The observations of a geologist in Utah show how heavy precipitation and the pre-existing topographic features of a landscape can result in arroyo formation. The above explanations are not contradictory, but instead they are complementary. Attempts to find a single cause for arroyo formation are doomed to failure because there were multiple causes. Additional future research will help delineate the relative importance of potential causes for the various arroyos currently found in the Southwestern United States.

The Upper San Pedro River has undergone the same changes from the alluvial cycle as those that occurred in other southwestern waterways. When European settlers first arrived, the river was a shallow channel with many marshes and cienegas and with riparian trees locally abundant but not extending to form long stretches of riparian gallery forest. Visitors and settlers found in the river fish that were as large as three feet in length. The river underwent entrenchment along with other southwestern rivers, and habitats greatly changed and over the period of a few decades became those of today.

The current widespread extent of cottonwood and willows is a legacy (Dixon et al., 2009) of several decades of channel narrowing and vegetation recruitment that followed the extreme channel widening during the late 19th and early 20th century. These large stands of forest are not in equilibrium with the currently low rates of channel dynamics and small areas of seedling recruitments. Analyses of computer-generated models suggest that these forest areas are already in decline and will probably decrease by approximately 2/3 in coverage from 2003 to 2103 (Dixon et al., 2009).

Studies on tributaries of the San Pedro River have been of crucial importance in helping scientists understand the sequence of prehistoric episodes of arroyo formation. Continued preservation of the river will provide an important resource in which scientists can conduct studies to understand better the geology and biology of southwestern rivers.

If humans refrain from removing water from the San Pedro River Valley, the river habitat will probably follow the course outlined by Stromberg, et al. (2009). The surfaces now occupied by cottonwood and willow trees will become elevated because of accretion of sediments around the tree bases and the incision of the channel. The frequency of flood inundation will decline in such raised areas, and the depth to groundwater will increase. The soil of these raised areas will accumulate additional organic matter, silt, clay, and litter cover. Cottonwoods and willow seedlings do not establish in their own understory and therefore will not reestablish seedlings on the elevated surfaces. Forest composition will gradually shift toward plants more adapted to drier and more stable conditions, such as mesquite and net-leaf hackberry. Sacaton grassland will become more predominant in the inter-spaces and understory of old cottonwood stands. The river channel will continue to fill in. Over time the river will gradually return to conditions of stage 0 (Fig. 1, 0) of the model proposed by Webb and Hereford (2010).

The drop in water tables that occurred with arroyo formation should not be confused with the more drastic changes in water tables that have recently resulted from excessive pumping of water from underground aquifers. Drops in water tables with arroyo formation are natural phenomenon and generally correspond to the depth of arroyos. In contrast, the drops in water tables resulting from excessive pumping of water are not associated with the natural process of arroyo formation and are limited only by the bottom of the aquifers. For example, in the Sierra Vista region of southeastern Arizona a cone of depression has developed because of excessive pumping of water (ADWR, 2005). Between 1940 and 1961 a decline of up to 50 feet in the groundwater level occurred. Measurements in 1978 indicated drops of water tables as much as 4 feet in some years. From 1990 to 2001 water levels in the cone of depression dropped from approximately 10 to 35 feet, depending on exactly where the water table is measured.

Water is the lifeblood that permits the existence of the current assortment of riparian plants. It also is the driving force behind the naturally occurring alluvial cycle. Through this cycle of habitat succession, riparian habitats establish themselves and then give way to other habitats. Removal of water will result in the production of a barren wash, nearly devoid of life, and similar to the wash along the former course of the Santa Cruz River in the Tucson area. The human destruction of the once thriving riparian ecosystem in the Tucson area serves as a warning to everyone. If humans refrain from removing water, the natural lifecycle of habitats along the San Pedro River will continue to progress through the alluvial cycle. The river will remain a dynamic and ever-changing liquid Phoenix.

