PAST FLOODING EVENTS AND A 400+ YEAR RING-WIDTH CHRONOLOGY OF BUR OAK ALONG THE RED RIVER IN NORTH DAKOTA AND MINNESOTA

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Program:
Natural Resources Management

March 2021

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Past Flooding Events and a 400+ Year Ring-Width Chronology of Bur Oak along the Red River in North Dakota and Minnesota

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

A paleoflood record of the United States portion of the Red River of the North was created utilizing rings of bur oak (*Quercus macrocarpa* Michx.). Emphasis was placed on the flood of 1826. Samples were collected from standing trees and historic log buildings. All samples were observed for flood rings and measurements were taken for 90% of physical samples. Flood rings for 1826 were disproportionately found at one specific site near Shelly, MN. Ring width measurements were taken from 179 physical samples and combined into a ring-width chronology spanning from modern times back to 1601. The results suggest that the flood of 1826 was not as severe in the United States as in Manitoba. Additional sampling from log buildings and subfossil logs could help further refine the extent of the 1826 flood, as well as extend the paleoflood record and ring-width chronology.

ACKNOWLEDGMENTS

This project was supported by the National Science Foundation, Award Number 1830640 to the University of Minnesota, subaward number A007306801.

First, I would like to thank those that pushed me towards pursuing graduate school. The summer of 2018 was a major learning curve for me and without the push from Mark Ranweiler and Erik Anthonisen with the Minnesota DNR from Fergus Falls, MN, I would never have applied to graduate school. A tremendous amount of support also came from my former adviser Dr. Christina Hargiss. Christina always kept class exciting and helped me so much with applying to graduate school. I would also like to thank Dr. Jack Norland for introducing me to GIS and never being too busy to offer help if help is needed. Jack was a major resource for me as an undergraduate.

Graduate school would not have been possible without the support from my family. My best friend and sister Jessica, who is always willing to listen to my problems, no matter the time or day. My mother Kelly, who has always supported my life decisions, whatever that might be. She also helped me see things from a different perspective when I was struggling with graduate school. My father Bruce, the hardest worker I have ever met in my life, has told me countless times how proud he is of me and that I can do anything I put my mind to. The last family member I would like to thank is Randy Jahnke. Even though we are not related by blood, Randy is like a second father to me. He has had the biggest influence on my life by any single person and he has helped mold me into the person that I am today. A friendship like no other that started on December 3, 2005.

This study would not have been possible without every member of my committee. Dr. Stephanie Day helped increased my understanding of working with GIS, programs that I foresee

myself using in my career after I graduate. Her expertise with GIS programs also helped me create most of the maps for this project. Dr. Scott St. George helped me get a better understanding for COFECHA, a program I used hundreds of times for this study. Scott was also extremely supportive in my study, even when things weren't going as planned. Dr. Edward DeKeyser, thanks for giving me a backup option for pursuing graduate school if getting this assistantship did not work out. This relieved a tremendous amount of stress in the fall of 2018.

Finally, I can't thank Dr. Joseph Zeleznik enough for generously offering me the assistantship for this project. Joe, you have impacted my life in more ways than you can imagine. Not only did you introduce me to dendrochronology and taught me so much about forestry, but you have also taught me several life lessons. One of those lessons is to slow things down and be more patient. Thank you for taking a chance on a kid who knew very little about forestry before the start of this project.

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INTRODUCTION

The Red River of the North is a slow-moving, single, meandering channel that flows northward for 880 kilometers, forming the border between North Dakota and Minnesota before entering Canada. The basin for the Red River spans roughly 104,000 square kilometers and receives drainage from parts of northeastern South Dakota, eastern North Dakota, western Minnesota, southern Manitoba, and eastern Saskatchewan (United States Geological Survey, n.d.) (Figure 1). The Red River starts at the confluence of the Bois de Sioux and Otter Tail Rivers in the community of Wahpeton-Breckenridge. The river also passes through the large communities of Fargo-Moorhead and Grand Forks-East Grand Forks while flowing north. Due to the flat landscape of the surrounding area, the river can spread over large distances once it overflows its banks, making spring flooding a recurring and destructive natural disaster, especially in recent years.

Red River spring floods occurring in 2011, 2009, 1997, 1979, and 1950 are recent floods that have had noticeable impacts on the communities surrounding the Red River. The Red River flood of 1997, which was given the name 'The Flood of the Century', forced the evacuation of over 50,000 residents from their homes and created damage across the basin costing more than US $4.8 billion (International Joint Commission, 2000; Shelby, 2003). During the flood, the river reached a maximum width of 40 kilometers (International Joint Commission, 1997; Burn, 1999; Rannie, 2016). Heavy precipitation in the fall of 1996 resulted in high soil moisture content during freeze-up. Record amounts of winter precipitation throughout most of the Red River Valley and a major blizzard occurring on April 5th, 1997, with up to 50 cm of precipitation in the catchment area, also played a role (Burn, 1999).

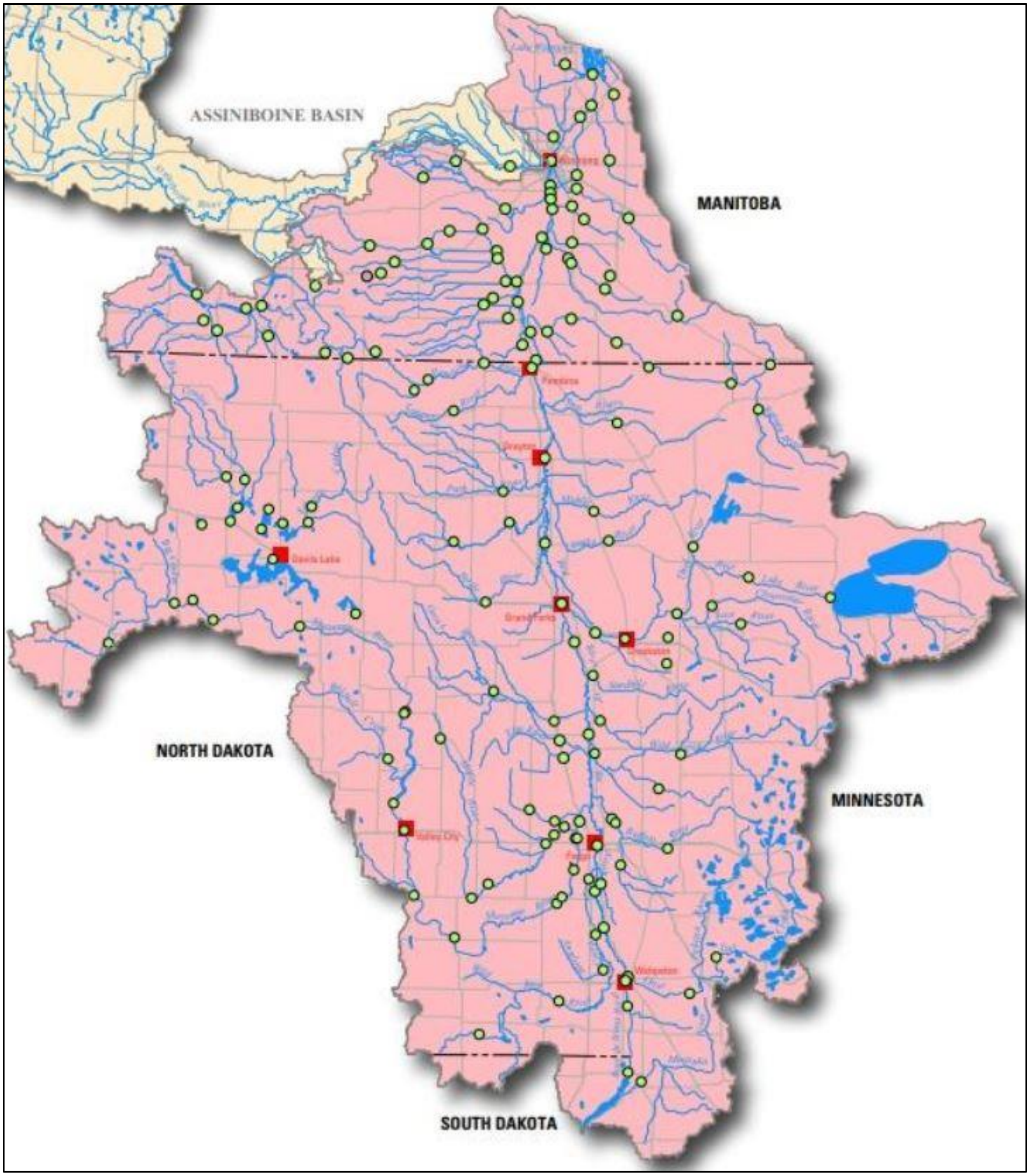

Figure 1. Red River Valley basin. Retrieved from https://www.usgs.gov/media/images/red-river-basin-snip (public domain).

Since the communities around the Red River have been experiencing significant damage from these large magnitude floods in recent years, there is a need for a better understanding of the long-term flooding history of the Red River. An extended flooding history may help determine if this pattern of multiple, large magnitude floods occurring in short time intervals has happened before for the Red River. Because Euro-American settlement of the Red River Valley in the United States did not begin until the 1870s, long-term flooding information and recorded river heights do not extend far back in time. In 1882, the first river gauge along the Red River was placed in Grand Forks, North Dakota. However, most river gauges were not introduced until the 1930s (Wertz et al. 2013). Due to this, other ways of documenting historic flood events need to be identified.

Paleofloods are historical or ancient floods that occurred without being recorded by modern hydrological instruments, recorded by historical observations, or documented by individuals who experienced the flood directly (Baker, 2008). Paleofloods can be recorded naturally by multiple indices including numerous effects on landscapes, changes in sediments, or changes in vegetation (Baker, 2008). Bur oak (*Quercus macrocarpa* Michx.) is one proxy that can be used to identify paleofloods because bur oak can create a ‘flood ring’ when the right flooding conditions occur.

Bur oak was used to identify paleofloods along the Red River in the early 2000s. However, those studies were only limited to the downstream portion of the river in Canada. By sampling standing trees, historic log buildings, and subfossil logs, St. George and Nielsen (2003) concluded that the flood of 1826 was the largest flood ever recorded based on discharge on the Red River in Manitoba, Canada. Flood rings in bur oak were not used to identify paleofloods along the Red River in the United States until the early 2000s (Wertz et al. 2013). That study was limited to sampling only standing oak trees, and the chronology spanned only 1853-2011, though 176 trees were cored (Wertz et al. 2013).

The goal of this project is to determine if, and where, the extreme flood of 1826 occurred on the United States portion of the Red River. To do this, samples from standing bur oak trees, historic log buildings, and subfossil logs located near or on the riverbanks of the Red River were collected and analyzed. The flood chronology built may also give insight on other paleofloods, not just the flood of 1826. Along with this goal, we are creating a larger ring-width chronology for bur oak along the Red River that extends further into the past.

A side project that was conducted at Oak Grove Park in Fargo, North Dakota will also be discussed after the main study. While it was not directly related to the main study, it showed that bur oak trees are imperfect recorders of all floods and that a day or two of flooding can be the difference in creating a flood ring or not. The goal of the project was to relate the timing of flooding to the start of cambial growth of bur oak trees.

LITERATURE REVIEW

Dendrochronology was first named by Andrew Douglass in 1941. Douglass, who established the Laboratory of Tree Ring Research at the University of Arizona, concluded that dendrochronology is an accurate science, after 30 years of research and analyzing over 20,000 specimens (Douglass, 1941). Since 1941, the study of dendrochronology has come a long way. Dendrochronology is a reliable science that not only can be used to determine the age of a tree by using patterns of the annual rings, it can also be useful in determining changes in climatic conditions over time.

Dendrochronology can also be used to identify paleofloods by using anatomical evidence, including flood rings or abrasion scars from ice or floating debris during floods (Yanosky, 1983; Gottesfeld & Gottesfeld, 1990). Understanding and identifying paleofloods is useful for determining the frequency of large, rare events that can have major impacts on communities located near a river, including extensive flooding damage to households and buildings, loss of livestock, and evacuation (Baker, 2008; Rannie, 2016). Shelby (2003) reported over 15,000 livestock were lost during the Red River flood of 1997 alone including cattle, hogs, sheep, chickens, and turkeys.

Flood rings

There are two parts that make up an annual ring: earlywood and latewood (Figure 2). Earlywood is created at the beginning of each growing season; in ring-porous hardwoods such as bur oak, this occurs from early spring until early summer (Stokes & Smiley, 1996; Speer, 2010). Earlywood in these trees is made up of mostly large diameter circular porous vessels and is lighter color than latewood, which can be used to determine the transition between the two. During a typical year, ring-porous species create single or multiple rows of earlywood vessels that are used to transport water and nutrients vertically throughout the tree (St. George & Nielsen, 2002). While vessels are still present in latewood, they are typically much smaller than the vessels in earlywood. Latewood is also denser than earlywood, giving it a darker color.

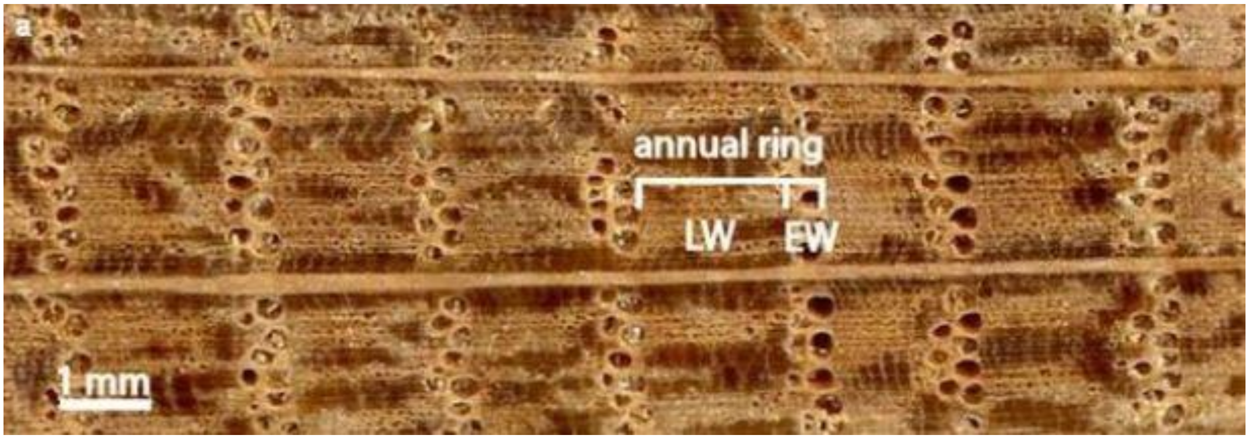

Figure 2. Differentiating the separate parts of an annual ring for a bur oak between earlywood (EW) and latewood (LW). In this diagram, the pith is towards the right and the bark is towards the left. Note: From *Climate Variability in Southwest France During the Last 2000 Years: Proxy Calibration and Reconstruction of Drought Periods Based on Stable Isotope Records from Speleothems and Tree Rings* (Doctoral dissertation, Paris 11), by Labuhn, I., 2014. (https://www.theses.fr/2014PA112077). Reprinted with permission.

During a year when spring flooding occurs, ‘flood rings’ can be created in ring-porous species such as bur oak (St. George & Nielsen, 2003; Therrell & Bialecki, 2015), English oak (*Quercus robur* L.) (Copini et al. 2016), overcup oak (*Quercus lyrata* Walter) (Therrell & Bialecki, 2015), white ash (*Fraxinus americana* L.) (Yanosky, 1983), green ash (*Fraxinus pennsylvanica* Marshall) (Yanosky, 1983), and black ash (*Fraxinus nigra* Marsh.) (Kames et al. 2016). Flood rings are characterized by one or more of the following characteristics; 1) shrunken earlywood vessels, 2) earlywood vessels extending into the latewood portion of the annual growth ring, 3) a combination of the two, or 4) increased parenchyma in the latewood portion of the annual growth ring (Yanosky, 1983; Astrade & Bègin, 1997; St. George & Nielsen, 2002; St. George & Nielsen, 2003; St. George, 2010; Wertz et al. 2013) (Figures 3 and 4).

