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CLIMATE INFLUENCES ON STREAM PROCESS IN YELLOWSTONE OVER THE LAST 7000 YEARS: A LOOK AT THE STRATIGRAPHIC RECORD

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INTRODUCTION

Yellowstone National Park (YNP), America's first National Park, experienced many different management strategies since its inauguration. By 1926, wolves were essentially eradicated from YNP as part of a widespread predator control program throughout the United States. Park managers, concerned that the excessively large elk populations were degrading riparian habitat in elk wintering areas, employed a widely unpopular elk-culling program in the 1960s (Keiter & Boyce, 1991). In 1995, in an attempt to restore the ecosystem, the NPS reintroduced gray wolves to the park (Wolf, Cooper, & Hobbs, 2007). This sequence of management decisions coincided with major variations in YNP ecosystems, leading to debate over the impacts of wolves in the park.

The Northern Range encompasses the northern portion of YNP at low elevation with minimal snowpack where the northern elk herd spends winters (Yellowstone National Park 1997). Impacts to the ecosystem related to wolf removal and restoration is the subject of significant debate (Yellowstone National Park 1997). When wolves were removed in the early 1900s, elk overconsumed willows and other woody plants along streams, depriving beaver of their food and dam-building materials. Beavers were effectively outcompeted for resources and extirpated from the ecosystem (Chadde & Kay 1991). Beschta and Ripple (2018) suggest that overconsumption of willows lowered root density in the stream banks, reducing their shear strength and increasing erodibility in floods, resulting in incised and widened streams. Following wolf reintroduction in 1995, some streams experienced taller willow, evidence of beaver activity, and a new inset floodplain (Beschta and Ripple 2018). These observations suggest that stream channels have begun to "recover" due to trophic cascade-initiated ecosystem processes. Similarly, songbird and bear populations increased during this period, which Ripple & Beschta (2012) tie to trophic cascades after wolf restoration. Other studies support the trophic cascade hypothesis as a driver for ecosystem change following wolf removal, but consider changes irreversible: Marshall, Hobbs, & Cooper (2013) compared willow regrowth in areas with and without artificial damming and elk herbivory, and found that without beaver damming, excluding elk did not result in significantly increased growth of willows. They concluded that willows could not recover following stream incision they connect to wolf removal. Others question the trophic cascade mechanism for willow recovery due to lack of evidence of recovery (Kauffman et al. 2010) or insufficient replication, control, or acknowledgement of other potential causes in trophic cascade studies (Ford & Goheen 2015; Peterson et al. 2014).

Commonly the late 19th and early 20th centuries, prior to wolf removal, is used as a guide for the natural condition of the YNP ecosystem. The period was, however, the wettest period in the past 700 years, followed by an unusually dry period (severe droughts in the 1930s and 1950s) during the time that wolves were absent (Gray et al. 2007). Climatic variability may be an important factor in the ecosystem changes and stream dynamics in Yellowstone. For example, previous radiocarbon dating work on streams in the Northern Range indicate that beaver abundance and channel aggradation can be influenced by millennial scale climate changes (Persico and Meyer 2013). Fire, which is often concurrent with dry periods in YNP, is

also a major control on stream dynamics (Meyer et al., 1995). Aggradation of alluvial fans occurs during warm periods, because periodic intense rain events after drought and fires trigger voluminous hillslope sediment transport and debris flow deposition on fan surfaces. This same process could also result in floodplain aggradation. Legleiter et al. (2003) also connect fires to stream morphology changes in YNP. Immediately after fires, excess sediment transported from hillslopes take 5-10 years to move downstream. Higher discharges on the sediment-depleted landscape then result in incision (Legleiter et al. 2003). These previous studies clearly link climate and stream changes.