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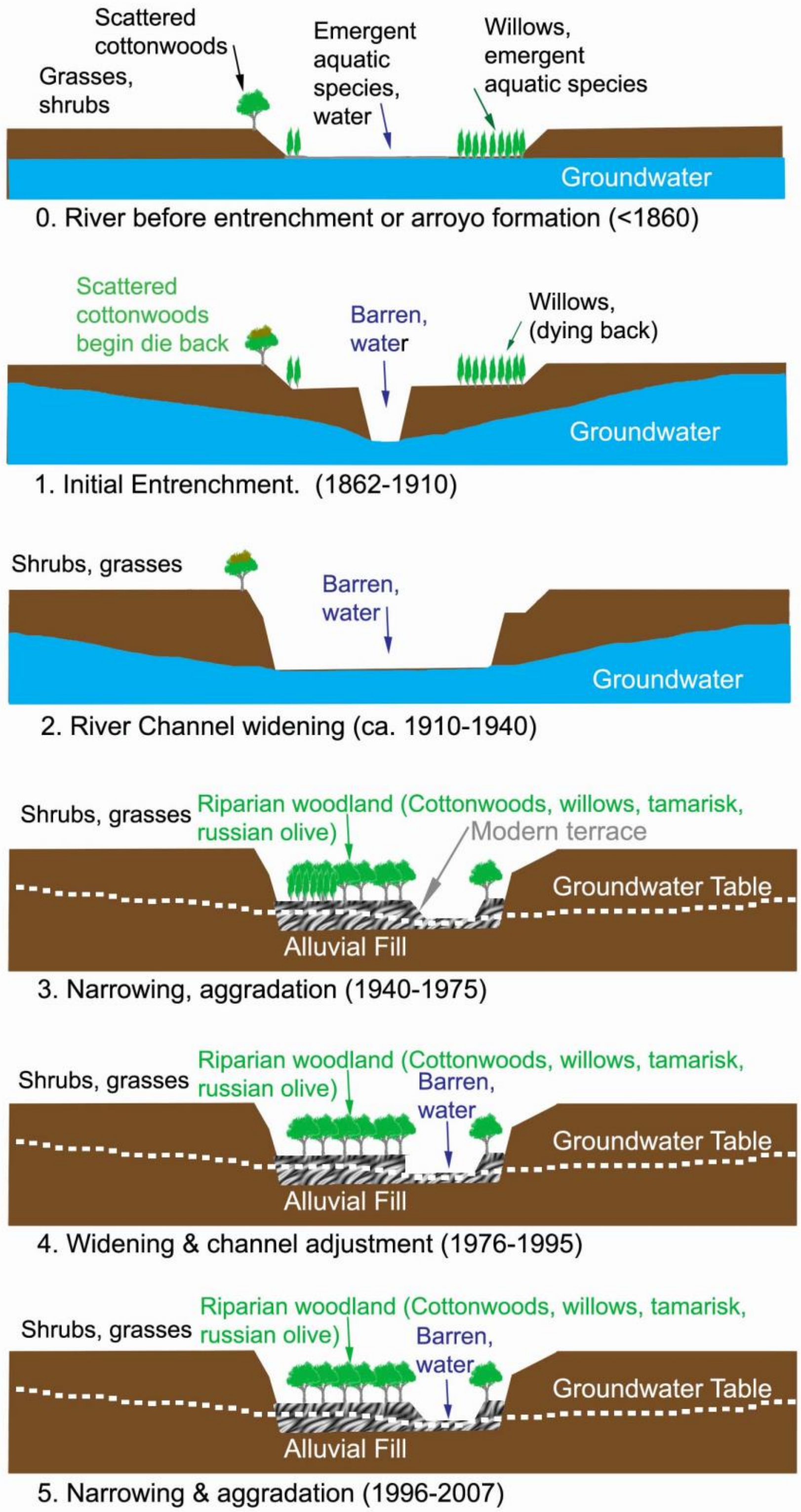


Fig. 1. Alluvial Cycle from settlement to present, in S. Utah & Arizona. Many exceptions to the generalized model occurred, especially where stages 4 & 5 did not occur. (Adapted from Webb & Hereford, 2010.)

Figs. 2-3. San Pedro River. G. R. Noonan. Fig. 2. Deeply incised river banks near the San Pedro House. Fig. 3. Entrenched channel just north of Charleston Bridge. Arrows point to banks.

Figs. 4-5. A belt of gallery forest lines much of the Upper San Pedro River. G. R. Noonan. Fig. 4. View looking E from terrace on rte 90. Fig. 5. View looking E from San Pedro House.

Fig. 6.