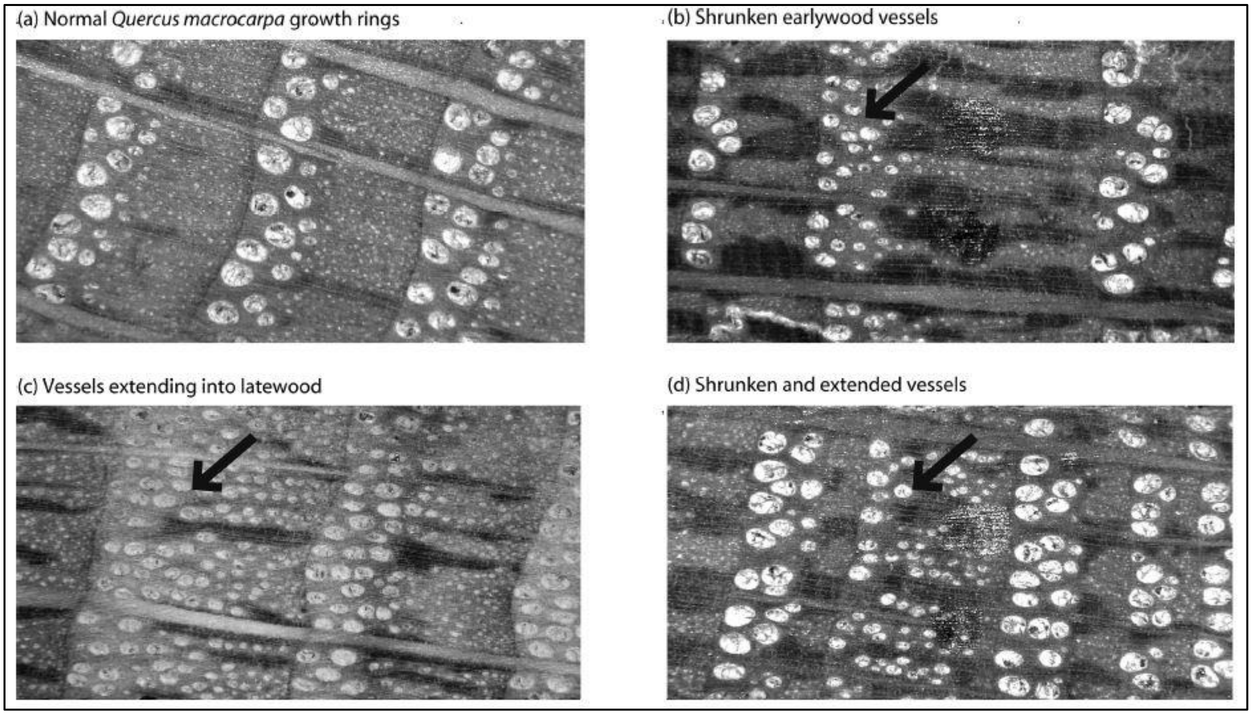

Figure 3. (a) Normal growth rings in bur oak (*Q. macrocarpa*) including several ranks of large earlywood vessels followed by latewood, (b) flood ring shown as shrunken earlywood vessels, (c) flood ring shown as earlywood vessels extending into the latewood, and (d) flood ring showing both shrunken vessels and vessels extending into the latewood. Note: From *Vessel anomalies in Quercus macrocarpa tree rings associated with recent floods along the Red River of the North, United States,* by Wertz, E. L., St. George, S., & Zeleznik, J. D., 2013, Water Resources Research (https://doi.org/10.1029/2012WR012900). Reprinted with permission.

Yanosky (1983) was the first researcher to discover flood rings within white ash and green ash growing along the Potomac River near Washington, D.C. The goal of the study was to correlate changes in wood anatomy (flood rings) to flood events. Yanosky (1983) also discovered that white and green ash that were affected by summer flooding exhibited enlarged latewood vessels.

Factors in creating flood rings

Not every tree that is flooded during the spring will create a flood ring. Flood rings can be highly variable, even within the same stand of trees. However, once a flood ring has been created, it is permanent. Therefore, flood rings can be found in living trees, within historic timbers, and in subfossil logs that are preserved in the soil alluvium (c.f. St. George & Nielsen, 2003). There are three factors that will determine if a flood ring is created.

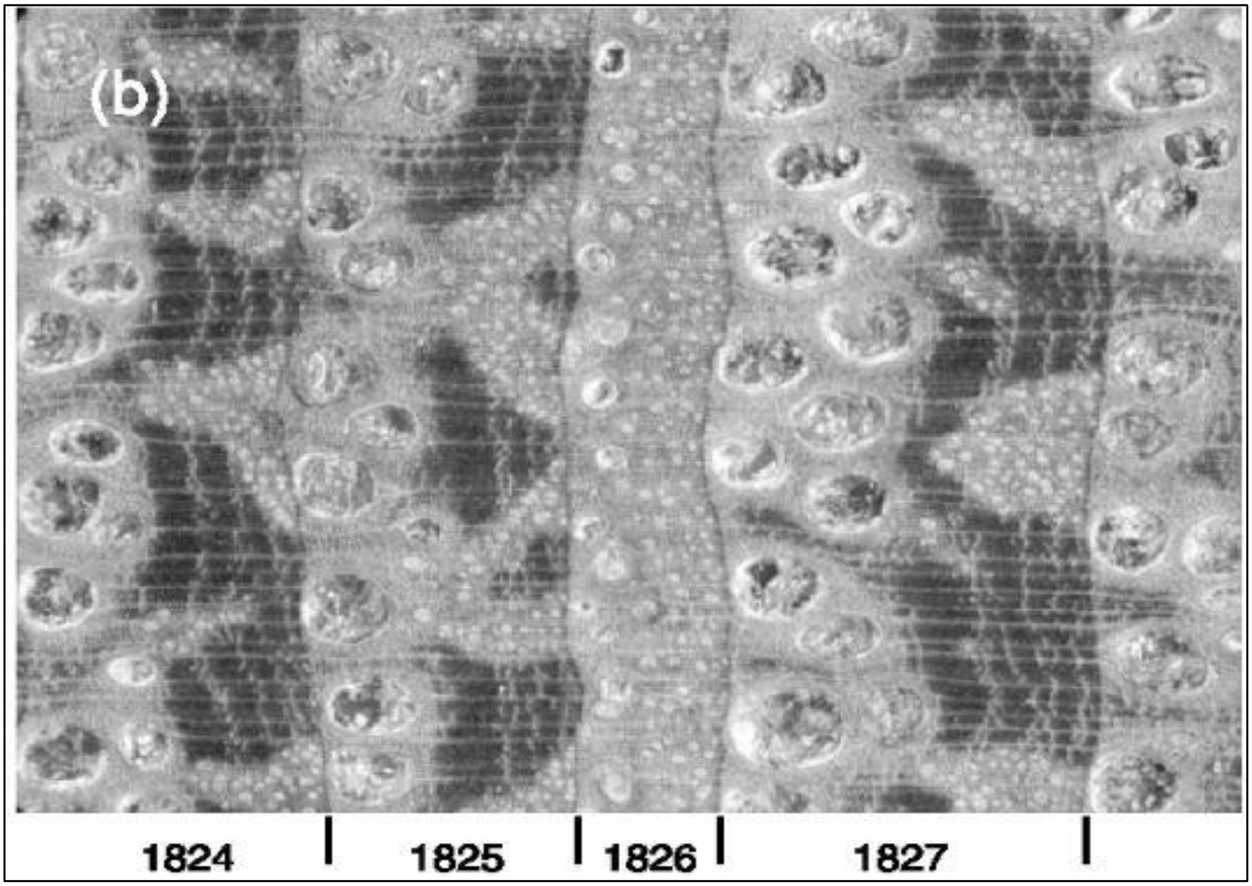

Figure 4. Flood of 1826 resulting in shrunken earlywood vessels and increased parenchyma. The dark portion of the latewood does not exist; instead, the latewood contains only parenchyma tissue. Note: From *Paleoflood records for the Red River, Manitoba, Canada, derived from anatomical tree-ring signatures,* by St. George, S., & Nielsen, E., 2003, The Holocene (https://doi.org/10.1191%2F0959683603hl645rp). Reprinted with permission.

The first factor and possibly the most important is the timing of the flood. The flood must occur during earlywood growth which varies from year to year (St. George & Nielsen, 2002; Copini et al. 2016). Flooding during dormancy does not create any flood rings (Yanosky, 1983; Astrade & Bègin, 1997; St. George & Nielsen, 2002; Copini et al. 2016). This appears to be the case for the Red River flood in 2006. The flood of 2006 was a top 5 flood event in Fargo, but it only created two flood rings out of 60 sampled trees from three sites located in Fargo (Wertz et al. 2013). The dearth of flood rings is most likely attributed to flood waters falling below flood stage by mid-April before most cambial growth had started.

Secondly, a flood ring will only be created at, or below, the height of the water on the stem of the tree (St. George et al. 2002). Therefore, it is important to collect samples as low to the ground as possible to increase the chances of finding a flood ring. Also, trees that are lower on the landscape, such as trees in riparian zones, should be sampled since they will be the first and the last to be flooded.

The third factor in creating a flood ring is the duration of the flood after cambial growth has begun. The longer the flood exists, the more likely it is to create a flood ring. Copini et al. (2016) concluded that an interval of only two weeks of flooding after cambial growth has started is enough to decrease earlywood vessel size in flooded stems. Therrell and Bialecki (2015) discovered that flooding events of 10 days or longer during earlywood growth created flood rings in bur oak and overcup oak along the Mississippi River. Either way, it appears that trees need to be submerged for a certain minimum amount of time for flood rings to form.

Bur oak trees are imperfect recorders of flood events. There is a large amount of variability of flood rings produced in bur oak, even within the same stand of trees (Wertz et al. 2013). So, to accurately use flood rings as records of past flooding events, many samples across a vast number of sites are needed. Wertz et al. (2013) hypothesized that the differences in bur oak trees creating a flood ring or not may be due to the slightest change in elevation among trees or among sites. Even though the change in slope of the main channel from the confluence of the Red River to the mouth at Lake Winnipeg is roughly 9.6cm/km (River Keepers, 2015), a slight elevation difference could have a large impact on the likelihood of creating a flood ring.

While not nearly as common, summer flooding events due to heavy precipitation have occurred along the Red River in the past. Because the majority of earlywood vessel formation has been completed by the early summer months, flooding in the summer does not produce shrunken earlywood vessels in bur oak like spring flooding does. However, Yanosky (1983) determined white ash and green ash exhibited enlarged latewood vessels during summer flooding.

Astrade and Bègin (1997) sampled European aspen (*Populus tremula* L.) and English oak along the Saône river in eastern France. English oak had visibly smaller earlywood vessels and had a larger porous earlywood zone in years of spring flooding events. Early spring floods occurring in, or prior to late April before earlywood growth started in English oak, did not result in any flood rings. The authors concluded that English oak cannot be dormant to create flood rings.

St. George et al. (2002) collected multiple cores at different heights from four bur oak trees along a flood-prone area by the Red River in Manitoba. At each height, samples were collected from several axes (e.g., north, south, east, west). Regardless of axes, multiple samples from the lowest height contained flood rings for 1950 and 1997, both years of major Red River floods in Canada. Earlywood vessels that were formed in 1950 were smaller than those exhibited in 1997. While the 1997 Red River flood had a higher peak flood stage, the 1950 Red River flood lasted 10 days longer, suggesting that flood duration may play a larger role in creating a flood ring than peak flood stage. The authors also believed flood ring development is based on timing of earlywood growth. The flood of 1979 had a peak discharge similar to that in 1950, and the timing of the flood was similar to that of 1997. However, the flood of 1979 did not result in any flood rings. Daily temperatures in 1979 were above freezing for almost three weeks before flooding occurred. The authors speculate that earlywood vessels may have been fully or near fully developed by the time the trees were inundated by the flood waters.

St. George and Nielsen (2002) conducted a study focusing on the climatic changes along the Red River in Manitoba by using local temperature and precipitation records and comparing them to ring width measurements from bur oak. Precipitation from August of the previous growing season through July of the current growing season played the most important role in ring width. Out of the 16 sites sampled for bur oak by St. George and Nielsen (2002), precipitation was significantly correlated with ring width ($r^2 = 0.426$, $p < 0.01$). When comparing ring width to annual temperature, most correlations, but not all, were negative and rarely significant.

Another study (St. George & Nielsen, 2003) conducted along the Red and Assiniboine Rivers in Manitoba used multiple sources of bur oak including standing trees, logs from historical buildings, logs from archaeological sites, and subfossil logs to create a centuries-long paleoflood record by using flood rings. The record started in modern times and extended back to 1448 AD. The authors concluded that the flood of 1826 was the largest flood in terms of discharge along the Canadian portion of the Red River by comparing the number of flood rings with the overall number of samples collected.

Therrell and Bialecki (2015) created the first multi-century paleoflood record along the Mississippi River by using tree rings. The authors collected samples from overcup oak and bur oak on the Lower Mississippi River in Big Oak Tree State Park in southeast Missouri. The authors recognized 39 separate years that had flood rings from 1770 to 2009. All flood rings corresponded with major floods in the 20th century, or with major floods that were documented in previous centuries. The authors suggested that large-magnitude floods that lasted longer than

10 days during the spring is the most likely way to create a flood ring. Therrell and Bialecki (2015) also explained that the creation of flood rings has a relation with magnitude, duration, and timing of the flood compared to earlywood development.

Tumajer and Treml (2016) examined vessel anatomy and the effects that climate has on English oak on the Elbe River floodplain in the Czech Republic. Similar to the Red River, the Elbe River’s highest discharge occurs during early spring when the trees are nearing bud break. A total of 148 cores were taken from standing trees from six separate sites in floodplain zones. Tumajer and Treml (2016) determined that earlywood vessel diameter in floodplain trees was limited by extreme amounts of water. The authors also stated that earlywood vessel size is determined during earlywood growth, which means the amount of precipitation received during late winter and early spring is critical in regard to creating a flood ring.

The only controlled experiment regarding flood ring formation was conducted by Copini et al. (2016) using four-year-old English oak trees. The authors used a control treatment and nine flooded treatments. The flooded treatments were inundated for intervals of 2, 4, and 6 weeks after the initiation of each phenophase (Figure 5) to determine how timing of flooding affected the earlywood growth of these young trees.

Earlywood vessel development for the flooded treatment during dormancy did not start until 6 weeks after flooding, but only above the water level (Copini et al. 2016). That is, flooding delayed development of earlywood vessels below the water level. Additionally, at the end of the growing season, two of the trees in the six-week flood treatment had shrunken earlywood vessel diameters for the samples below water level. The authors believed the shrunken vessel diameters was caused by these trees moving onto the next phenophase between week four and week six of flooding.

Figure 5. Different phenophases of the trees that were flooded in Copini et al. (2016). Dates below the phenophase names indicate the dates of initiation of flood treatments within each phenophase. Dates are listed as day first and month second. Note: From *Flood-ring formation and root development in response to experimental flooding of young Quercus robur trees*, by Copini, P., Den Ouden, J., Robert, E.M., Tardif, J.C., Loesberg, W.A., Goudzwaard, L., & Sass-Klaassen, 2016, Frontiers in Plant Science (https://doi.org/10.3389/fpls.2016.00775). Reprinted with permission.

Similar results were seen in trees that were flooded at the beginning of the bud swell stage, but impacts were seen more quickly (Copini et al. 2016). After only four weeks of flooding, there were significant differences in earlywood vessel size between the flooded and control treatments. Six weeks after bud swell had begun, minimal numbers of small earlywood vessels had been formed below flood level, compared to control trees which had created one full row of normal-sized earlywood vessels (Figure 6).

Flooding treatments at the beginning of the internode expansion phenophase affected vessel diameter even more quickly (Copini et al. 2016). At the end of the growing season, all flooded treatments below the water level showed significantly smaller mean and maximum earlywood vessel area when compared to the flooded treatments above water level (Copini et al. 2016). This indicates that only two weeks of flooding is enough time to alter the visual characteristics of the annual ring in English oak once internode expansion has begun.