We hypothesize that beaver pond deposits will be more frequent during wet periods, while fire-related deposits and floodplain aggradation will occur more during periods of drought. In order to determine the relationship between climate, beaver activity, and stream incision/aggradation in YNP, we compare the record of stream deposits, including beaver activity with climatic records over the last 7000 years. Dated beaver-pond sediments will provide information about the times that beaver activity was high over this period, while ages of different surfaces such as floodplains will constrain the timing of stream deposition and incision. Climate-related trends in beaver-pond deposits over the late Holocene will draw into question the singularity of the trophic cascade hypothesis as a mechanism for ecosystem change.

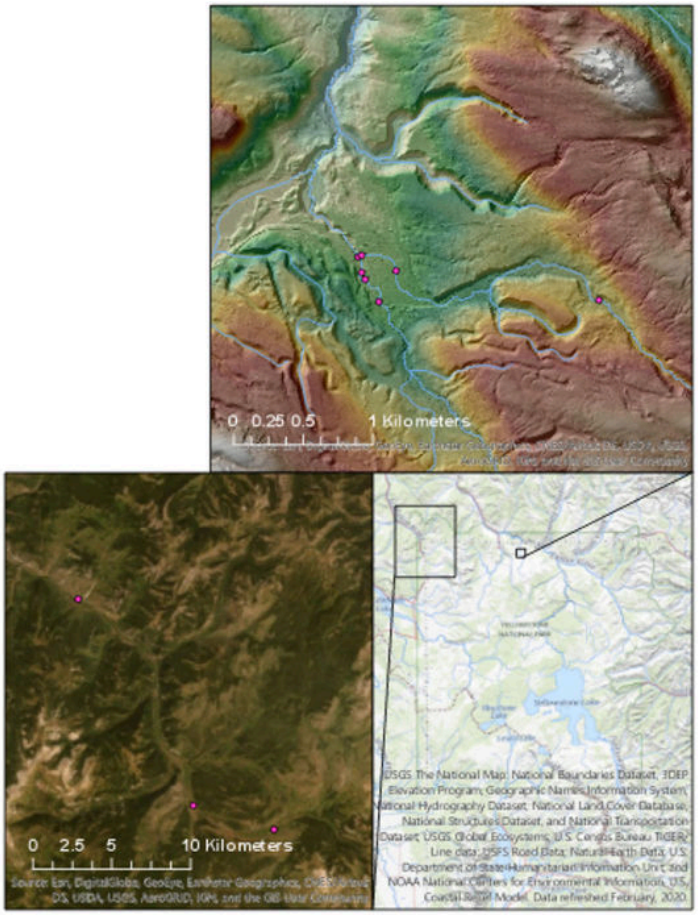

Figure 1. Blacktail Deer Plateau sampling sites (top) and Gallatin River sites (left) where we dated radiocarbon samples are identified here with pink dots, compared to their position in Yellowstone National Park (bottom right). Topographic surface is courtesy of LIDAR data provided by NEON.

If climate plays a major role in controlling ecosystem and stream dynamics in YNP, future aridification of the west could be an important influence on stream behavior in addition to trophic cascade events.

METHODS

We spent four weeks during the summer of 2019 in the Northern Range of Yellowstone National Park collecting data for this project. The project focused on Blacktail Deer Creek and the Gallatin River, as both are locations where channels have possibly changed by trophic cascade-related events (Beschta & Ripple, 2006, and 2018). The East and West Forks of Blacktail Deer Creek drain 27 and 35 square kilometers, respectively. Radiocarbon samples were collected along 12 sites on the Blacktail Deer Plateau, near the north entrance of Yellowstone, and at 9 sites along the Gardiner River, in northwest YNP (Figure 1).

Sources sampled for radiocarbon included cutbanks, terraces, floodplains, and beaver pond deposits, which will provide information of beaver activity, rates of deposition of streams, and ages of geomorphic surfaces over the last 7000 years, independent of wolf removal. The majority of these sites are within the elk winter range, where the impacts of elk overpopulation caused by wolf removal (including stream widening and reduced beaver populations) would be most apparent. Areas we sampled that extend beyond the northern range of the elk herd should exhibit completely different geomorphic characteristics, if wolf control of elk populations are the main factors influencing stream morphology in this area.