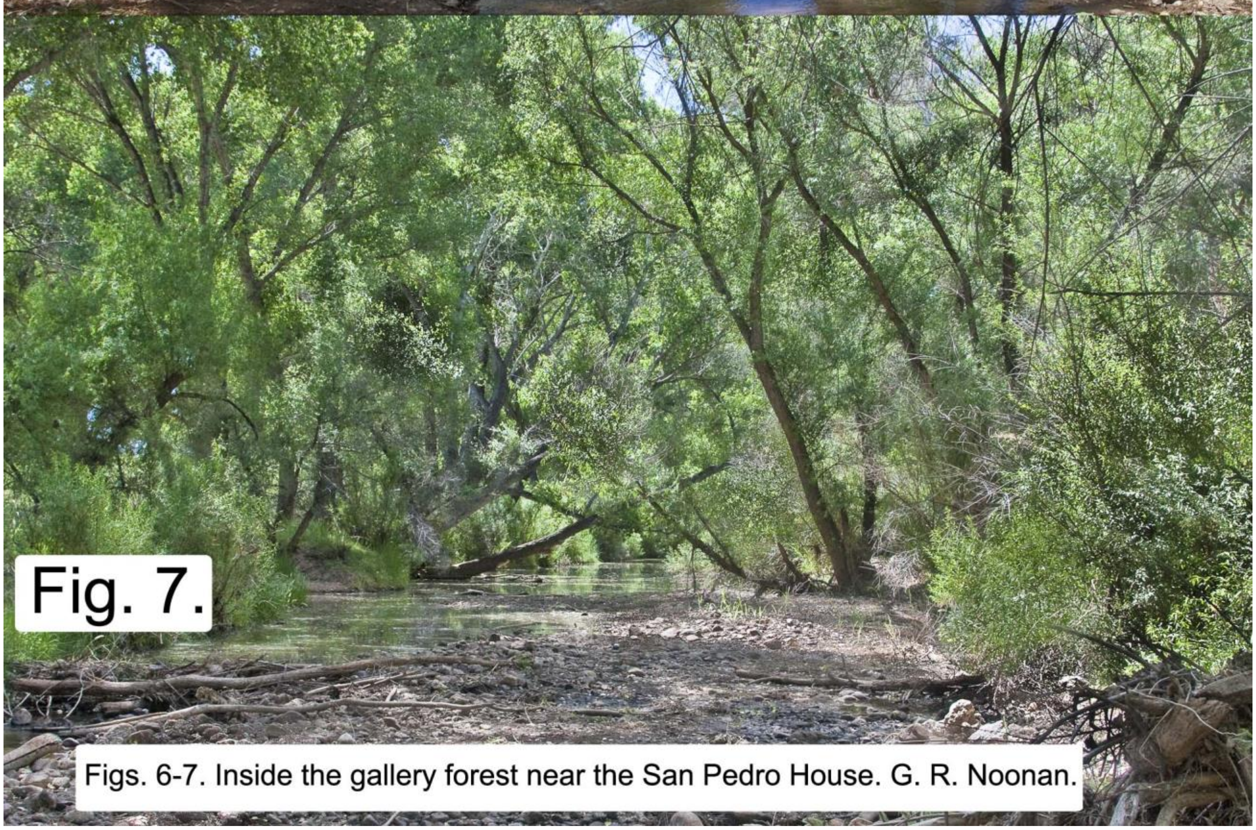


Fig. 7.

Figs. 6-7. Inside the gallery forest near the San Pedro House. G. R. Noonan.