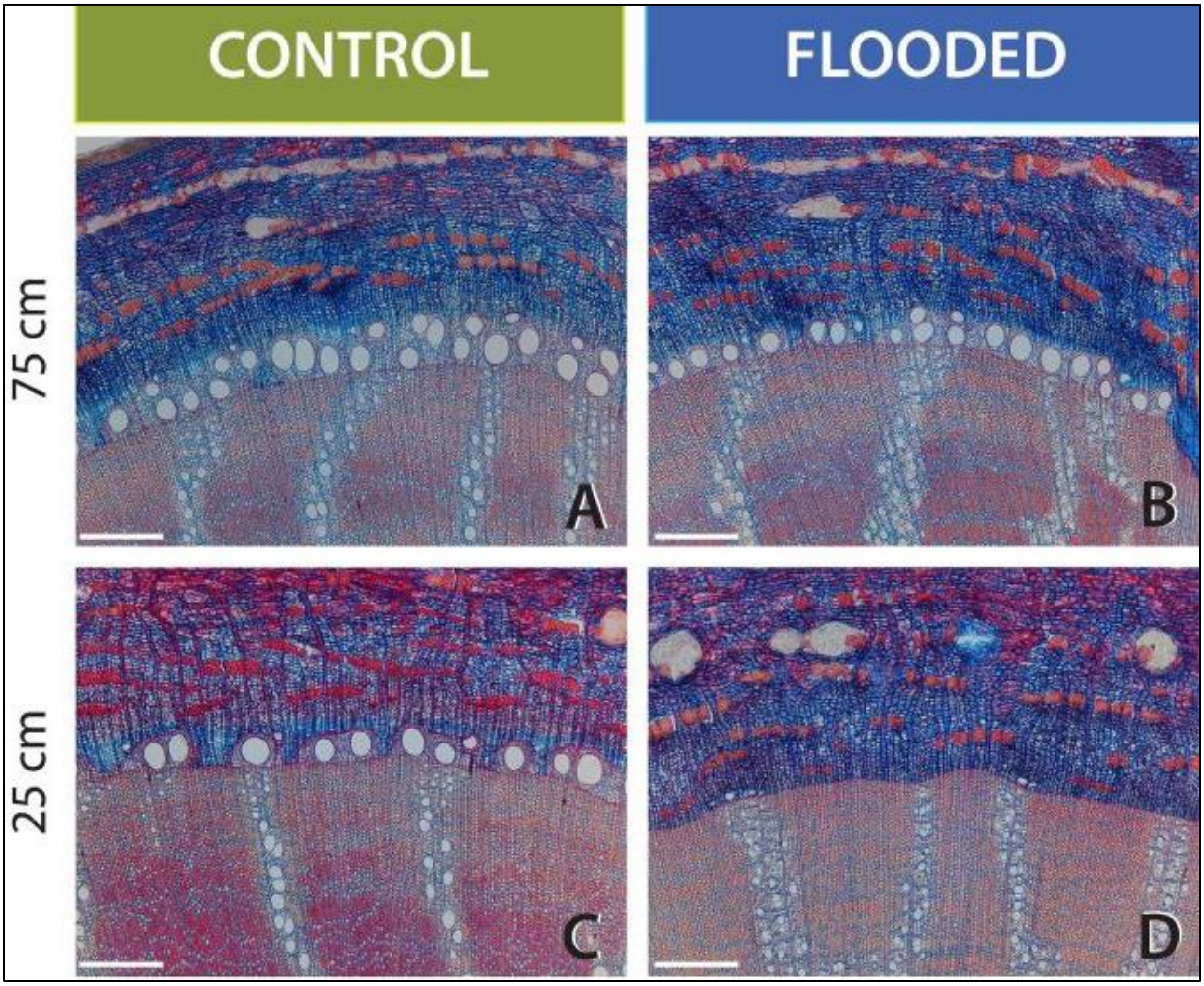

Figure 6. Earlywood vessel development in English oak, comparing non-flooded trees (A& C) to trees flooded for six weeks (B & D) beginning at the bud swell phenophase. The 25 cm height (C & D) was below flood level. For flooded trees, normal earlywood vessels were produced above flood waters, but very few and extremely small vessels were produced below flood waters. Note: From *Flood-ring formation and root development in response to experimental flooding of young Quercus robur trees,* by Copini, P., Den Ouden, J., Robert, E.M., Tardif, J.C., Loesberg, W.A., Goudzwaard, L., & Sass-Klaassen, 2016, Frontiers in Plant Science (https://doi.org/10.3389/fpls.2016.00775). Reprinted with permission.

Flood ring chronology

Flood ring chronologies have been created by sampling multiple sites across a broad area. St. George and Nielsen (2003) created a flood ring chronology along the Red and Assiniboine Rivers in Manitoba by using bur oak. The sites were spread out over a 100-kilometer corridor next to the Red River. The area covered for the Assiniboine River was not listed. Fourteen (14) separate years of floods were recognized via flood rings throughout their chronology. The flood ring chronology created contained three periods of high magnitude floods during the mid-1700s, the mid-1800s, and the latter half of the twentieth century. This flood ring record also hints that little to no ‘extreme flooding’ was recorded 1648-1746, 1763-1825, and 1862-1949 (St. George & Nielsen, 2003).

Therrell and Bialecki (2015) created the first multi-century flood ring chronology along the Mississippi River. However, all trees were located within Big Oak State Park, so the study area was not as large as St. George and Nielsen (2003). The authors stated that to improve their flood ring chronology, more samples needed to be collected from a larger range of locations along the Mississippi River. The authors also compared their results to Stahle (1980), who did a similar study over 480 kilometers downstream from Big Oak State Park on the Mississippi River. Out of the 39 flood years found in Big Oak Tree State Park, eight of those years formed flood rings in common with the site downstream.

A flood ring chronology was created for the Lake Duparquet region, which spans 50km^2 in north-western Québec by Kames et al. (2016). Two cores each were taken from 12 black ash trees from five separate sites surrounding the lake. Flood rings were identified by smaller earlywood vessels which were all positively associated with high discharge in May and June. Kames et al. (2016) believe ‘continuous earlywood vessel chronologies’ may be helpful in determining the effect of altered environments in floodplains regulated by spring flooding.

Similarly, Therrell and Bialecki (2015) believe future studies can offer insight to climate variability over North America. Specifically, Therrell and Bialecki (2015) attempted to relate their results to the Pacific North American (PNA) teleconnection pattern, which they say has a strong effect on rainfall and streamflow in late winter and early spring where their study occurred. However, the results did not appear to be have a clear relationship with the climatic pattern. Therrell and Bialecki (2015) state that the PNA has large scale seasonal variations and acknowledge that their study is spatially limited.

Flood of 1826

Euro-American settlement began on the United States portion of the Red River Valley following construction of railroads during the 1870s after the U.S. Homestead Act of 1862 (Drache, 1970). European settlement on the Canadian side of the Red River began several decades earlier (Ross, 1856). In 1812, the Red River Colony, or the Selkirk Settlement was established on the Canadian portion of the Red River (Ross, 1856; Bumstead, 1997). Fourteen years after establishment, the settlement was nearly wiped out from the flood waters of 1826 (Bumstead, 1997; St. George & Rannie, 2003).

The flood of 1826 was the largest Red River flood, based on discharge, to occur on the Canadian portion (St. George & Nielsen, 2003). With an approximate flow of 6,370 cubic meters per second (Rannie, 2002), this discharge was roughly 40% larger than the discharge of the Red River flood of 1997 (St. George & Rannie, 2003). Even though the records of this flood came from Winnipeg where the Assiniboine River connects with the Red, most of the damage from the 1826 flood was believed to be due to the waters of the Red River. However, there were several other factors that contributed to the vast flood waters that spring.

During the spring of 1826, strong south winds, and flood waters from one of the Red River’s major tributaries, the Assiniboine River, combined to increase the damage (St. George & Rannie, 2003). In one study, the Assiniboine River was believed to produce a flow equivalent to 20% of the upstream discharge from the Red River that spring (St. George & Rannie, 2003). However, there has been some controversy on exactly how much of a role the Assiniboine played in the flood of 1826. Warkentin (1999) stated that the Assiniboine played a minor role in the flood, with a discharge of only 650 cubic meters per second.

It is rare for the Assiniboine and the Red River to flood at the same time. The correlation between annual peak discharges for both rivers is low (r = 0.40) (Rannie, 2002). However, Rannie (2002) believes that this is what happened in both the 1826 and 1852 floods. He believes the discharge from the Assiniboine River for both of these historic floods to be within 1,200-1,500 cubic meters per second. The return period for discharges of this size is 100 and 200+ years for the Assiniboine, respectively (Rannie, 2002).

Other uses of dendrochronology

Dendrochronology can be coupled with different techniques to help strengthen research conclusions. Incorporating dendrochronological practices into studies has been used to create hydroclimate reconstructions by looking at widths of tree-rings, creating fire histories by analyzing fire scars, and creating flood histories by analyzing ice scars from spring flooding.

Shapley et al. (2005) used dendrochronology and several other techniques to create a 1,000-year hydroclimate reconstruction in eastern South Dakota in the Waubay Lakes complex. Landsat imagery and aerial photography were used to confirm water levels in 1939, 1976, 1995, and 1997. Core samples from standing bur oak trees and samples from historic logs collected from Fort Sisseton helped the authors develop a ring-width chronology from 1674-1998. Once tree-ring records were collected, they were coupled with shell geochemistry of Ostracodes (*Candona rawsoni*), which also respond to changes in precipitation. The Ostracode data then extended the hydroclimate reconstruction back 1,000 years.

Dendrochronology can be useful for determining fire history as well. Leys et al. (2019) examined the fire history of an eastern Minnesota savannah containing a mix of oaks, other hardwoods, and pines. While analyzing fire scars from annual rings coupled with the amount of sediment charcoal, the team determined there were eight fire events from 1822-1924 by using fire scars and 13 fire events from 1696-2001 by using charcoal signatures.

Tardif and Bergeron (1997) reconstructed the flooding history in a western Quebec boreal forest by measuring the maximum height of ice scars on eastern white cedars (*Thuja occidentalis* L.). They determined that there was an increase of 100 centimeters in the highest ice scar height since the end of the ‘Little Ice Age’, which ended in 1850 (Tardif & Bergeron, 1997). The water levels during floods at their study site, Lake Duparquet, were reaching higher elevations than previous floods had ever reached. The authors also determined there was a large increase in spring flooding since the beginning of the 20th century.

FLOOD RISK PERCEPTION

Literature review

Flood risk perception is an in-depth process that is determined differently by laypeople and risk managers. Laypeople tend to determine flood risk perception by both emotional and behavioral aspects (Miceli et al. 2008). Risk perception for risk managers is defined several ways by different authors. Overall, risk perception is based on the assessment of the perceived likelihood of a hazard and the potential consequences of that hazard, most often being negative (Grothmann & Reusswig, 2006; Miceli et al. 2008; Bubeck et al. 2012; Becker et al. 2014).

Risk perception is difficult to understand. One reason is the polarized understandings of the word 'risk' (Lindell & Hwang, 2008). Risk, within the field of risk perception, is defined by risk managers as "the chance of injury, damage, or loss" (Slovic, 1999, p.690). Risk managers tend to correlate risk highly with technical estimates of fatalities (Slovic, 1987). However, risk may not be calculated the same by laypeople. Slovic (1987) states that laypeople may use technical estimates of fatalities to determine risk, but they also may incorporate other factors like catastrophic potential and threats to future generations. Because of this, risk is a generalized term and it has been that way since studies on flood risk perception began (Slovic, Personal Communication, July 24, 2020).

Overall, there are three basic elements that determine flood risk perception for laypeople: preparedness, awareness, and worry (Raaijmakers et al. 2008; Lechowska, 2018) (Figure 7). Figure 7 is a theoretical model used to understand flood risk perception and the relations of its elements. These three elements are found within most literature and within each element, there are many factors that influence it. One factor, direct experience, was found to influence each element differently.

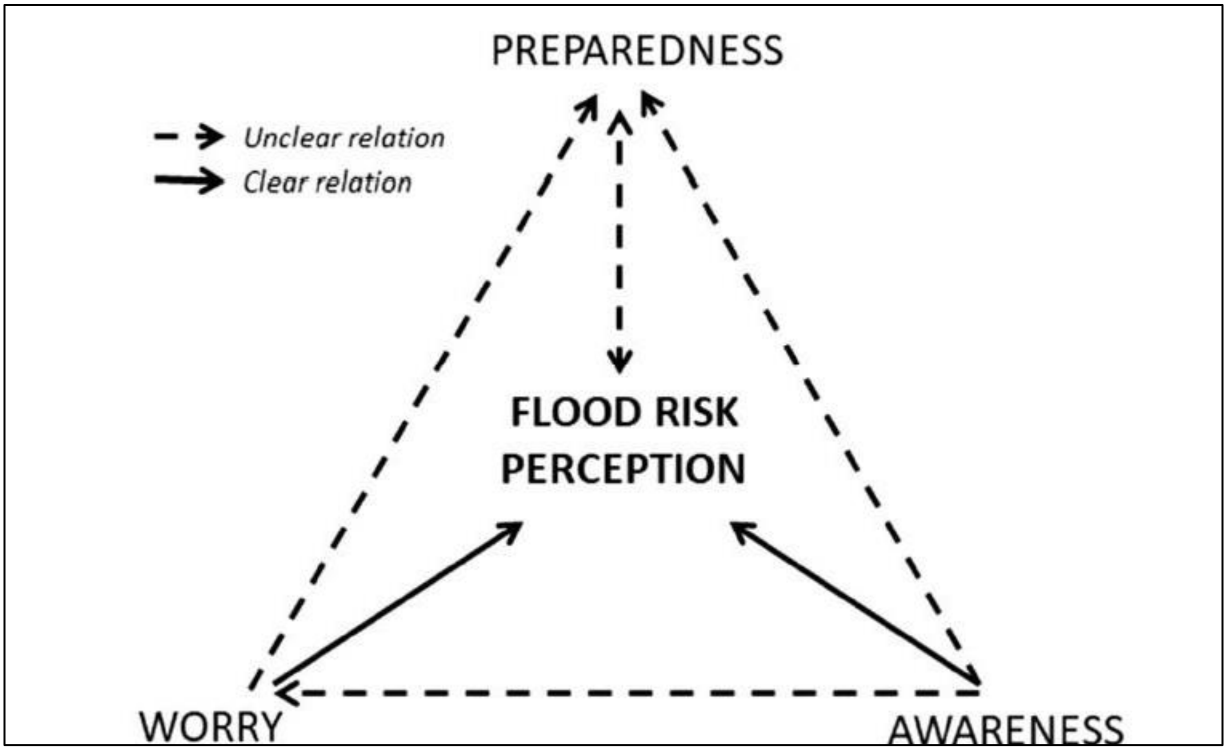

Figure 7. Flood risk triangle and how each element relates to flood risk perception. Note: From *What determines flood risk perception? A review of factors of flood risk perception and relations between its basic elements,* by Lechowska, E., 2018, Natural Hazards (https://doi.org/10.1007/s11069-018-3480-z). Reprinted with permission.

Some of the results in studies of flood risk perception are contradictory depending on who conducted the study and where the study took place. As stated above, determining risk perception is a complex process that has many variables. The different fields and expertise of researchers who conducted the studies, the way surveys were conducted, and where the surveys took place can all play a role in how risk perception is determined. Humans are also complicated, and feelings and attitudes play a role in flood risk perception.

Preparedness

Understanding levels of preparedness for private households can have mixed results, but there are several factors that play a role. Location of the household, direct experience with flooding, and social and economic factors can all influence preparedness (Miceli et al. 2008; Siegrist & Gutscher, 2008; Duží et al. 2017).

Location of the household compared to the hazard zone can influence preparedness. Duží et al. (2017) state that households are more apt to adopt mitigation techniques if they are aware they are living within a zone that has a high probability of flooding, compared to households that are not within the high-risk zone. This is an example of two of the elements, preparedness and awareness, working together. Similarly, O'Neill et al. (2016) discuss a correlation between how an individual reacts to a flood and the distance they are away from the predicted flood zone. Individuals living within the predicted flood zone of an upcoming flood are more likely to react and mitigate prior to the flood. Individuals who are living outside of the predicted flood zone or on the edge of the predicted flood zone are more likely to not be as prepared.

Previous flood experience influences an individual's choice to prepare for a flood and adopt mitigation measures (Thieken et al. 2007). There is a positive relationship between personal mitigation measures of private households and previous flood experiences (Grothmann & Reusswig, 2006; Siegrist & Gutscher, 2008; Biernacki et al. (2009) in Lechowska, 2018; Thistlewaite et al. 2018). Siegrist and Gutscher (2008) believe the relationship of past flood experience and preparedness is due to the difference in strong emotions from those who have experienced floods compared to those who have not. Those who have experienced a large flood usually take more precautionary steps to limit damage caused by flooding; they limit the amount of valuables that they store in their basement, they are likely to acquire more information about an upcoming flood, and they are more likely to seal windows and build new walls to protect against floods (Siegrist & Gutscher, 2008).

Social and economic factors have been linked to preparedness as well. Duží et al. (2017) found a relationship between gender and flood preparedness and found a relationship between flood preparedness and having children in the household. Having one male within the household increased mitigative measures by 25%, which in turn, increased preparedness. Miceli et al. (2008) believe that males are more likely to be open to protective behaviors than females are. Having ‘more’ children within a household increased risk reducing measures, however, the authors did not state the increase in number of risk-reducing measures or give specific values for number of children.

Individuals living in smaller communities or rural areas are at a higher risk for flooding damage and therefore need to be more prepared compared to those living in larger communities (Biernacki et al. (2009) in Lechowska, 2018). Larger communities implement more flood protection measures for their citizens in the form of flood walls and dikes since the community has more money to spend on flood protection. Therefore, individuals living in small communities or rural areas need to be more prepared for potential floods.