Sample collection: At each site, I cleared a fresh,

Table 1. All samples collected and dated for this study.

Sample Name	Stream	Depth of sample (cm)	Material	Interpretation	Cal yr. BP	1 σ	Weighted Cal yr. BP	Easting	Northing
2019EBTwallow5	EBT	11	1 charcoal fragment	A horizon	64	22	n/a	532638	4977785
2019WBT4	WBT	62	3 pinecones	Beaver deposit	Modern		n/a	532372	4977890
2019WBT6	WBT	25	1 charcoal fragment	Slip off terrace	34	21	n/a	532422	4977724
2019EBT16	EBT	10*	1 charcoal fragment	Very fine grained deposit	961	24	860	534099	4977578
2019WBTBS6	WBT	79	1 charcoal fragment	Floodplain deposit	1098	32	1010	532524	4977569
2019WBTBP7	WBT	60	Beaver chewed wood	Beaver deposit at water table	52	24	n/a	532596	4977437
2019BanGal6	Gallatin	100	Beaver chewed wood	Beaver pond wood	3457	27	3730	501142	4973756
2019BearGal3	Gallatin	55	1 charcoal fragment	Floodplain deposit	1630	28	1520	488708	4988296
2019UpperGal4	Gallatin	30-35	1 pinecone	Beaver pond organic layer	229	22	220	496067	4975264
2019EBThighterrace	EBT	78-88	1 charcoal fragment	High terrace	1953	24	1900	532400	4977897
2019WBTstratinset	WBT	36	1 charcoal fragment	Inset floodplain	867	32	790	532400	4977778

10 centimeters below the modern channel bottom

vertical face of stratigraphy to analyze. I sampled any exposed organic material such as charcoal, beaver-chewed wood, or pinecones. Large angular charcoal fragments were sampled to avoid errors associated with inbuilt age (e.g. redeposition or organic material that is significantly older than the deposit). Each sample was bagged individually (without touching the sample) with depth from the surface, soil/stratigraphy description, and GPS location. Each soil and stratigraphic layer was also described (color, texture, material, etc.), interpreted, and sampled. I also photographed the stratigraphy with a scale for future interpretation.

Sample preparation: I refrigerated soil and radiocarbon samples until I could dry them in an oven at 105 degrees Celsius for several hours, to evaporate off all the water. Then, I used a binocular microscope, tweezers, and x-acto knives to clean all modern organic matter or contaminants off the radiocarbon samples for dating, such as small roots and clay. Cleaned samples were then placed into new, sterile, labelled packages for shipping.

Radiocarbon dating: Two shipments with 20 total samples were shipped to DirectAMS, a radiocarbon dating lab. I used Calib704, a radiocarbon dating calibration program, to determine the potential distribution of ages for the samples given a variable record of C14 production over time in the atmosphere (Stuvier, Reimer, & Reimer 2020). We summed the probability that a deposit was associated with each year multiplied by the year to produce a weighted calibrated age. Weighted calibrated ages better estimate the potential age of the sample and are more stable than using the intercept alone (Telford et al. 2004).

RESULTS

Streams on the Blacktail Plateau are inset within glacial outwash channels amongst higher kame terraces from the Last Glacial Maximum (Pierce 1979). In the outwash, 1.5 meters above the current channel and associated abandoned meanders, there is a consistent, extensive fluvial surface along both forks of the Blacktail stream. We sampled radiocarbon from this surface and surfaces inset within it at a range of depths and sites (Table 1 has a full list of sites sampled; Fig. 2 shows examples of floodplain and beaver-pond deposits sampled). Many of the analyzed stratigraphies exhibited thick, developed A-horizons (Fig. 2).