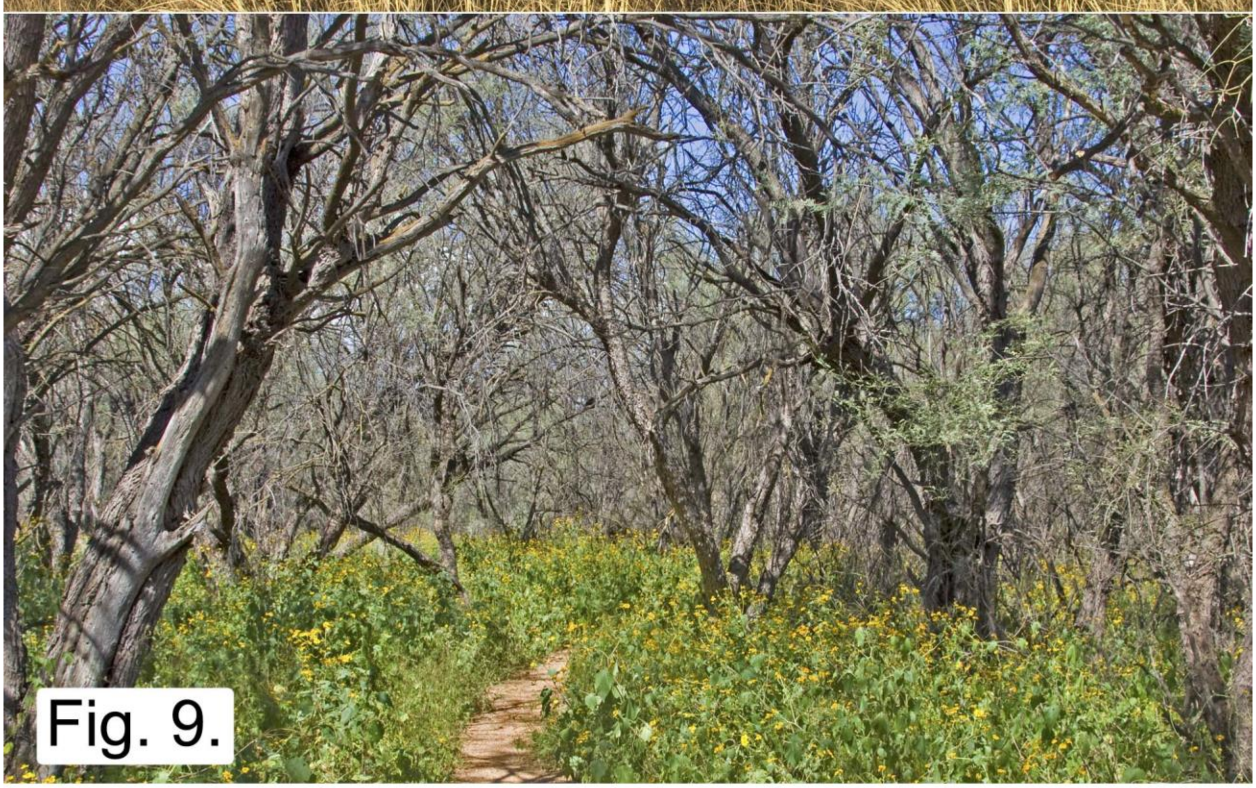


Fig. 8. Sacaton grassland near Green Kingfisher Pond. Fig. 9. Mesquite bosque near Fairbank. G. R. Noonan.

Fig. 10. St. David Cienga (ca. between arrows, from background to foreground). J. Mahoney, Bureau of Land Management.

Fig. 11A.

Fig. 11B.

Fig. 11C.

Fig. 11D.

Fig. 11. Palominas Area 31.379883333333 -110.111266666667. Stake 1011. 1289 m. **A**. Aug. 13, 1953, P. Nady. **B**. Jan. 23, 1981, R. M. Turner. **C**. Feb. 7, 1995, D. P. Oldershaw. **D**. Oct. 8, 2000, D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 12A.

Fig. 12B.

Fig. 12C.

Fig. 12D.

Fig. 12. Palominas Area 31.379900000000 -110.111466666667. Stake 1008. 1289 m. **A**. Nov. 2, 1959, WDM. **B**. Jan. 23, 1981, R. M. Turner. **C**. Feb. 7, 1995, D. P. Oldershaw. **D**. Oct. 8, 2000, D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 13A.

Fig. 13B.

Fig. 13C.

Fig. 13D.

Fig. 13. Palominas Area 31.379950000000 -110.110933333333. Stake 1009. 1289 m. **A**. May 24,1939, R. H. Monroe. **B**. Jan. 23, 1981, R. M. Turner. **C**. Feb. 7, 1995, D. P. Oldershaw. **D**. Oct. 8, 2000, D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 14A.

Fig. 14B.

Fig. 14. Palominas Area 31.380016666667 -110.111050000000. Stake 1954.1289 m. **A**. April 17, 1930, W. E. Dickinson. **B**. Oct. 8, 2000, D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