While flood risk perception and disaster preparedness are typically positively correlated, that is not always the case. Miceli et al. (2008) explains that the sometimes-poor correlation is due to the definition of risk perception. The authors believe the description of the term ‘risk perception’ does a poor job at incorporating both emotional and behavioral components. Slovic (1987) also states that risk perception can be difficult to estimate because ‘risk’ has a different meaning to different people, especially between risk managers and laypeople.

Awareness

An individual that has awareness they are living within an area at risk of flooding can increase their perception of flood risk. Two factors will be discussed that play a role in an individual’s awareness: direct experience and knowledge (Lechowska, 2018). Generally, previous experience with a flood increases an individual’s awareness of flood risk more than an individual who has not been exposed to past flooding (Lindell & Hwang, 2008; Bradford et al.

2012). However, depending on the size of the flood, how often a disaster occurs in that area, or where the flood takes place, it can be difficult to understand how direct experience will change an individual's awareness.

Biernacki et al. (2009) in Lechowska (2018) claim that awareness is much more difficult to calculate for private households living in areas that are rarely affected by disasters, due to the lack of previous experience those communities have. This lack of experience can lead to misunderstandings of how much damage a flood may create (Biernacki et al. (2009) in Lechowska, 2018). Awareness is also difficult to calculate in rural areas. Most studies done on flood risk perception are carried out in cities because flood damage can cost cities more money than rural communities. The awareness of individuals in rural communities may not be the same as individuals in larger communities (Lechowska, 2018).

Distribution of information, as well as education has been linked to an increase in awareness in a community (Raaijmakers et al. 2008). Shen (2009) in Lechowska (2018) states that when little information about flood risk is dispensed to the community, overall awareness of the risk will decrease. Therefore, it is important for experts to distribute the correct information to the community before a flood. However, it is important for the citizens of the community to stay up to date with local news sources because weather can change quickly, which could lead to the damage of the flood becoming more or less severe.

Individuals in the community who underestimate the flood risk or have a lack of awareness can create major problems in how risk managers handle a flood (Becker et al. 2014). These individuals exist in every community. Therefore, risk managers need to be aware of them to create an effective warning that will motivate them to react positively if they are within a high-risk area (Becker et al. 2014). To properly warn a community about upcoming flood damage, early warnings need to be distributed to the public.

Understanding early flood warning signs plays a role in how individuals living in a community react to and mitigate against potential damage that comes with flooding (Burn, 1999). Every individual in a community will perceive flood risks differently; therefore, it is important to not generalize the citizens of a community all as one. The better the community knows its citizens, the better warnings that can be created. However, the lack of similarity of individuals living in some communities makes the job of creating effective warning systems to promote proper mitigation techniques even more difficult for risk managers (Burn, 1999).

Worry

There are two factors that will be discussed in determining worry: past experience with flooding and education. There's no doubt that experience with flooding can play a role in increasing level of worry among individuals. This feeling of worry is also multiplied when there are significant losses that stem from flooding (Lechowska, 2018). However, levels of worry tend to be low for individuals that reside in high-risk areas for flooding that have not experienced flooding in recent years (Biernacki et al. (2009) in Lechowska, 2018). The authors believe that people tend to forget about past flood events, and that people believe they will be more prepared than they are.

Similarly, levels of worry may stay the same, regardless of the difference of flood risk from year to year. Howe (2011) found that levels of worry of individuals in Florida did not change much between different floods since these individuals believed that future floods would be the same or comparable to floods of those already experienced.

Level of education and income can also play a role in worry. Typically, those with higher levels of education also have higher income. Bradford et al. (2012) found that those who earned more and had higher levels of education did not worry as much about the effects of flooding. Even though they may endure more losses monetarily, they are equipped with better flood insurance and are able to recover from damaged goods and property more effectively than individuals who do not earn as much. Similarly, those who have less education are linked to having more feelings of worry from flood risk (Bradford et al. 2012). This is believed to be because these individuals do not have enough money to afford good flood insurance, if any. That is, these individuals may have less to lose, but whatever they lose, may not be covered by their insurance.

Living in a community that has been overwhelmed by a past flood can have a negative impact on flood risk perception. Burn (1999) states that in extreme cases with major floods, individuals in communities can have a sense of helplessness if a past flood created devastation. Furthermore, Paton (2003) stated that if individuals experience increased anxiety from the flood forecast, preventative actions may not be taken if the consequences of an expected flood look overwhelming.

Summary

Understanding flood risk perception is a difficult and time-consuming process. While it is easier said than done, the term ‘risk’ needs to be better defined. I am not an expert in this field but from the papers I read and the interview I conducted with Dr. Paul Slovic, a risk perception expert and the founder and president of Decision Research, the way risk is understood between risk managers and the general public is vastly different. Risk managers use projections of estimated casualties and flood damage that may come with a flood in order to properly distribute flood warnings for future floods. If risk managers were able to incorporate the emotional and behavioral aspects of citizens in a community into these flood warnings, the flood warnings may be better understood. However, it is not that easy because risk managers cannot generalize every individual in a community as one because humans are complex, and every individual behaves differently and has different emotions.

MATERIALS AND METHODS

Overview

The study was conducted in the United States portion of the Red River Valley. Samples were collected along the Red River, in both Minnesota and North Dakota. Sampling was conducted primarily during spring through late fall, although, some samples were retrieved during winter. Samples were collected on both public and private property.

Since most of the land surrounding the Red River is rural area, a large portion of the land is privately owned. Getting permission to access land or contacting landowners was generally difficult. Therefore, many sites that were sampled in this study were on public lands and near the community of Fargo-Moorhead. Standing trees on multiple publicly owned sites in the communities of Pembina-St. Vincent, Grand Forks-East Grand Forks, and Wahpeton-Breckinridge were already sampled by Wertz et al. (2013).

Since this was a joint project with the University of Minnesota, a shared folder was created in the spring of 2019 using Google Drive. All project-related information was put into the shared drive including photos of field work, tree-ring measurements, and a spreadsheet containing additional information about every sample. The shared drive helped with communication between the two research teams.

Samples were collected as far north as the LaDoux (LDX) site, west of Pembina, ND and as far south as the Fort Abercrombie (FTA) site in Abercrombie, ND (Table 1). A large number of sites were located within and near the Fargo-Moorhead community. Samples came from standing and fallen bur oak trees, historic log buildings, and sub-fossil logs from the riverbanks of the Red River (Figure 8). Samples were collected from log buildings (Figures 9 and 10) and from standing bur oak trees (Figures 11 and 12). Samples were collected as increment cores, cross-sections, and photos. Some samples were chunks of wood that broke off from logs (Figure 13). While they are not truly cross-sections, they are closer to a cross-section than a core.

Table 1. List of site names, abbreviations, and coordinates.

Site Names	Site Abbreviations	Site Coordinates (DMS)
LaDoux	LDX	48°58’11”N, 97°25’11”W
Pembina Cabin	PEM	48°57’57”N, 97°14’28”W
Drayton	DTN	48°37’02”N, 97°07’04”W
EGF Rod and Gun Club	RGC	48°03’47”N, 97°05’11”W
Grand Forks Post Office	GFC	47°53’49”N, 97°01’39”W
Climax, MN	VRA	47°36’29”N, 96°49’26”W
Craig Alan Peterson	CAP	47°26’53”N, 96°48’56”W
Chuck Bernhardson	CBS	47°25’54”N, 96°49’01”W
Perley	PRL	47°10’01”N, 96°44’55”W
Hudson Bay Company	HBC	47°05’23”N, 96°49’05”W
South Georgetown	SGT	47°04’01”N, 96°49’20”W
Harwood	HWD	46°59’42”N, 96°53’47”W
Sheyenne Gardens	SHY	46°59’26”N, 96°53’36”W
Bultman	BUL	46°59’36”N, 96°49’23”W
Riverwood Park	RRW	46°56’39”N, 96°48’05”W
Cassel Woods	CSL	46°56’33”N, 96°47’15”W
Edgewood Golf Course	EGC	46°55’43”N, 96°45’59”W
Probstfield	PFD	46°55’19”N, 96°45’11”W
Sam DeMarais	SAM	46°54’50”N, 96°45’52”W
Lunde	LDE	46°54’34”N, 96°37’21”W
Bergquist	BQS	46°53’09”N, 96°46’07”W
Burbank Station	BBS	46°52’36”N, 96°46’07”W
Lions Conservancy Park	LCP	46°48’52”N, 96°48’08”W
Nyquist	NYQ	46°47’47”N, 96°47’57”W
Horace	HRC	46°45'17”N, 96°54’32”W
Bernhardson House/Cabin	BHH/BHC	46°41’34”N, 96°47’06”W
Oxbow Golf Course	OXB	46°40’04”N, 96°47’45”W
Ness	NES	46°36’57”N, 96°46’30”W
Daniel Anderson	DAN	46°34’52”N, 96°45’30”W
Fort Abercrombie	FTA	46°26’44”N, 96°43’11”W

Tree characteristics

Bur oak trees were studied since they provide a useful proxy for determining past flood events (St. George & Nielsen, 2002). In the Red River Valley, bur oak trees are generally found within 100-200 meters of the river (Wertz et al. 2013). Areas right next to the river are typically dominated by eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall), green ash, and boxelder maple (*Acer negundo* L.). Bur oak is not as competitive as close to the river as these other species are, so bur oak trees are commonly found farther from the river. Bur oak is more fire tolerant than these other species and they tend to dominate the forest-prairie ecotone (Peterson & Reich, 2001).

Euro-American settlement on the United States portion of the Red River Valley began during the 1870s. With settlement, most trees were harvested for construction of houses and barns, firewood, and other purposes. Bur oak was a popular tree to use for construction due to its large size and the decay resistance of the wood. This left few young and smaller bur oak trees in the region. Therefore, in this study, bur oak trees establishing earlier than the 1870s were difficult to find, but not impossible. For the purpose of this study, 'old' refers to standing bur oak trees that pre-date Euro-American settlement.

Figure 8. (A) Sampling a standing bur oak tree with an increment borer, (B) Using a belt and orbital sander on log ends to prepare for photos of a log building located in Pembina, ND, (C) A subfossil bur oak log on the banks of the Red River.

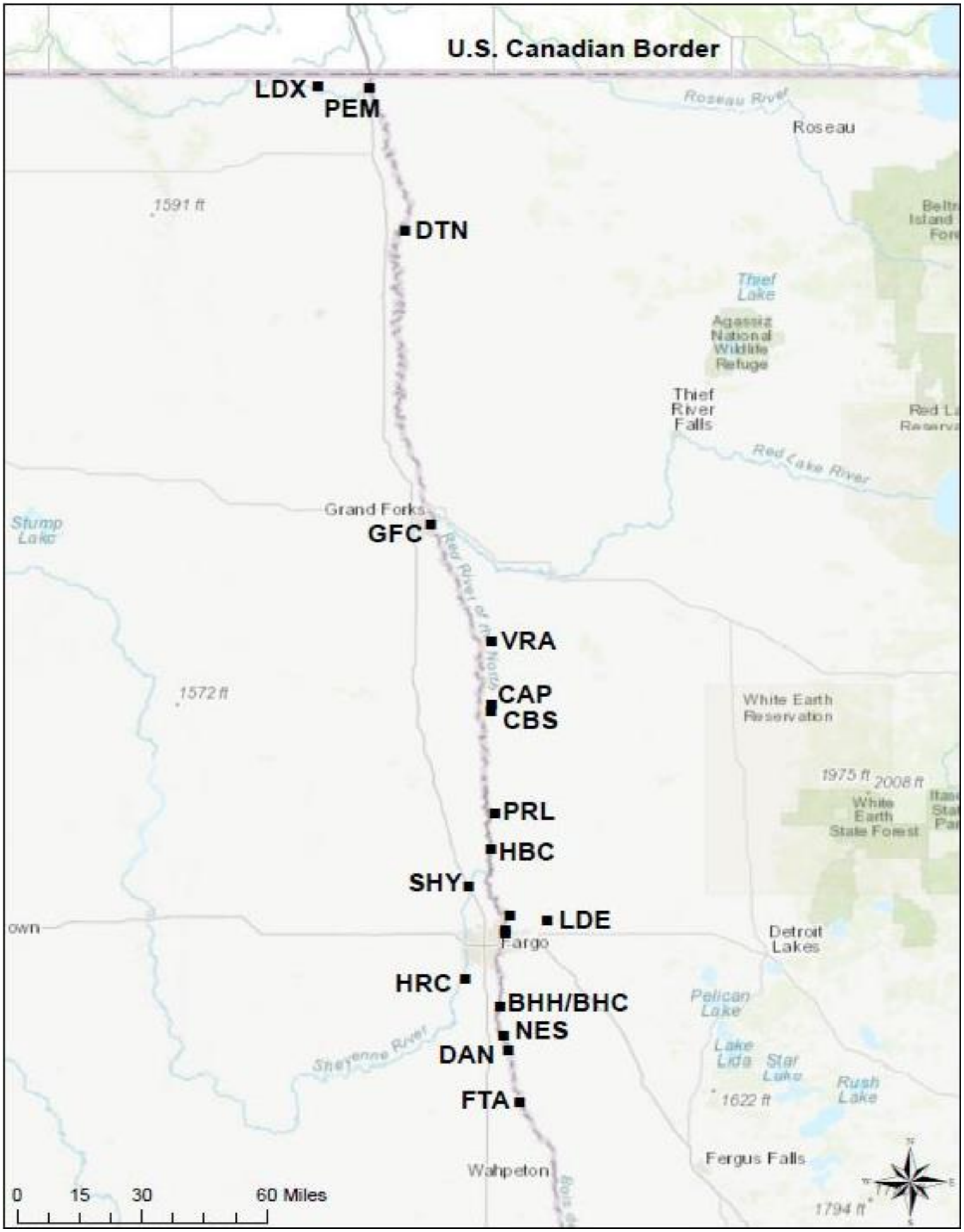

Figure 9. Log building sites outside of the immediate Fargo-Moorhead community.

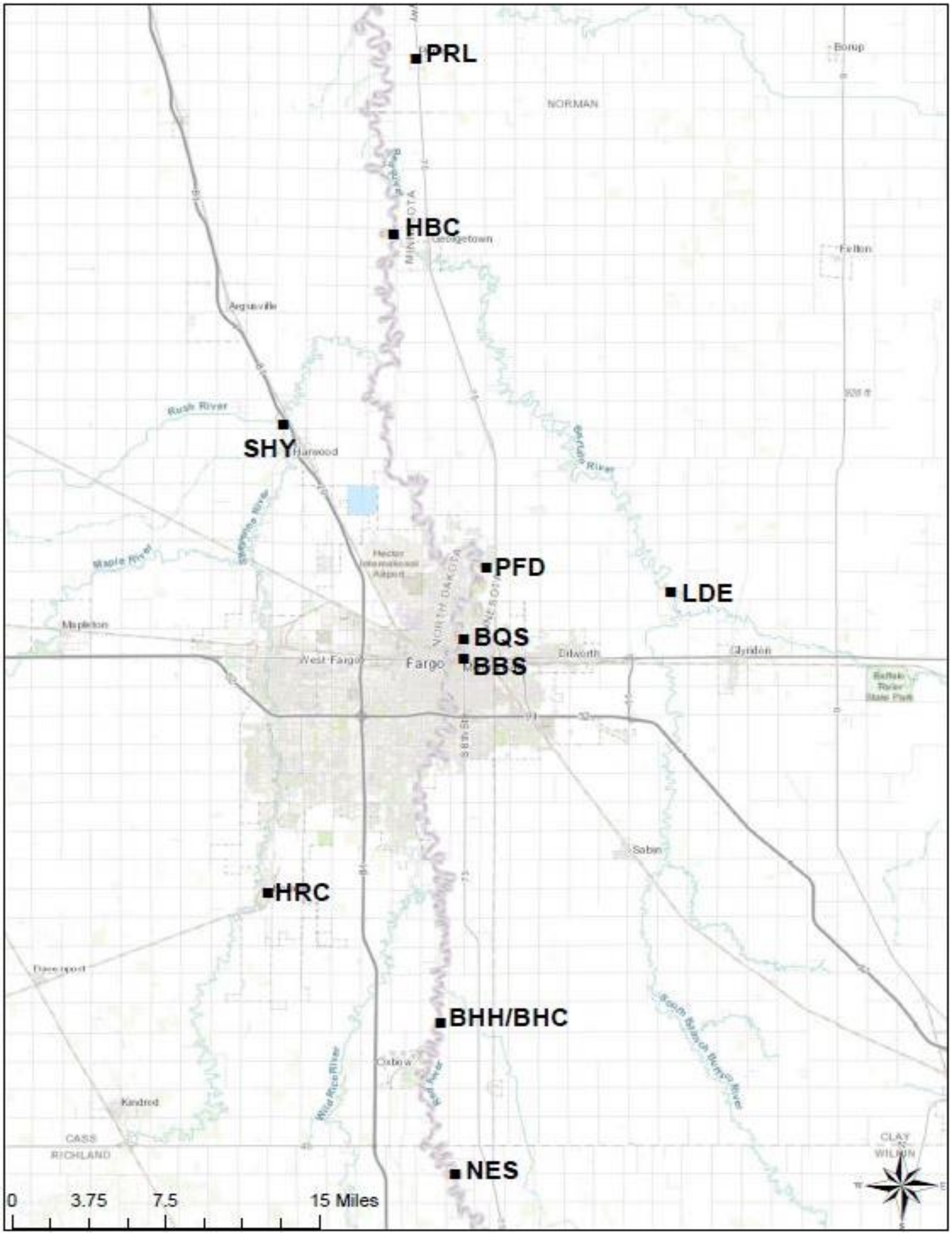

Figure 10. Log building sites within close proximity of the Fargo-Moorhead community.