Most beaver activity is within the last 500 years, a wetter period. Ages of beaver-pond deposits overlap between this and previous studies (Persico & Meyer 2013). Conversely, floodplain deposits are concentrated around 1000 and 2000 cal yr. BP, corresponding with drought as recorded by the drought index reconstruction (Fig. 3).

Dates for some samples were excluded due to of inbuilt age (i.e. sample age > deposit age). Inbuilt

Figure 2. Left: Sampling for charcoal at a cutbank stratigraphic column along the Gallatin River. This stratigraphy had large channel cobbles topped by floodplain deposits and soil development at the top, indicating a long period of stability (it is unlikely that this surface was abandoned as recently as 1920). Orange flags mark locations of charcoal samples. The charcoal sample that is second from the bottom, "2019BearGal3", has been dated at ~1520 cal yr. BP, in a sandy lens with abundant charcoal of floodplain deposits. This sample is likely from a fire-related flood. Right top: A zoomed-out view of the area surrounding that stratigraphy. Right bottom: A beaver pond deposit near the current waterline on the West Fork Blacktail Creek. The root-filled layer may be an old beaver dam. The lowest orange flag denotes a beaver-chewed wood sample, "2019WBTBP4", dated at ~50 cal yr. BP. Although the beaver pond deposit is from historic times, we believe that it does not represent the age of the stratigraphy it was found in, as beavers may have placed sticks at variable heights across the channel.

age is identified where samples collected higher in the stratigraphy had older ages than those lower in the stratigraphy. These samples likely represented redeposited material from older deposits. Even for other samples, it is possible that the age represents older charcoal redeposited from earlier deposits or a very old tree. Care was taken to choose angular charcoal pieces that were less likely to be redeposited, but this is a potential source of error in ages.

DISCUSSION AND CONCLUSION

The stratigraphic record in the Northern Range of YNP provides evidence for correlations between climate, beaver activity, and stream morphology over the last 7000 years. Beaver activity in this broad area is more prevalent during cooler, wetter periods. Conversely, most floodplain deposition occurs during warmer, drier periods. The long-term relationship between climate and YNP ecosystems, combined with the thick

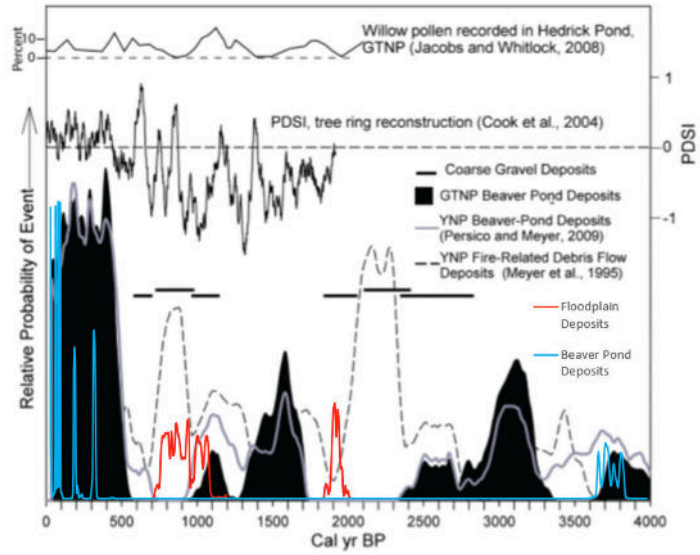

Figure 3. Age probabilities of radiocarbon samples in floodplain deposits (red lines) or beaver pond deposits (blue lines) compared with records of drought, willow prevalence, and ages of fire-related and beaver-related deposits from Persico & Meyer 2013.

A-horizons that take time to develop after incision (Fig. 2), make the theory of recent incision due to a trophic cascade after wolf removal alone dominating ecosystem change unlikely.