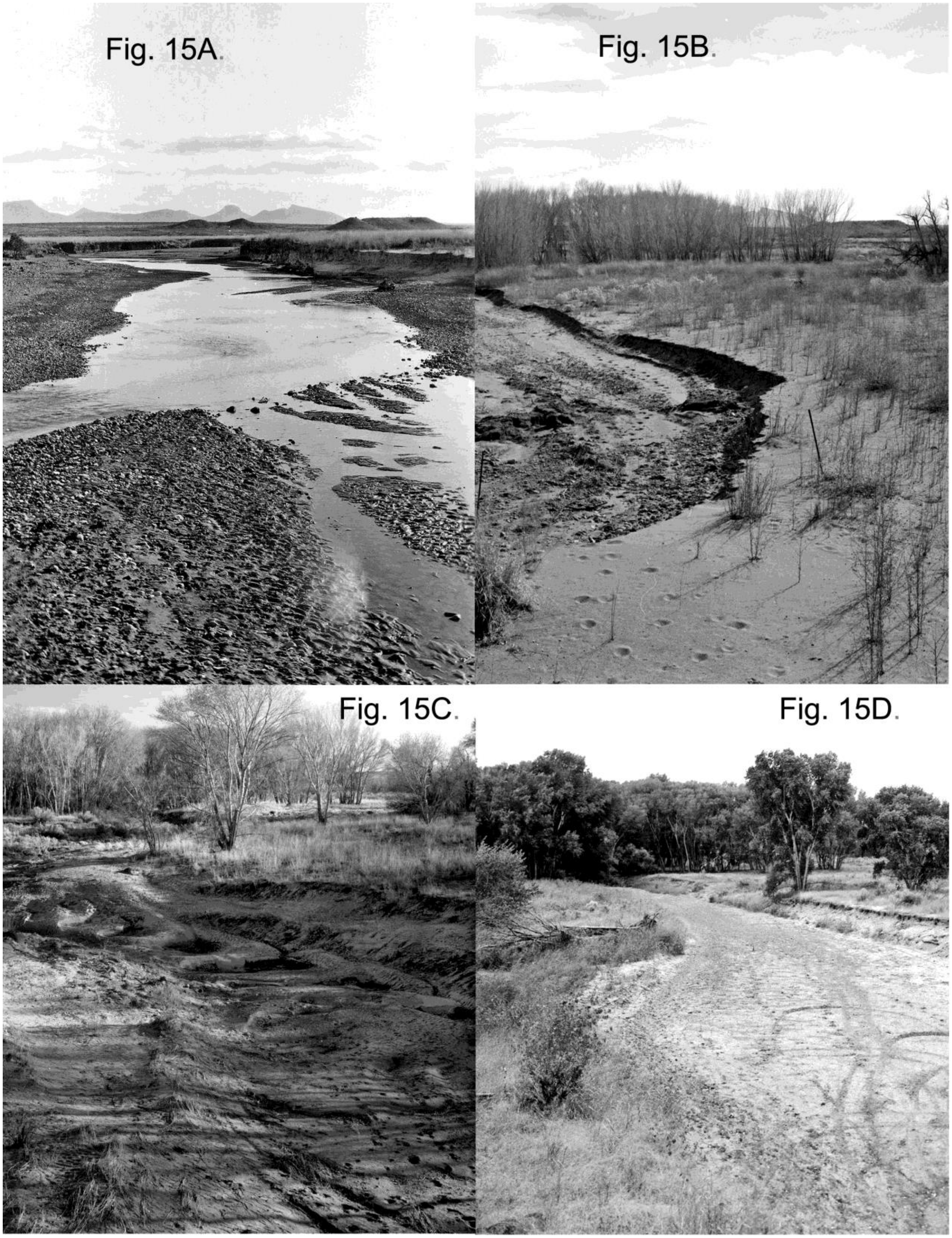


Fig. 15. Palominas Area 31.383250000000 -110.110766666667. Stake 1007. 1292 m. **A**. April 17, 1930. **B**. Jan. 23, 1981, R. M. Turner. **C**. Feb. 7, 1995, D. P. Oldershaw. **D**. Oct. 8, 2000, D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 16A.

Fig. 16B.

Fig. 16C.

Fig. 16. Charleston Bridge, South Side 31.626100000000 -110.174150000000. Stake 946. 1211 m.
A. Dec. 14, 1942, Wandke. **B**. June 15, 1986, R. M. Turner. **C**. Nov. 9, 2009, G. R. Noonan, view looking N. at bridge from within arroyo. (17A & 17B courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 17A.

Fig. 17B.

Fig. 17C.

Fig. 17D.

Fig. 17. Charleston area 31.626000000000 -110.174366666667. Stake 945. 1219 m. **A**. June 11, 1943, C. T. Pynchon. **B**. June 15, 1986, R. M. Turner. **C**. Feb. 19, 1995, D. P. Oldershaw. **D**. 2000. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 18A.

Fig. 18B.

Fig. 18. Charleston Area 31.638850000000 -110.175283333333. Stake 289. 1212 m.
A. Jan. 4, 1925, W. E. Dickinson. **B**. July 29, 2000, D. P. Oldershaw.
(Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 19A.

Fig. 19B.

Fig. 19. Charleston Area 31.639900000000 -110.177516666667. Stake 296. 1219 m. **A**. May 4, 1954, C. A. Baker. **B**. July 29, 2000, R. M. Turner. (**C**ourtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 20A.

Fig. 20B.

Fig. 20. Fairbank Area 31.643116666667 -110.179566666667. Stake 295. 1238 m.
A. April 17, 1930, W. E. Dickinson. **B**. July 29, 2000, D. P. Oldershaw.
(Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

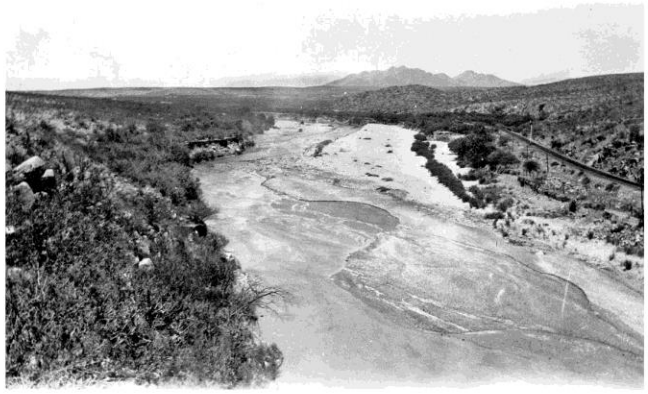


Fig. 21A.

Fig. 21B.