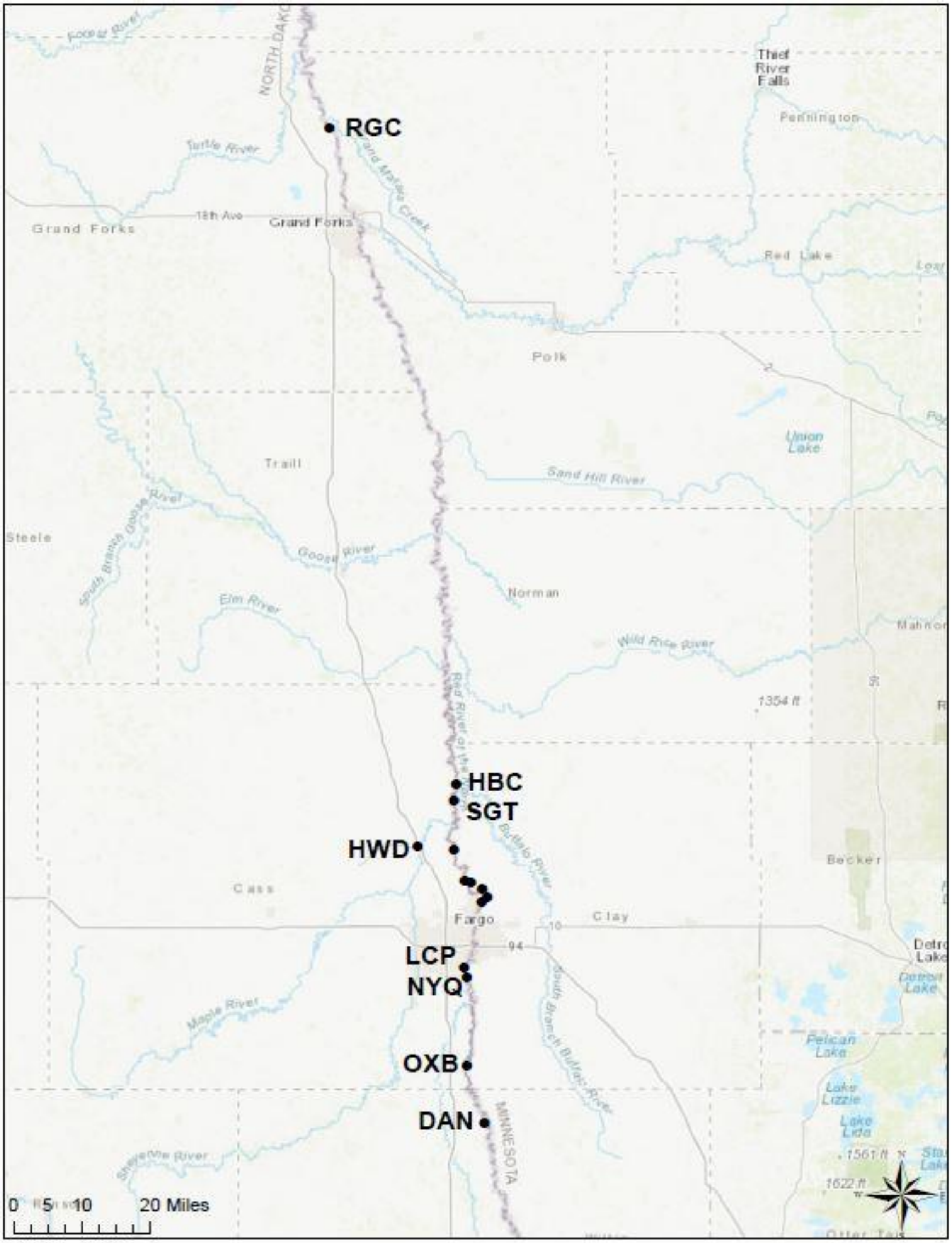

Figure 11. Bur oak tree sites outside of the immediate Fargo-Moorhead community.

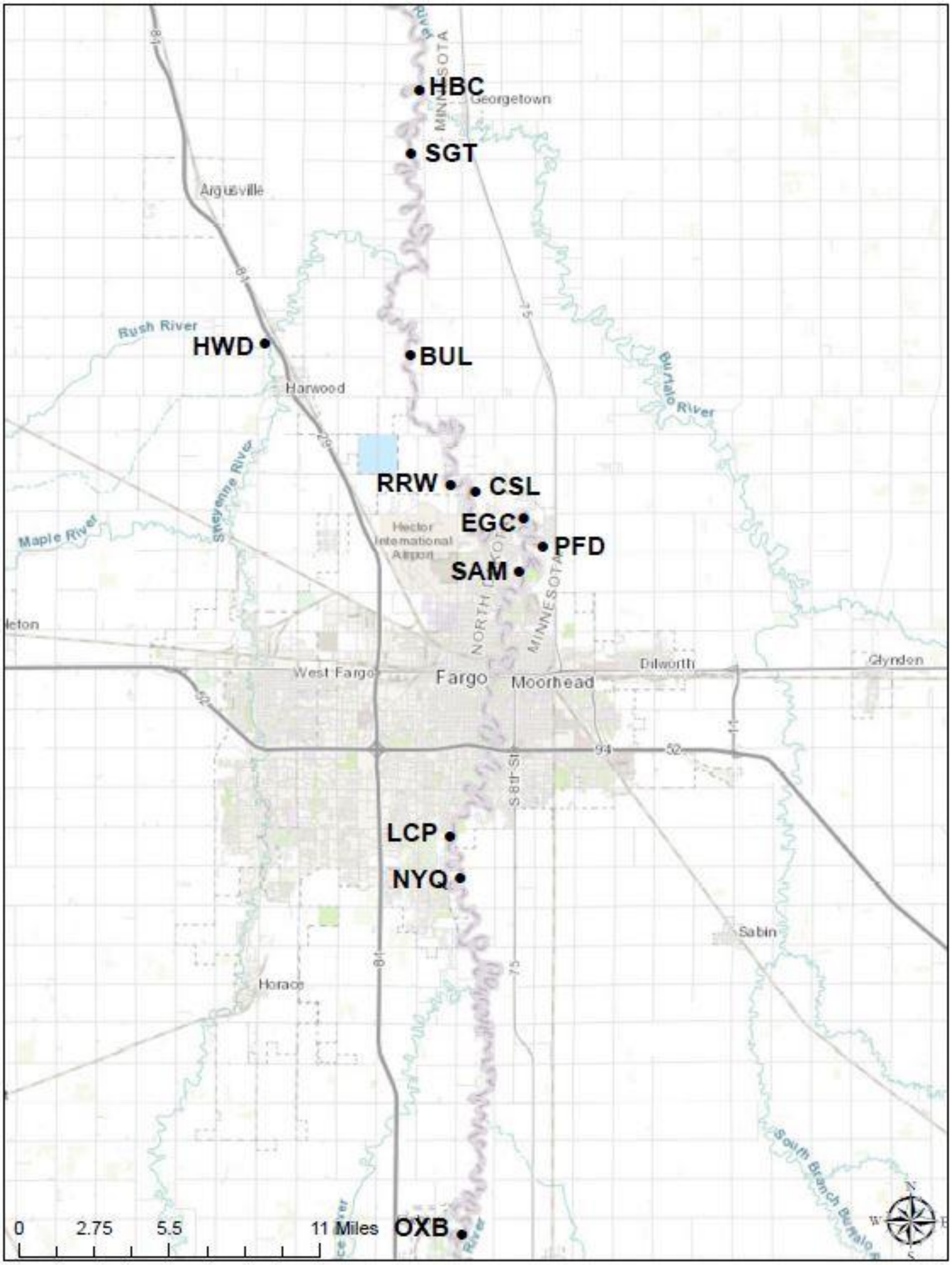

Figure 12. Bur oak tree sites within close proximity of the Fargo-Moorhead community.

Figure 13. A typical cross-section collected from a historic log building (above), a wood chunk collected from the LDE site (below).

Two characteristics were used to identify old bur oaks – trunk size and branch diameter at height. Older bur oaks are usually going to have larger trunks than younger oaks. However, location of the tree was taken into consideration when analyzing trunk size. Several bur oak trees that were open-grown were not sampled. Though they had large-diameter stems, they were likely not ‘old’ as defined above. Older oak trees also tend to have larger diameter branches higher up in the crown than do younger oak trees.

Sites and individual oak trees were located in a number of different ways. For sampling sites, larger patches of woods along the Red River were targeted by using Geographic Information Systems (GIS) from each adjacent county to help search for sites likely to hold old bur oak trees. While there is no hard data proving that large patches of forest always hold old bur oak trees, it gave us a larger number of trees to search through in any given site. Although the use of GIS was successful in identifying these sites, most forests were found on private land. Once the sites were selected, phone calls were made to the landowner, if a phone number existed on the county's GIS website. If the number was not listed on the county's GIS website, a short Whitepages search for the landowner's name was done.

Phone calls were made to roughly 40 landowners during May of 2019. Most phone calls were unanswered, and voicemails were left if possible. Only one landowner returned a phone call after receiving a voicemail. Ten landowners answered, four of whom did not wish to participate in the study. The other six were interested in participating, and three of these sites were sampled once permission was granted. One more site was visited but was not sampled because very few trees fit the description we wanted. I did not visit the other two sites because other work got in the way and visiting these standing tree sites were not as high of a priority.

Site visits on public lands in the Fargo-Moorhead community were beneficial in locating standing old bur oak trees. Wertz et al. (2013) had previously sampled Lindenwood Park, Oak Grove Park, and the Red River Trail in Fargo, ND. Those sites were avoided for this study. Instead, Riverwood Park, Cassel Woods, Edgewood Golf Course, and Lions Conservancy Park were public sites that were sampled for this study. Word-of-mouth from private landowners, help from an employee in the Fargo Parks District, and personal local connections also helped in identifying sites and potentially old bur oak trees.

Sampling bur oak trees

For standing oak trees, increment borers were used to retrieve core samples. To increase the likelihood of finding a flood ring, cores were taken as low to the ground as possible.

However, the sampling height had to be high enough to properly turn the handle of the increment borer. Most samples were taken within 35-50 centimeters from the base of the tree. Sampling height was recorded for some, but not all standing bur oak trees. Diameter at breast height was also recorded for some but not all standing trees. This information was stored in the spreadsheet in the shared drive.

Typically, two cores were taken from each tree on opposite sides to ensure at least one useable sample. If there was an inadequate spot to sample on the opposite side of the first core, the second core would be extracted at a different spot on the tree. Sometimes only one core was taken for reconnaissance purposes. After the first core was extracted, we would estimate the age roughly by counting the number of annual rings. If the tree was not estimated to be pre-1870, we would only collect one core and move on to the next tree. Bur oak trees that showed signs of rot were avoided unless the tree had promise of extending earlier than the 1870s. In some cases, if a large bur oak tree had fallen or was cut down, a cross-section was taken (Figure 14).

Sampling historic log buildings

Samples from historic log buildings helped to extend the chronology several hundred years past the chronology that was created from standing bur oak trees. Most of the logs sampled from these buildings were structurally intact with the building. However, some historic log samples were from dismantled or destroyed buildings and the leftover logs were in someone’s possession. Also, it’s important to note that some buildings also had reconstruction work done in the past and documentation of replacement logs by the owners or those who reconstructed the buildings was poor or even non-existent. Therefore, some logs that were sampled might not have been original logs used in the construction of the building.

Whenever possible, samples were collected from the bottom of the log, which would be the closest to the bottom of the tree. However, it wasn't always possible to identify which end of the log was the bottom. Subtle differences in sizes of the two ends helped determine which end of the log was the bottom. Another sign used to determine the bottom of the log was remnants of branches. Branches have a downward angle that can help determine which end of the log was the bottom. Once the bottom of the log was identified or estimated, cores or cross-sections were taken.

Figure 14. Sample from a fallen bur oak tree at the NYQ site. A narrow section was taken off the log on the left side of the photo to avoid hollow spot.

Collecting cross-sections with a chainsaw was the preferred method for taking samples from historic log buildings because it was less time consuming than other methods. However, it was not an option every time since some of these buildings are well preserved and the owners did not allow this destructive practice. Additionally, collecting a cross-section can only be done if the log ends stick out beyond the joinery. When using a chainsaw, most times, two radii could be measured for the sample, unless rot or other issues arose that made the second radius immeasurable. Two radii helped increase the likelihood of properly crossdating a sample.

Core samples were collected from historic log buildings by using an increment borer or an ‘archaeo borer’. Archaeo borers are designed for use with a power drill for collecting cores from dry wood. Two styles of archaeo borers were used and were supposed to be the main method for collecting samples from historic log buildings. However, these tools did not perform as expected, so we discontinued using them after only one core was collected. Dr. Zeleznik had more success prior to the study, collecting 16 cores from log buildings.

We assume the logs used for the construction of these buildings came from trees that were growing immediately adjacent to where the building was originally located. Though this assumption may-or-may-not be true, it’s very difficult to prove either way. Also, we have sites that are located near more than one tributary of the Red River making it even harder to determine where the logs came from. For example, for the Chuck Bernhardson (CBS) site, it’s not possible to tell if the logs came from the Marsh River (0.9 miles North) or if the logs came from the Red River (1.5 miles West).

In some cases, collecting physical samples from a log building was not always possible. In these instances, photo samples were collected. First, the ends of the logs were sanded down the same way cross-sections were sanded. To have a better contrast for the picture, a Sharpie marker and chalk were used on the log ends after the sanding process (Figure 15). Digital photos were then taken with a Sony Alpha 500 camera with a 100-macro lens mounted onto a tripod. Pictures were taken in a straight line along a mounted 15-centimeter ruler on the log end. The ruler was added to provide scale. Additionally, the ruler acted as a marker between pictures to ensure each picture had overlap with the previous picture. Once all photos were taken, the pictures were uploaded into a folder, incorporated into the shared drive, and the photographs were visually analyzed. The photographs were then visually crossdated, if possible.

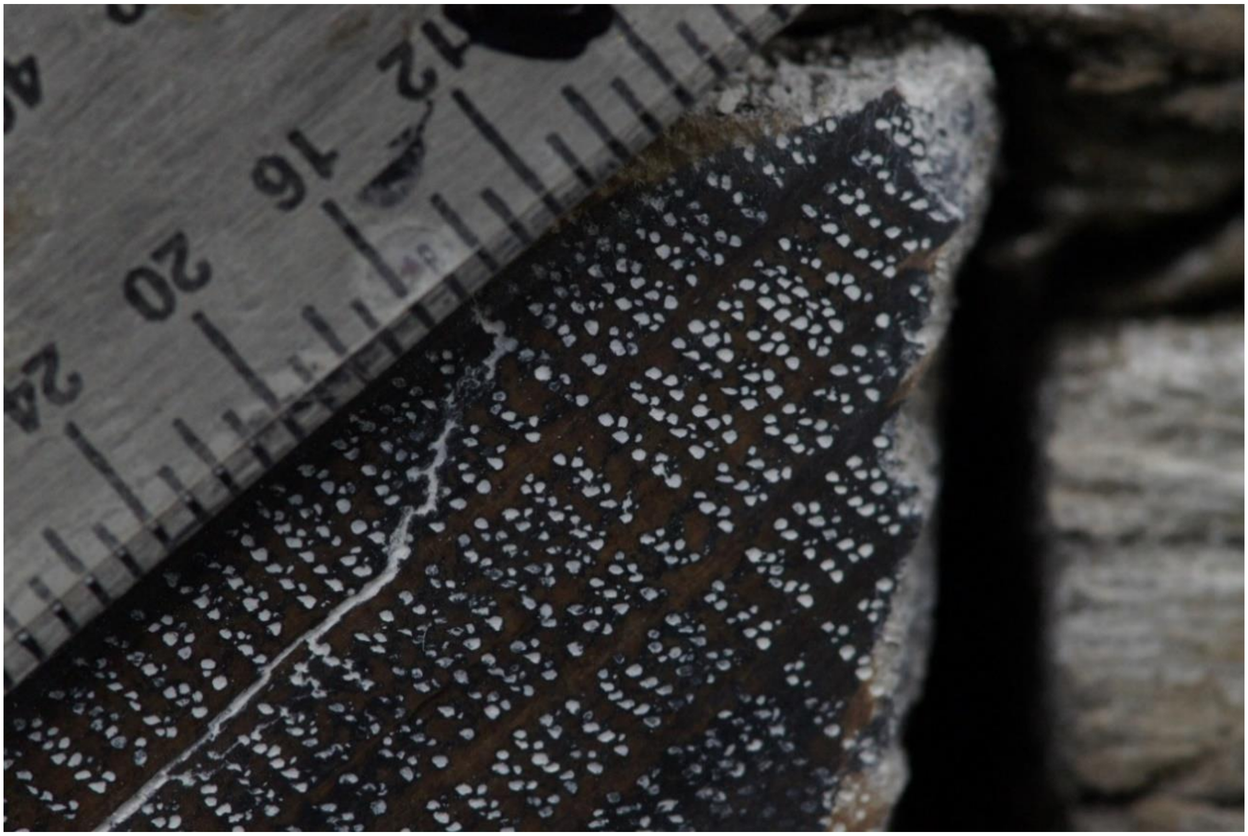

Figure 15. Example of the Sharpie and chalk method with the ruler on upper left-hand side of the photo.