Three samples provide evidence for general timing of stream processes on East Fork Blacktail. From Persico and Meyer (2009), radiocarbon dates at the surface of a laterally continuous, high fluvial terrace date to around 3300 cal. yr. BP, dating the end of a period of infill and floodplain aggradation. A sample dated from an inset slip-off terrace at 1450 cal yr. BP documents timing of incision. 2019EBT16, from ~860 cal. yr. BP, which was found 10 centimeters below the modern channel bed, suggests incision occurred long before the historical period.

The timing of fluvial processes in the greater Yellowstone ecosystem are controlled by millennial-scale climatic variability; beaver pond deposits are more prevalent in wetter, less drought-prone periods (Persico and Meyer, 2013). Most of the beaver pond deposits in this study have similar timing patterns—particularly the last 500 years and between 3600 and 4800 cal. year BP (Table 1). The overlap suggests that regional-scale climate variability, rather than localized impacts of wolves in the Northern Range alone, are a control on fluvial processes including beaver-pond aggradation. Beaver pond deposit ages also closely correspond to ages from Persico and Meyer, 2009,

which is focused on other Yellowstone Northern Range streams (Fig. 3). Additionally, 2019WBT4, a beaver pond deposit in the incised terrace surface of the West Fork of Blacktail Deer Creek was modern, indicating that stream incision occurred prior to 1950 and beavers have been active on WBT since 1950 despite the absence of wolves.

Terrace formation coincides with cool periods during the Holocene, as higher discharges and lower sediment loads result in incision (Meyer, Wells, & Jull 1995). Conversely, variable and intense precipitation occurs during warm periods, combined with fires, which result in fire-related floods and alluvial fan deposition (Meyer et al. 1995). This same mechanism could produce floodplain deposits with charcoal. We found charcoal ages in floodplain deposits to be concentrated within the Medieval Warm Period (700-1100 cal yr. BP) and between 1800 and 2000 cal yr, BP, which corresponds with ages of fire-related debris flows and sedimentation in Meyer et al. 1995, and with periods of drought (Fig. 3). For example, sample 2019EBT16 is a charcoal sample found in a very fine-grained floodplain deposit 10 centimeters beneath the modern channel bottom dated at ~860 cal yr. BP. It represents floodplain deposition during a warm period, and also indicates overall infill of channels since this period. Similarly, 2019WBTstratinset, dated at 790 cal yr. BP, also falls within this warm period and represents infill of a paleochannel inset in a higher kame surface. This supports the idea that floodplain deposition occurs in warmer, drier periods.

The prevalence of both beaver pond deposits and potentially fire-related floodplain deposits in the stratigraphic record of the Northern Range of YNP and the broader Greater Yellowstone Ecosystem emphasizes the importance of both processes over the late Holocene. A state with abundant beaver, wolves, and large willows, and reduced elk populations that occurred during the early 1900s is not necessarily the default. Rather, climate changes may dictate varied megafauna populations and stream conditions.

The history of beaver activity and stream morphology over the last 7000 years in Yellowstone National Park is complicated by variable underlying geology, many climatic changes, and complex ecosystem dynamics. A selection of radiocarbon dates along a large swath of the Northern Range is insufficient to confidently describe thousands of years of history, but nonetheless suggest a story more complex than the trophic cascade theory. Rather, our results supported our hypothesis that beaver activity corresponds to wetter periods, while floodplain deposits correspond to drier periods.

Climate models, such as the Great Plains Regional Climate Trends report from the United States Global Change Research Program (Kunkel et al. 2013), predict that Yellowstone and the surrounding areas will experience wetter winters and hotter seasons within the next 20+ years. Beaver health is reduced during warmer spring conditions and wetter falls (Campbell et al. 2013), so populations may be impacted by continued warming. Additionally, they are limited by a maximum flow that they can maintain their dams in (Persico & Meyers, 2009), so extreme flooding during higher-than-average spring flooding would potentially cause more dam failures resulting in less sustainable beaver habitat. More broadly, if climate is a significant driver of ecosystem changes in Yellowstone, there may be large alterations to the ecosystem balance in the future.

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