Fig. 21. Fairbank Area 31.643250000000 -110.179850000000. Stake 293. 1218 m.
A. April 17, 1930, W. E. Dickinson. **B**. July 29, 2000, D. P. Oldershaw.
(Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

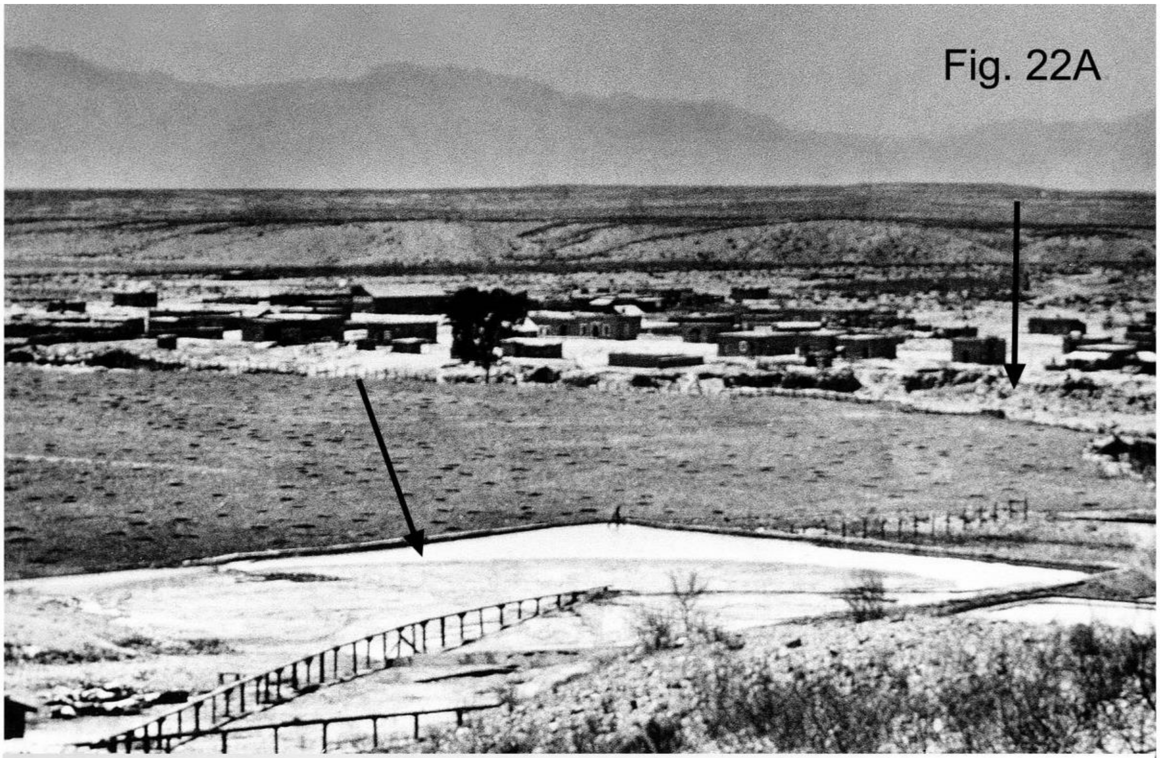


Fig. 22. Charleston. 31.6608 -110. 1228 m. **A**. 1880. C. E. Watkins. **(C**ourtesy of the Arizona Historical Society/Tucson, AHS Photo Number 14819. Places-Charleston) Vertical arrow denotes narrowly entrenched San Pedro River. Slanted arrow points to tailings pond associated with Gird Mill. **B**. 1960. Stake 61. James R. Hastings. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 22C. Charleston. 31.6608 -110.1942. Stake 61. 1228 m. 1994. D. P. Oldershaw. (Courtesy of the USGS Desert Laboratory Repeat Photography Collection).