Sampling subfossil logs

Searching for subfossil logs was completed by taking a boat on the Red River and traveling at a slow speed while looking for large or dark colored logs sticking out of the riverbanks. Larger logs were focused on since smaller logs may not have enough annual rings to be properly crossdated. These logs turn dark, almost black, when they have been buried for several hundred years.

The first year of the study (2019) was extremely wet in the region, especially during the fall. The Red River in Fargo stayed at or above flood stage 5.45 meters (18 feet) for 23 days from October 12th to November 4th. These two months are when the Red River is typically at a lower water level (https://waterdata.usgs.gov/nd/nwis/uv/%3Fsite_no=?station=05054000). The Red River never dropped below 4.57 meters (15 feet) for the months of August, September, October, or November 2019. One trip was made on the Red River in north Moorhead on September 3, 2019 to try and identify possible locations that would hold subfossil logs. The height of the Red River on that day in Fargo was 4.72 meters (15.5 feet). We launched from the M.B. Johnson Park landing in Moorhead and traveled both upstream and downstream. While on the river, Garmin 93sv and 73sv fish finders were used to side scan the bottom of the river and along the riverbanks. The goal was to find subfossil logs on the bottom of the river or sticking out of the banks, beneath the surface of the water that were not otherwise visible. This attempt was beneficial in locating logs, but no samples were collected because we were unable to determine a successful way of sampling these logs underwater. Later, we determined that collecting subfossil logs beneath the water surface would be too difficult. We decided to only sample above the water surface.

Water levels for the Red River were lower in 2020, though still not ideal. One trip was made on June 30, 2020 near Halstad, MN, when the river level was at 2.6 meters (8.5 feet, 17.5 feet below flood stage at that site). The river height in Fargo was 4.57 – 4.59 meters (15.00 – 15.06 feet) for that day. While on the water, each researcher scanned one side of the river while traveling at a slow pace. Mid-summer rainfall caused the Red River to rise so the next trip wasn’t until the fall of 2020.

Two trips were taken near Pembina, ND, during consecutive weeks in October of 2020. At the time, the Red River was at its lowest point for the year. The heights of the river were at 3.96 meters (13 feet) on October 7, and 3.81 meters (12.5 feet) on October 13. Flood stage for the Red River in Pembina is 11.89 meters (39 feet). The river heights in Fargo were 4.51 and 4.48 meters (14.8 and 14.7 feet), respectively for those dates. During the October trips, the researchers both focused on the same bank for half the time allotted for the day. Once the day was half over, the other side of the river was scanned by both parties while returning to the landing. Two additional trips had been planned later in the year, however, a COVID infection and poor weather and road conditions led to these trips being cancelled.

If a possible subfossil log was discovered, a small piece of wood was cut off the log using a handsaw to determine the species. Since it was difficult to identify species without sawing off a piece of wood, there was a large portion of time each trip that was spent working on species other than oak. As time went on, we got better at identifying which logs to sample and less time was spent working on species other than oak. Once an oak was found, a chainsaw was used to remove a cross-section. Cross-sections were taken as close to the base of the log as possible, if the base of the log could be identified. That is, minimal digging – if any – was done to uncover the base of log. Sample locations were marked by GPS.

Sample processing

Cores from standing oak trees were dried out for one week before they were glued into slotted mounts. These samples were then sanded by hand using 120, 220, and 320 grit sandpaper to more clearly define the annual rings. Cross-sections from standing or fallen trees were dried out for at least six months before the sanding process began. Cores and cross-sections that were collected from historic log buildings did not need to be dried out and they could be sanded down immediately if they were in good condition. Some cross-sections had major cracks throughout the sample, were punky or rotten, or had been severely weathered. Cross-sections that were in poor condition were stabilized with an epoxy resin to keep them from falling apart. Once the epoxy resin set, samples were sanded down by a belt sander using 36, 80, and 120 grit sandpaper. This was followed up by sanding with a random-orbit sander using 120, 220, and 320 grit sandpaper until the annual rings became more visible and the surface of the cross-section was smooth.

Dating/crossdating

After sanding, samples were viewed through a boom-mounted dissecting microscope, 10X-40X. First, samples were dated using visual clues. Samples that were taken from standing bur oak trees typically had a last year of growth (LYOG) from the year the sample was collected. The LYOG for a sample was recorded only for the sample's last full measured annual ring in the shared spreadsheet. Some sample's true LYOG was incomplete because it was sampled in the growing season and these rings were not measured. The true LYOG was noted in the spreadsheet as an incomplete LYOG.

If possible, samples that came from a dead/fallen tree or a log building were visually crossdated by using marker years if they could be identified. Marker years for bur oak trees in the Fargo-Moorhead area had been identified before this study (Table 2). Marker years are typically especially narrow and especially wide rings. However, they can also be identified in years where most samples show flooding or there are other distinguishable characteristics within the annual ring. A marker year used for some log building samples was 1826. Flood rings were commonly found in one site for the study, making it a useful marker year. Another marker year was 1910. There is ‘delayed earlywood’ in several samples that can be visually recognized. If marker years weren’t visually recognized, the sample was crossdated statistically (see below).

Next, whether the samples were visually crossdated or not, the ring widths of most physical (non-photo) samples were measured to the nearest 0.001 millimeter using an Acu-Rite slide scale interfaced with Measure J2X software. Overall, at least 80% of the physical samples collected were measured. The only physical samples that weren’t measured were samples that went to the University of Minnesota shortly after collecting. Samples were then statistically crossdated against the master chronology utilizing the program COFECHA. An initial master chronology for the Fargo-Moorhead area was created by Dr. Zeleznik prior to this study. Even if samples had been visually crossdated, the ring widths were statistically crossdated to ensure the sample was crossdated properly. If the sample was unable to be visually crossdated, statistical crossdating usually helped determine the years of growth for the sample.

Table 2. Potential marker years for bur oak trees in this region, listed chronologically. Index values created in the program COFECHA (Holmes, 1999). An index value of 0 indicates an ‘average’ relative ring width.

Marker Year	**Index Value (Narrow Rings)**	**Marker Year**	**Index Value (Wide Rings)**
1980	-2.137	1999	1.793
1955	-1.401	1998	2.193
1936	-1.482	1974	1.500
1900	-1.703	1949	1.703
1889	-1.656	1928	1.804
1865	-1.764	1927	1.633
1863	-1.514	1902	1.688
1846	-1.512	1892	1.797
1839	-1.900	1882	1.698
1823	-1.967	1856	1.945
1810	-1.659	1853	2.323
1793	-2.297	1813	1.721
1791	-2.365	1802	1.428

Statistical crossdating against the Fargo-Moorhead master chronology did not always help determine the years of growth for every sample. Samples collected from the LDX site near Pembina, ND, did not crossdate well with the master chronology from the Fargo-Moorhead area (data not shown). In this case, the samples were compared against a master chronology of bur oak trees from southern Manitoba to offer insight.

A new master chronology with ring-width measurements from 179 radii was created towards the end of the study for the Red River Valley in the United States. A total of 179 radii were measured from cores and cross-sections from standing trees (78) and cores and cross-sections from log buildings (101) However, this chronology does not contain data from every sample. Some of the samples were photographs, which we were unable to measure. Some samples also did not statistically crossdate well with the master chronology, even though marker years were identified. There were also multiple samples that were transferred to the University of Minnesota before ring widths were measured.

After the samples were properly crossdated, years were marked clearly on the samples using standard dendrochronological techniques (Stokes & Smiley, 1996). Visual analysis for flood rings was focused on next, looking for any of the four characteristics of a flood ring (Figure 3). Flood rings were noted within the shared spreadsheet. Special attention was focused on 1997, 1852, and 1826, years that were documented to have large floods on the Canadian and/or the United States portion of the Red River.

RESULTS

Overall project results

Table 3. Summary of project data. This includes all information except for the subfossil logs and photo samples that could not be crossdated.

# Sites	# Series Dated	Chronology	# Flood Rings	# 1826 Flood Rings	# Annual Rings
29	228	1601-2019	97	32	31,077

Overall, 14 sites were sampled for standing oak trees or oak trees that had fallen over. From these sites, 69 cores were collected from 48 standing trees. Four cross-sections were also taken. The ring count from standing trees totaled 11,140 annual rings from 77 radii. The chronology for standing oak trees was 1733-2019. Sample depth for standing bur oak trees stayed at 10 or greater, 1822-2019. Sample depth is sample size for a given year. Sample depth for standing oak trees peaked at 71, 1943-1958 and 1966-2003.

Cross-sections, cores, and photographs from historic log buildings helped extend the chronology even further. A total of 20 log structures – either standing buildings or logs from torn down buildings – were sampled from 18 sites (two structures at the BHH/BHC site and the DAN site). In total, 63 cross-sections, 16 cores, and 18 photo samples were collected from log buildings. The ring count for log buildings is 19,937 from 151 radii. This includes the photo samples that were visually crossdated from each site. There were an additional 63 photo samples (radii) that could not be crossdated from PEM (54), GFC (5), PFD (3), and HRC (1). The chronology for the log building samples was 1601-1908. Sample depth for log buildings stayed at 10 or greater, 1681-1877. Sample depth peaked at 104, 1822-1829 and 1838-1847.

Subfossil logs were intended to help extend the chronology even further back in time. However, only one radius from a subfossil log (RED10) was measured and the number of annual rings (66) was too small to crossdate. Hence, no subfossil logs were used for the results in this study. Subfossil logs are discussed more below.

Flood rings

Ninety-seven (97) flood rings were visually identified in 28 separate years among the samples (Table 4). The most common year for a flood ring was 1826, which made up 33% of all flood rings in the project with 32. The sample depth for 1826 was 132 and 24% of the samples showed flood rings. However, 28 of the 32 flood rings for 1826 came from the CBS site. The other flood rings came from the VRA (2), HBC (1), and SHY (1) sites. Twelve (12) flood rings were also recorded for 1997 and 1852. A flood ring for 1997 occurred in nearly 17% of the samples for the year. A flood ring for 1852 occurred in nearly 10% of the samples that had a ring for the year. Similarly, the CBS site contained 10 of the 12 flood rings for 1852.

The most common flood ring characteristics identified in the study were shrunken earlywood vessels (Figures 16 and 17) and/or increased parenchyma (Figure 18) in the latewood portion of the annual ring. Note: most of the 1826 flood rings did show shrunken vessels, though Figure 18 did not. For unknown reasons, increased parenchyma in the latewood portion of the annual ring occurred mostly in flood rings in the 1800s, specifically in 1826. Extending earlywood vessels and a combination of shrunken and extending earlywood vessels did not appear in our study.

Table 4. Flood years, number of flood rings, and sample depth at each flood year.

Flood Year	# Flood Rings	Sample Depth
2011	5	65
2009	2	67
2001	4	71
1998	1	71
1997	12	71
1996	1	71
1993	1	71
1985	1	71
1975	1	71
1950	2	71
1948	1	71
1944	1	71
1941	1	70
1934	1	70
1873	1	84
1853	1	127
1852	12	127
1826	32	132
1824	2	132
1803	1	124
1801	1	122
1791	2	117
1789	2	117
1780	2	113
1778	2	113
1762	1	99
1622	2	3
1621	2	3

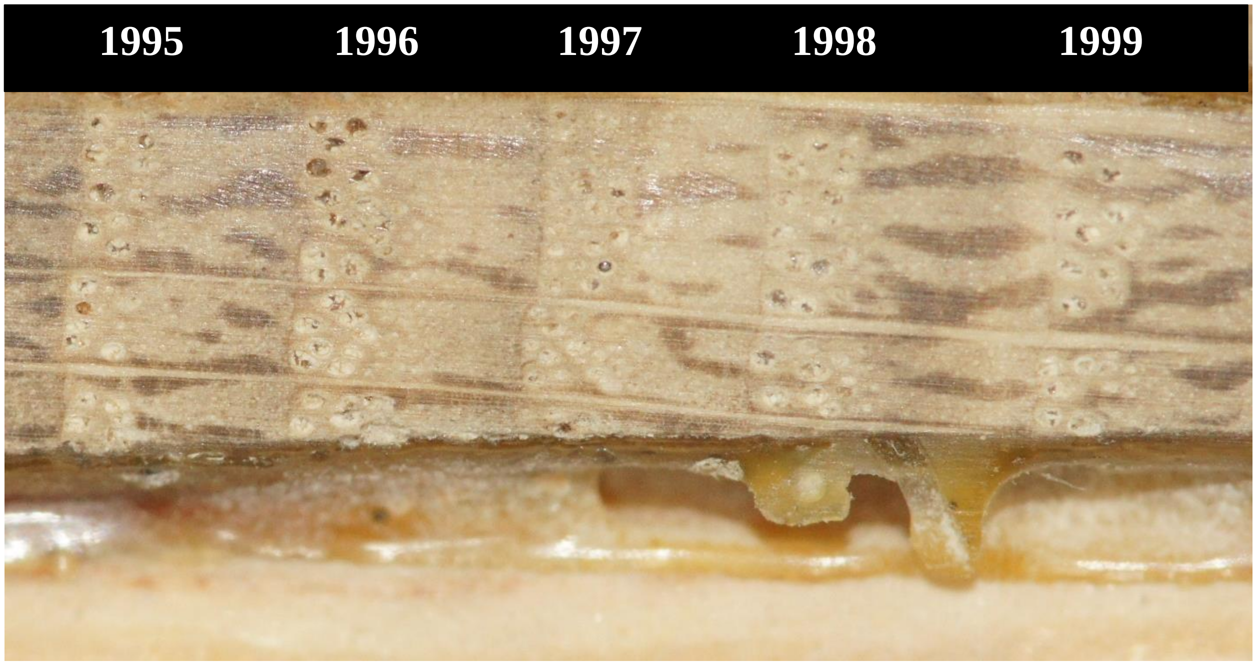

Figure 16. Flood ring in 1997 for sample HBC01 showing shrunken earlywood vessels.

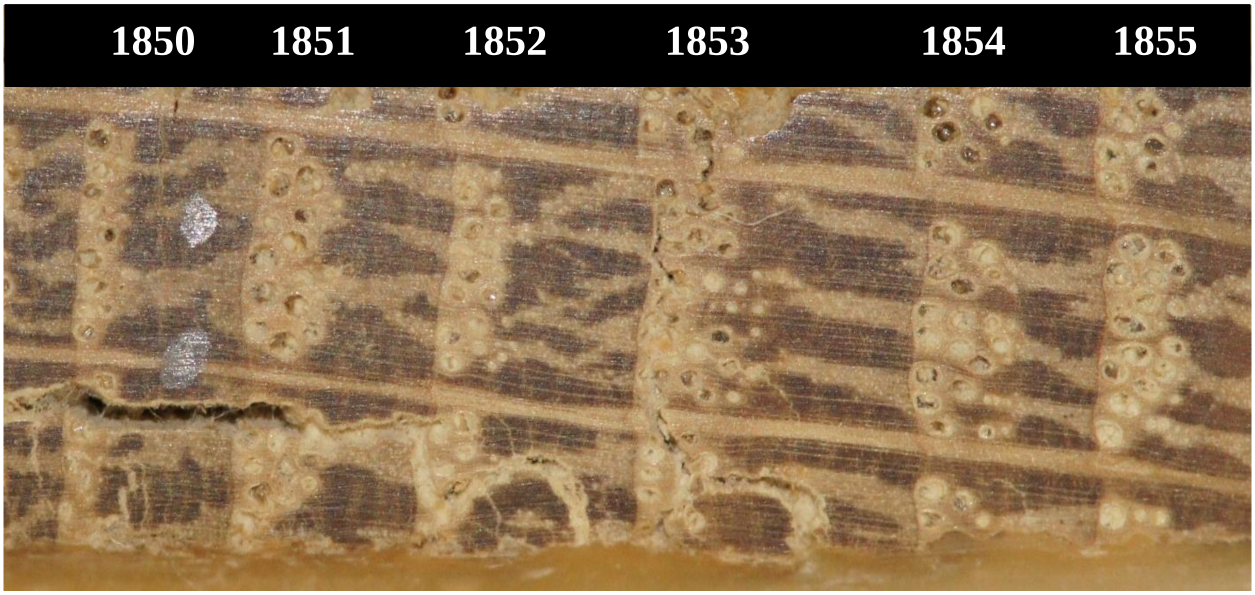

Figure 17. Flood rings in 1852 and 1853 for BBS01 showing shrunken earlywood vessels.

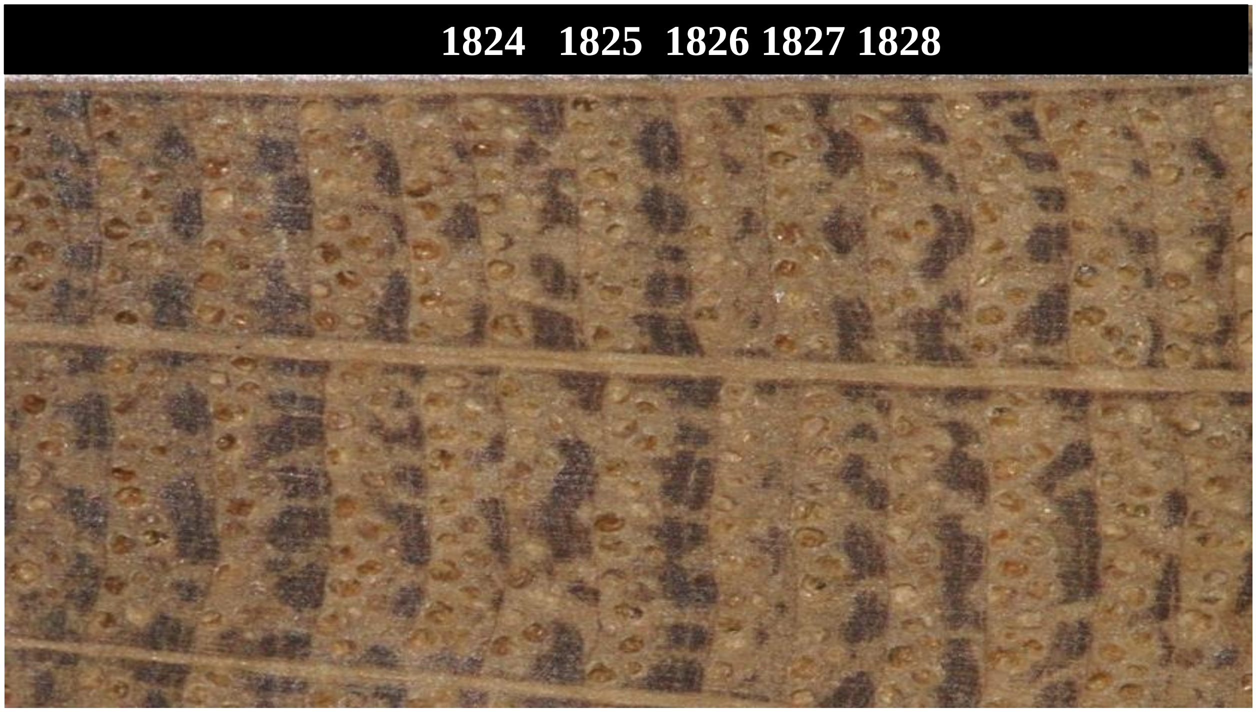

Figure 18. Flood ring in 1997 for HBC01 showing shrunken earlywood vessels and increase parenchyma.

Individual site results

Individual sites are presented below in Table 5 and in the text. The sites are presented in order as they are located north to south. The site abbreviation and name are listed, along with its general location, if it was located along a tributary of the Red River, sources of samples, radii collected, ring-width chronology, and number of flood rings. Additional notes are also presented in the text.

Table 5. Individual sites used for the study. Sites are listed from north to south. Subfossil logs and undated photograph samples are not included in this table.

Site Name	**Site Abbreviation**	**# Radii**	**Chronology**	**# Flood Rings**	**# 1826 Flood Rings**	**# Annual Rings**
LaDoux	LDX	6	1712-1878	0	0	954
Drayton	DTN	4	1751-1890	4	0	322
Rod and Gun Club	RGC	1	1899-2019	0	n/a	120
Grand Forks' First Post Office	GFC	5 (5 photos)	1732-1875	0	0	483
Climax, MN	VRA	5	1660-1881	2	2	906
Craig Alan Peterson	CAP	1	1753-1873	0	0	120
Chuck Bernhardson	CBS	40	1601-1876	46	28	6,772
Perley	PRL	5	1750-1908	0	0	572
Hudson Bay Company	HBC	10	1781-1852, 1869-2019	7	1	1,262
South Georgetown	SGT	3	1853-2019	1	n/a	456
Harwood	HWD	22	1882-2019	6	n/a	2,538
Bultman	BUL	2	1889-2019	0	n/a	198
Sheyenne Gardens	SHY	9	1716-1879	2	1	1,123
Riverwood Park	RRW	1	1924-2019	4	n/a	95
Cassel Woods	CSL	13	1800-2018	0	0	2,049
Edgewood Golf Course	EGC	13	1733-2019	9	0	2,406
Probstfield	PFD	16 (7 photos)	1663-1869, 1887-2018	1	0	2,045
Sam DeMarais	SAM	2	1867-2019	0	n/a	294
Lunde	LDE	3	1822-1872	0	0	140
Bergquist	BQS	7	1708-1870	1	0	746
Burbank Station	BBS	3	1788-1860	2	0	165
Nyquist	NYQ	2	1741-2007	4	0	527
Lions Conservancy Park	LCP	1	1883-2019	3	n/a	136
Horace	HRC	5 (5 photos)	1673-1877	3	0	753
Bernhardson House/Cabin	BHH/BHC	7 (1 photo)	1752-1879	0	0	699
Oxbow Golf Course	OXB	2	1875-2019	0	n/a	284
Ness	NES	2	1802-1870	0	0	136
Daniel Anderson	DAN	36	1712-2019	2	0	4,604
Fort Abercrombie	FTA	2	1744-1829	0	0	170

LDX – LaDoux

The LaDoux site is a log building located along the Pembina River, 13 kilometers due west of Pembina, ND. The Pembina River connects with the Red River on the northeast part of the town of Pembina. Three cross-sections were taken from the building and six radii were measured. The chronology from the site was 1712-1878. These samples did not statistically crossdate well with the Fargo-Moorhead master chronology. When statistically crossdated against the master chronology from the Southern Manitoba region, the results were slightly better (data not shown). No visual characteristics of flood rings were recognized.

PEM – Pembina Cabin

The Pembina Cabin is a log building located at Fort Daer Landing and Recreation Area in Pembina, ND, near the confluence of the Pembina River and the Red River. Its original location is unknown but is believed to be nearby. The site was visited in the fall of 2020 and 30 separate log ends and 54 radii were viewed as photo samples. Although most photographs turned out well, the majority of samples had extremely narrow rings. Visual crossdating was not possible. No flood rings were found in any of the samples. The only table including any information from PEM is Table 1.

DTN – Drayton

The Drayton building was originally along the Red River, roughly six kilometers northeast of Drayton, ND in Kittson County, MN (Figure 19). Overall, five cross-sections were collected but only two were used. The logs that were sampled had been salvaged from a torn down log building. The log home was apparently built in the early 1900s (Ox Cart Trails Historical Society, 2020). The building was torn down in 2007 and the logs were initially going to be used to create another log building at a different site. However, that did not happen. All the logs were left on a trailer and had weathered and decayed for years, making three of the cross-sections unusable. The chronology from the two cross-sections was 1751-1890, and a total of four radii were used. Flood rings were visually recognized in both 1791 (2) and 1789 (2) in the two radii of one of the cross-sections.

Figure 19. The original DTN building in Kittson County, MN near Drayton, ND (left); stacking logs from the dismantled building on trailer (right) in 2007. Photos from Ox Cart Trails Historical Society (2020).

RGC – East Grand Forks Rod and Gun Club

The East Grand Forks Rod and Gun Club site is located along the Red River in Minnesota, roughly 16 kilometers north of East Grand Forks, MN. The site was forested throughout much of the property. However, most bur oaks on the site appeared to be relatively young. Only one core was extracted from a standing oak tree. The years of growth for this sample was 1899-2019. Due to the young age and lack of large bur oak trees on the property, only one core was taken. No flood rings were found in the sample.

GFC – Grand Forks' First Post Office

Grand Forks' First Post Office is a historical log building currently located on the grounds of the Grand Forks Historical Society in Grand Forks, ND. The building was supposedly constructed in 1868 on the corner of Cottonwood Street and Second Avenue South in Grand

Forks, ND (Grand Forks Historical Society, Personal Communication, n.d.). The building was moved to its current location and reconstructed in 1975. However, documentation of the reconstruction and the relocation is minimal, and we can only assume the logs we sampled are original logs.

The sanding and photographing technique was used at this site and six log ends were sampled. Most of the logs in the building were actually American elm (*Ulmus americana* L.). We were able to visually crossdate four out of the six logs from five radii and the chronology was 1732-1875. We did not visually recognize marker years in the other two logs. No flood rings were visually identified from the photograph samples.

VRA – Climax, Minnesota

Three cross-sections were collected from John Vraa who lives near Climax, MN. While the Sand Hill River runs through Climax before entering the Red River 2.5 kilometers to the southwest, it is unknown where each sample from Vraa originally came from. Vraa collected logs during the 1990s from multiple sites in the local area. The three cross-sections from the salvaged log building(s) resulted in five radii, three of which were measured. Combined, the chronology was 1660-1881 from the three cross-sections. Only two flood rings were found from this site, both in 1826.

CAP – Craig Alan Peterson

The Craig Alan Peterson site is a log building within a modern house near Shelly, MN. This site is located along the Marsh River, which deposits into the Red River four kilometers to the northwest. One cross-section was collected, and one radius was measured. The location (within the building) of the specific log that provided this sample is unknown and the specific source of this cross-section on the log is unknown. Dr. Zeleznik received this sample in 2018 from the current landowner. The years of growth for this sample was 1753-1873. Overall, no visual evidence of flood rings appeared in the cross-section.

CBS – Chuck Bernhardson

The Chuck Bernhardson site is a log building located in Minnesota, south of Shelly. This building is two kilometers south of the Marsh River and the Craig Alan Peterson site. Twenty (20) cross-sections were collected and 40 separate radii were measured. The chronology from this site was 1601-1876. This site accounted for 47% of the total flood rings in the project (46/97), 87.5% of the flood rings for 1826 (28/32), and 83% of the flood rings found for 1852 (10/12). Other flood rings seen in the CBS samples include 1780 (2), 1778 (2), 1622 (2), and 1621 (2). Our longest-lived log (275 years) and oldest log from log buildings from this study was sample CBS08. The sample spanned the whole chronology of 1601-1876. A total of 20 radii from the CBS site had growth rings in the 1600s.

PRL – Perley

The Perley samples were collected in Minnesota from Hatchet and Company sawmill in Moorhead. The mill owner gathered the samples from a torn down barn near the town of Perley, MN. Perley is located roughly 1.6 kilometers east of the Red River and 32 kilometers north of Moorhead. The barn was built of sawn oak lumber, but the previous owner claimed that the lumber came from a local source. That is likely true as the samples crossdated well with the project chronology. Overall, five small pieces were collected and due to the size, only one radius was measured per sample. The chronology from the site was 1750-1908. No visual characteristics of flood rings existed in the samples. However, we have no idea where, on the original boards, these samples came from. They could be from the bottom of the board (or tree), or the middle, or the upper end.

HBC – Hudson’s Bay Company

The Hudson’s Bay Company site is located along the Red River in Minnesota, 2.5 kilometers northwest of Georgetown and 24 kilometers north of Moorhead. The site is located at the confluence of the Buffalo River and the Red River. Nine cores were collected from five standing oak trees, and one core was collected from a historic log. Most of the logs came from the Hudson’s Bay Trading Company warehouse that was located on the site; currently the logs make up the frame of a picnic shelter. Some logs in the frame are replacements and it is unknown which ones they are, or where they came from. Altogether, the chronology for the site was 1781-1852 and 1869-2018. The gap in the chronology is from the last year of growth of the core from the log structure and the first year of growth of the core from the oldest tree. Six total flood rings were visually identified in the cores from standing oak trees including 1997 (2), 1985 (1), 1975 (1), and 1950 (2). The core from the log building also showed one flood ring in 1826.

SGT – South Georgetown

The South Georgetown site is located along the Red River in Minnesota, 2.5 kilometers southwest of Georgetown and about 21 kilometers north of Moorhead. Two standing oak trees were sampled and a total of three cores were taken. The chronology for the site was 1853-2019. Only one flood ring was identified in 1997 for the site.

HWD – Harwood

The Harwood site is west of I-29 on the north side of Harwood, ND, and is located along the Sheyenne River, 7 kilometers upstream of its confluence with the Red River. Overall, 22 cores were collected from 12 standing oak trees. Most of these samples were collected in 2011 with assistance from students from the University of Minnesota. The chronology was 1882-2019. In all, 6 flood rings were identified in 2011 (2), 1948 (1), 1944 (1), 1941 (1), 1934 (1).

SHY – Sheyenne Gardens

The Sheyenne Gardens site is a nursery located in Harwood, ND. It is located along the Sheyenne River, roughly half a kilometer south of the HWD site. Five logs stored in an out-building came from a log building that had been torn down some years earlier on the HWD site. A short search for the remains of the possible homestead was conducted in 2020 with no success. Five cross-sections were collected from the logs and nine radii were measured. The chronology spanned from 1716 to 1879. Two flood rings were identified from the site for 1873 (1) and 1826 (1).

BUL – Bultman

The Bultman site is located along the Red River in Minnesota, five kilometers west of Kragnes and 13 kilometers north of Moorhead. Sampling occurred during the summer of 2019 and several trees were identified for potential sampling, but equipment failure resulted in collecting just one core sample from one standing oak tree. However, the core sample went past the pith and two radii were used. The chronology for this site was 1889-2019. No visual evidence of flood rings was identified.

RRW – Riverwood Park

The Riverwood Park site is located along the Red River, just north of Fargo, ND. One tree was sampled and only one core was collected. The rest of the site was searched, but most other standing oak trees appeared to be relatively young. The years of growth for the tree was 1924-2019. Four flood rings were recorded in the sample including 2011 (1), 2009 (1), 2001 (1), and 1997 (1).

CSL – Cassel Woods

The Cassel Woods site is an NDSU-owned property and is located within one kilometer of the Red River in Minnesota. The site is in north Moorhead (Oakport Township) and is located 1.2 kilometers east, and 1.3 river kilometers upstream of the RRW site. Cassel Woods is located east of Broadway Street and receives some protection from floods by the roadway. Overall, 11 cores and one cross-section were collected from nine standing oak trees, resulting in 13 radii. The chronology for the site was 1800-2018. No samples contained any flood rings.

EGC – Edgewood Golf Course

The Edgewood Golf Course site is located along the Red River in north Fargo, ND. Throughout the site, nine core samples and two cross-sections were collected from nine standing oak trees and 13 radii were used. The chronology was 1733-2019. Flood rings were numerous in this site with nine flood rings occurring in 1998 (1), 1997 (6), 1996 (1), and 1993 (1). Our longest-lived tree (277 years) and oldest sample from standing trees from this study was sample EGC02. The sample spanned 1733-2010. The tree was cut down by Fargo Park District personnel as it was in serious decline following the flooding in the mid-to-late 2000s.