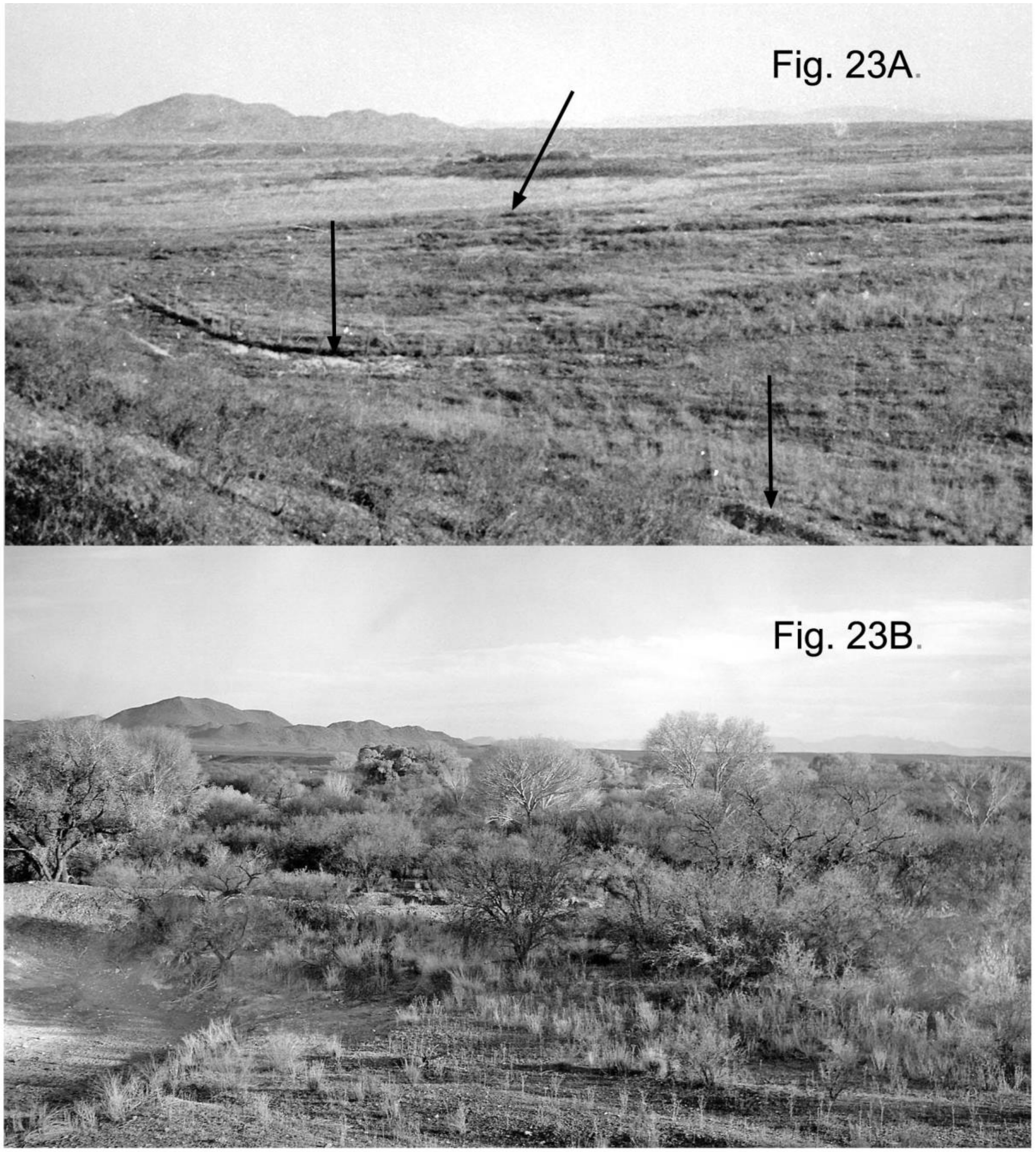
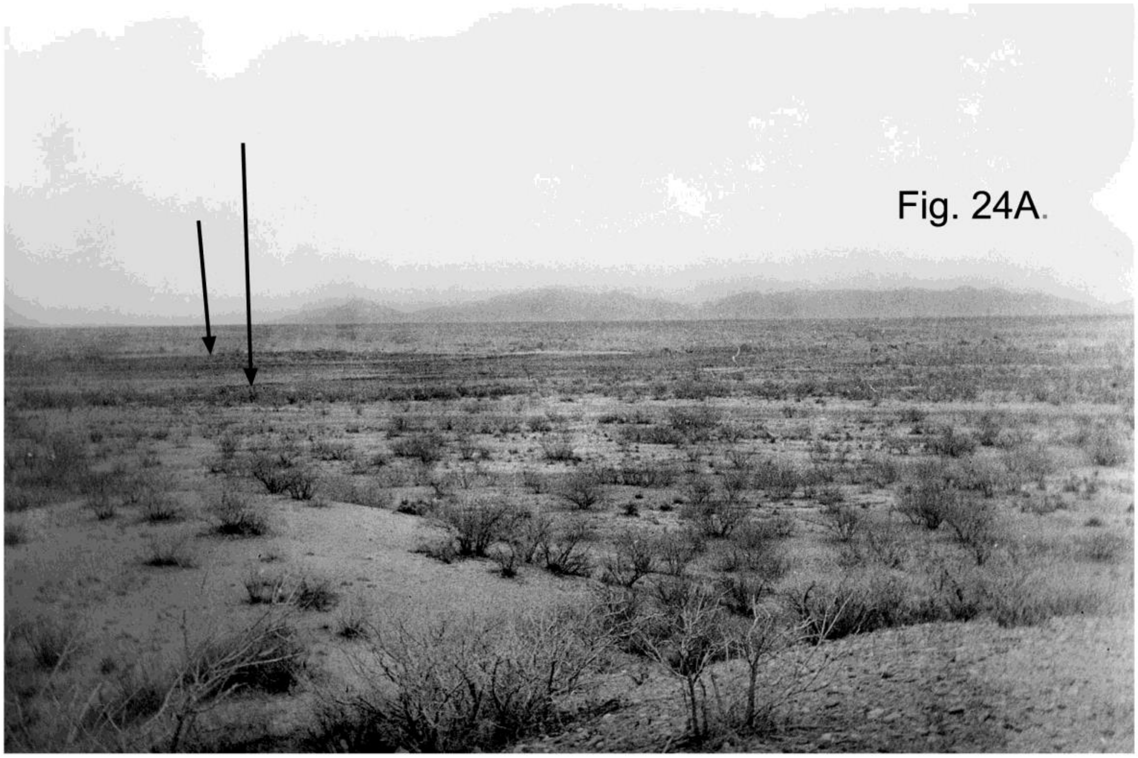


Fig. 23. Fairbank Area. 31.7222 -110. 1167 m. **A**. ca. 1890. Junction Babocomari & San Pedro Rivers. G. Roskruge. **(C**ourtesy of the Arizona Historical Society/Tucson, AHS Photo Number PC114_B2_F31_46404.) Right most vertical arrow denotes irrigation ditch. Left most vertical arrow indicates open water. Slanted arrow points to San Pedro River. **B**. 1962. Stake 150. J. R. Hastings. Babocomari River channel (left side foreground). Brush obscures view of San Pedro River. **(C**ourtesy of the USGS Desert Laboratory Repeat Photography Collection).

Fig. 23C. Fairbank Area. 31.7222 -110.1964. Stake 150. 1167 m. D. P. Oldershaw. 1994. Babocomari River channel (left side foreground). Brush obscures view of San Pedro River. **(C**ourtesy of the USGS Desert Laboratory Repeat Photography Collection).



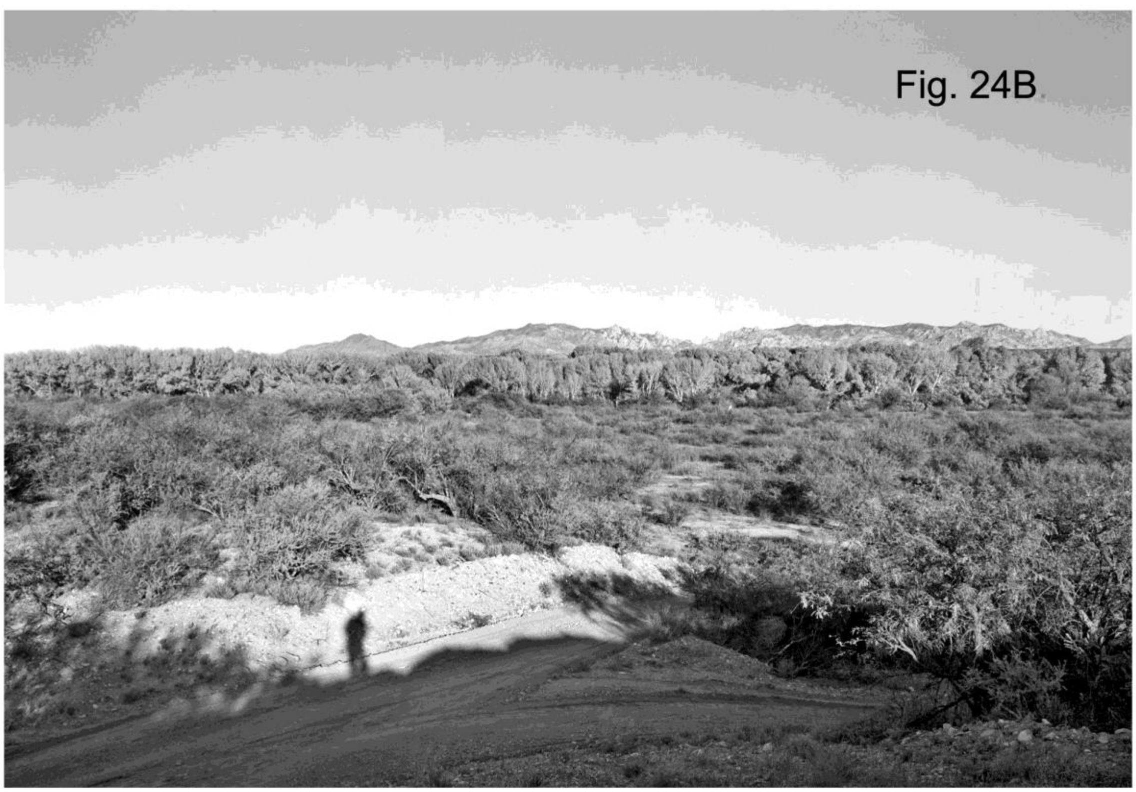


Fig. 24. Apache Powder Site, NE end MacFarland's Hill. 31.871280000000 -110.222470000000. 1112 m. **A**. ca. 1890, G. Roskruge. (**C**ourtesy of the Arizona Historical Society/Tucson, AHS Photo Number PC114_B2_46420.) **B**. Nov. 20, 2003. Stake 3734, R. H. Webb. (**C**ourtesy of the USGS Desert Laboratory Repeat Photography Collection).