PFD – Probstfield

The Probstfield site is a small patch of woods containing a log building that is located along the Red River in north Moorhead, MN. It is 1.3 kilometers southeast of the EGC site. Three cross-sections, three cores, and seven photo samples were collected from the log building at the site, resulting in 15 radii. Since some samples from the PFD site are photos, not all radii could be measured. One core from a standing oak tree was collected. The combined chronology of the site was 1663-1869 and 1887-2018. Despite the 302-year chronology including over 2,000 annual rings, only one flood ring was identified in 1824.

SAM – Sam DeMarais

The Sam DeMarais site is a private patch of woods located along the Red River on the north side of Fargo, ND. Two separate cores were taken from one standing oak tree. The chronology of this site was 1867-2019. No flood rings were visually recognized from the cores.

LDE – Lunde

The Lunde site is a log building located approximately five kilometers northwest of Glyndon, MN, along the Buffalo River. This site is 24 kilometers upstream from the confluence of the Buffalo and Red Rivers. The LDE building has been incorporated into a modern home. Two wood chunks (Figure 12) were collected from the log building and three radii were used. The chronology was 1822-1872. No flood rings were identified.

BQS – Bergquist

The Bergquist site is a log building located along the Red River in Moorhead, MN. The building was reconstructed in the 1970s with limited documentation. Therefore, the samples we collected may-or-may-not be the original logs used for construction of the original building. Two cross-sections and three cores were collected from the building resulting in seven radii. Combined, the chronology of the site was 1708-1870. The samples had visual characteristics of flood rings in 1852 (1) and 1745 (2).

BBS – Burbank Station

The Burbank Station site is a log building located along the Red River in Riverfront Park in Moorhead, MN. This building has been moved at least two times with limited documentation of when the building was moved. The design of the current building may-or-may-not reflect the original design. Little to no documentation exists regarding which logs were replaced. Two separate cores were collected from two logs resulting in a chronology of 1787-1860. One of the core samples went all the way through the log and had two radii. Flood rings were recognized in 1853 (1) and 1852 (1).

LCP – Lion's Conservancy Park

Lion's Conservancy Park is located at the confluence of the Rose Coulee and the Red River in Fargo, ND. One large standing oak tree was sampled, and the years of growth from the sample was 1883-2019. Three flood rings were recorded within this sample including 2011 (1), 2009 (1), and 2001 (1).

NYQ – Nyquist

The Nyquist site was a single tree that was sampled along the banks of the Red River south of Moorhead, MN (Figure 14). The tree had fallen over and a cross section near the bottom was collected and two radii were measured. The chronology of the cross-section was 1741-2007. Both radii contained visual characteristics of flood rings in 2001 (2) and 1997 (2).

HRC – Horace

The Horace samples came from a log building that was once located along the Sheyenne River in Horace, ND, but is now located five kilometers north/northwest of West Fargo. Five photograph samples came from three log ends and five radii were visually analyzed. The chronology from the photograph samples was 1673-1877. There were also three visual characteristics of flood rings occurring in 1803 (1), 1801 (1), and 1762 (1).

BHH/BHC – Bernhardson House and Bernhardson Cabin

The Bernhardson House and Bernhardson Cabin are two separate buildings at the same site located along the Red River in Minnesota, roughly three kilometers northeast of Oxbow, ND and 20 kilometers south of Moorhead. One core and one photo were collected from two logs on the house resulting in two radii. Three cores were collected from three logs on the cabin resulting in five radii. Two of the cores taken went all the way through the logs, resulting in two radii for each core. Overall, the chronology from the site was 1752-1879. No flood rings were recognized within the samples.

OXB – Oxbow Golf Course

The Oxbow Golf Course site is located along the Red River in Oxbow, ND. Two standing bur oak trees were sampled, and one core was collected from each tree. The chronology from the OXB site was 1875-2019. No flood rings were visually recognized in either of these samples.

NES – Ness

The Ness sample was collected from a log building located along the Red River in Minnesota, roughly 6.5 kilometers southeast of Oxbow, ND. Mr. Ness was told by his grandfather that the logs for this building came from the original Fort Abercrombie. Only one cross-section was collected, and two radii were measured. The chronology from the Ness site was 1802-1870. No visual characteristics of flood rings were identified within the sample.

DAN – Daniel Anderson

The Daniel Anderson site contains a log building, log granary, and 16 hectares of forest and is located along the Red River in North Dakota, three kilometers east-northeast of Christine, ND. We collected samples from both the log building and the granary, however, the building is missing the east wall. Though unproven, we believe that that wall was torn down and those logs were used in the construction of the granary. Altogether, 15 cross-sections were collected from the buildings and 30 radii were measured. Six cores from six standing oak trees were also collected. The total chronology for the site spanned 1712-2019 from 36 radii. Only two flood rings were recognized in the samples, occurring in 2011 (1) and 1824 (1).

FTA – Fort Abercrombie

Fort Abercrombie is a historic site located along the Red River in Abercrombie, ND. One cross-section was collected from a log at the site. However, where the log came from originally is unknown. The log was found on the bank of the river and is thought to be from a previous bridge at the site (L. Krueger, Personal Communication, n.d.). Two radii were measured from the cross-section and the chronology was 1744-1829. No flood rings were recognized in the cross-section.

Subfossil log search

We covered roughly eight total river kilometers on our first trip searching for subfossil logs on September 3, 2019 in the Fargo-Moorhead community. This trip resulted in finding three to four logs by using a fish finder to search for subfossil logs underneath the surface of the water. However, no samples were collected.

We covered roughly 12 river kilometers upstream on the Red River on our second subfossil log search on June 30, 2020 near Halstad, MN. On the return trip, we covered an additional five river kilometers along the Wild Rice River for a total of 17 river kilometers for the day. We collected only one subfossil log, and this was the only subfossil log visually analyzed for the study (RED10). The log had 66 annual rings and ring width measurements were taken. However, we were unable to visually or statistically crossdate the log. The sample did not appear to have any visual characteristics of flood rings.

We covered roughly 25 river kilometers on our third subfossil log search on October 7, 2020 near Pembina, ND. The trip resulted in collecting five logs along the banks of the river and marking the location of another log for future sampling. A rough visual estimate of ring counts was conducted on the samples collected and all logs appeared to have less than 65 years of growth (Table 6). These samples were never visually analyzed under the microscope due to the low number of rings.

We covered roughly 23.5 new river kilometers on our last subfossil log search on October 13, 2020 near Pembina, ND. This trip resulted in collecting 11 samples. A rough visual estimate for ring count was done on these samples as well, and all samples appeared to be under 70 annual rings (Table 6). These samples were never visually analyzed under the microscope.

Landowner visits

During July of 2020, Mr. Schlauderaff spent 3 ½ days conducting door-to-door visits asking residents for leads on log buildings along the Red River. Visits were conducted during the week from roughly 9:00 a.m. to 3:00 p.m. These visits took place in Pembina and Walsh counties in North Dakota, and Kittson and Marshall Counties in Minnesota. These counties were targeted since there was a low number of samples north of the community of Grand Forks-East Grand Forks. A total of 28 stops were made at random household locations along the Red River (Pembina – 4, Walsh – 7, Kittson – 8, Marshall – 9). Visits were focused on households very close to the Red River, since most oak trees that were used to create log buildings during Euro-American settlement most likely came from the banks of the Red River.

Overall, the visits were unsuccessful. No residents were aware of any historic log buildings that were still standing. Multiple people stated that many of these log buildings were destroyed or torn down in the 1960s and 1970s after weathering and suffering consistent flood damage. There were also several stops where landowners did not wish to speak. To be noted, the study occurred during the COVID-19 pandemic, which could have led to some individuals not wanting to come in close contact with another person.

Table 6. All logs collected during subfossil searches including Sample ID, estimated ring counts, and dates samples were retrieved. RM = River Miles

Date Retrieved	Sample ID	Estimated Ring Count	Upstream End Point	Downstream End Point
6.30.20	RED10	66	RM 393.5 (additional 5 river kilometers on Wild Rice River)	RM 381.5
10.07.20	RED11	41	RM 167.5	RM 155
	RED12	30		
	RED13	26		
	RED14	26		
	RED16	63		
10.13.20	RED15	Unable to determine	RM 182	RM 167.5
	RED17	63		
	RED18	67		
	RED19	35		
	RED20	40		
	RED21	50		
	RED22	26		
	RED23	26		
	RED24	50+		
	RED25	65		
	RED26	46		

DISCUSSION

Three assumptions regarding log buildings need to be discussed before moving further. The first assumption is trees that were harvested for the construction of log buildings came from a very close source to the original locations of the buildings. For example, we assume the logs used to construct the buildings at the DAN site came from the banks of the Red River on site. The second assumption is that all samples we collected came from the bottom end of the log/tree. This was true in some cases (e.g., many of the CBS samples), but for others (e.g., CAP and PRL), we have no idea where on the log the sample came from. These latter samples were given to us, rather than us collecting the samples in-person. Finally, we assume the samples collected are original logs for the construction of the building, they are not replacements. Multiple sites (e.g., BBS, BQS, and GFC) had poor or non-existent documentation of reconstruction work. Therefore, we were not always able to determine if the logs we sampled were original or replacements.

Flood rings

We considered 'large floods' to be those that were seen in 10% or more of samples. This was a threshold that was used by Therrell and Bialecki (2015). Beckers (2007), in studying fire scars of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), also used a threshold of 10% with the additional stipulation that sample size had to be 20 or more. In the current study, each year that has only one or two flood rings is not considered to be a large magnitude flood.

Between our study and St. George and Nielsen (2003), there were five years that formed flood rings in common (Table 7). These five years (1997, 1950, 1852, 1826, and 1762) are described as high-magnitude floods within St. George and Nielsen (2003). There were 21 years that recorded flood rings in our study that were not recorded in St. George and Nielsen (2003), given the overlap in sample years. In this study, 1826 is the only ‘large flood’ as defined above. In St. George and Nieslen (2003), there were 12 years that recorded flood rings that were not recorded in our study given the overlap in sample years. Seven years of flooding appear to be ‘large floods’ in St. George and Nielsen (2003) using the criteria listed above. However, 1538 and 1510 have a sample depth of only three and one, respectively. St. George and Nielsen (2003) do not list these years as high-magnitude floods.

St. George and Nielsen (2003) found flood rings in 1798 and 1764, which they did not believe were high-magnitude floods since they were recorded only by one tree. The authors believe the appearance of a flood ring was caused by poor local drainage. We also found apparent flood rings that seemed unusual given the year. Specifically, the HWD site contained what appeared to be flood rings in 1934, 1941, and 1944. However, according to the data from the river gauge in Fargo, flooding did not occur in those years. Instead, we believe these anomalous characteristics were caused by physical damage to the tree.

Table 7. Comparison of flood rings found in the current study and St. George and Nielsen (2003). The exact sample depth of each year for St. George and Nielsen (2003) was not available.

Year	# Flood Rings/Sample Depth and % Flood Rings Occurring in Study	# Flood Rings/Sample Depth and % Flood Rings Occurring in St. George and Nielsen (2003)
2011	5/65 (7.7%)	n/a
2009	2/67 (3%)	n/a
2001	4/71 (5.6%)	-
1998	1/71 (1.4%)	-
1997	12/71 (17%)	1/33+ (<3%)
1996	1/71 (1.4%)	-
1993	1/71 (1.4%)	-
1985	1/71 (1.4%)	-
1979	-	1/33+ (<3%)
1975	1/71 (1.4%)	-
1950	2/71 (2.8%)	45/111+ (<40.5%)
1948	1/71 (1.4%)	-
1944	1/71 (1.4%)	-
1941	1/70 (1.4%)	-
1934	1/70 (1.4%)	-
1873	1/84 (1.2%)	-
1853	1/127 (.8%)	-
1852	12/127 (9.5%)	13/52+ (<25%)
1826	32/132 (24%)	18/53+ (<34%)
1824	2/132 (1.5%)	-
1811	-	1/53+ (<1.8%)
1803	1/124 (.8%)	-
1801	1/122 (.8%)	-
1798	-	1/21+ (<4.8%)
1791	2/117 (1.7%)	-
1789	2/117 (1.7%)	-
1780	2/113 (1.8%)	-
1778	2/113 (1.8%)	-
1768	-	1/50+ (<2%)
1764	-	1/50+ (<2%)
1762	1/99 (1%)	1/49+ (<2%)
1757	-	1/50+ (<2%)
1747	-	9/49+ (<18.4%)
1741	-	1/49+ (<2%)
1727	-	1/39+ (<5.1%)
1726	-	2/38+ (<5.2%)
1682	-	1/12+ (<8.3%)
1658	-	1/8+ (<12.5%)
1622	2/3 (66%)	-
1621	2/3 (66%)	-
1538	n/a	2/3+ (<66%)
1510	n/a	1/1+ (<100%)

The flood of 1826 was recorded at four separate sites, including VRA, CBS, HBC and SHY (Figure 20). The VRA site recorded two flood rings for 1826. However, the specific origins of those logs are unknown. The CBS site is located just under 20 kilometers south of VRA near the confluence of the Goose and Marsh Rivers. The CBS site had a large number of flood rings, which was unexpected. The HBC site is roughly 40 kilometers south of CBS and contained a single 1826 flood ring. The HBC site is located at the confluence of the Buffalo and the Red Rivers. The SHY site recorded one flood ring for 1826 and is roughly 12 kilometers southwest of HBC. The original site of the SHY building was along the Sheyenne River. This could mean several things. The log that created a flood ring could have been harvested from the banks of the Red River. Or perhaps the log was taken from the banks of the Sheyenne River, assuming it flooded that year. Finally, it could be that the log was taken from the Sheyenne River but the Red River flooded so severely that its flood waters extended back to the Sheyenne River for six kilometers to the SHY site.

None of the four sites north of VRA contained a flood ring for 1826, even though the flood of 1826 was also recorded in Manitoba. However, only 13 radii were collected at these sites that spanned through 1826. While the photos from PEM could not be crossdated, if we assume that these photographs reach back to 1826, no flood rings appeared to be present. Under this assumption, an additional 54 radii would have covered the 1826 time frame. Similarly, the flood of 1826 was not recorded any further south than the SHY site. If it did occur south of SHY, it seems odd that no flood rings were created, especially given the number of radii that had a year of growth for 1826 (80+). There is also a 40-kilometer gap between the CBS and HBC sites that did not record flood rings for 1826. However, there is only one site (PRL) that is between these two sites.

Relative magnitude for each flood in St. George and Nielsen (2003) was estimated by comparing the number of flood rings to the overall number of samples collected. Using this method, the flood of 1826 was the largest magnitude flood for five out of eight (5/8) sites that spanned to that date. Hyland Park was sampled for 17 standing oak trees and the site did not record a flood ring for 1826, even though the chronology was 1823-1999. However, the number of samples that had a year of growth for 1826 is unknown. Kildonan Park was sampled for 38 standing oak trees and the flood of 1826 and 1747 were considered to be similar magnitude. A total of 15 samples from standing oak trees (chronology 1822-1994) and 22 samples from historic log buildings (chronology 1644-1865) were taken from various locations in Winnipeg. However, the data for what sites were sampled is not listed specifically in the paper. Three samples were collected from a historic log building at Fort Dufferin and the chronology was 1723-1872. However, no flood rings were recognized for 1826.

In this study, 17 sites spanned through 1826 that did not record a flood ring. Overall, 15 of these sites were log buildings. At most of these sites (13/15), seven or fewer radii were collected.

Only 11 total flood rings were recorded in nine years from subfossil logs within St. George and Nielsen (2003), none of which had a flood ring for 1826. The chronology of subfossil logs from the Red River was 1448-1997. However, we do not know how many samples spanned through 1826. While it is impossible to determine exactly where each subfossil log originated, each log had to come from the site it was located or else further upstream. The bulk of subfossil logs collected for St. George and Nielsen (2003) were collected between Emerson and Morris, which means it is possible that some of these logs came from the United States. The furthest south site that recorded the flood of 1826 in Manitoba was at ‘Rat River House’, 30 kilometers south of where the Assiniboine River connects with the Red River in Winnipeg (St. George & Nielsen, 2003).

We tried to determine why the CBS site had so many flood rings compared to other sites. It is possible the flood of 1826 was more severe in the area from Shelly, Minnesota to Climax, Minnesota. However, as flat as it is (Table 8), it seems unlikely that this specific 16-kilometer section between the two sites would have faced more extreme flooding than sites to the north and south. During the 1997 flood (https://pubs.usgs.gov/gip/2007/49/), the area from Shelly to Climax flooded, but not as severely as the area from Grand Forks north to Pembina.

Another possibility of why the CBS site contained so many flood rings is that these logs came from Manitoba. However, statistical crossdating was conducted on three samples (six radii) from the CBS site and correlations were much better with the Fargo-Moorhead chronology than with the master chronology created in southern Manitoba (data not shown). The results suggest these logs came from somewhere along the United States portion of the Red River Valley. This supports the first assumption listed above.

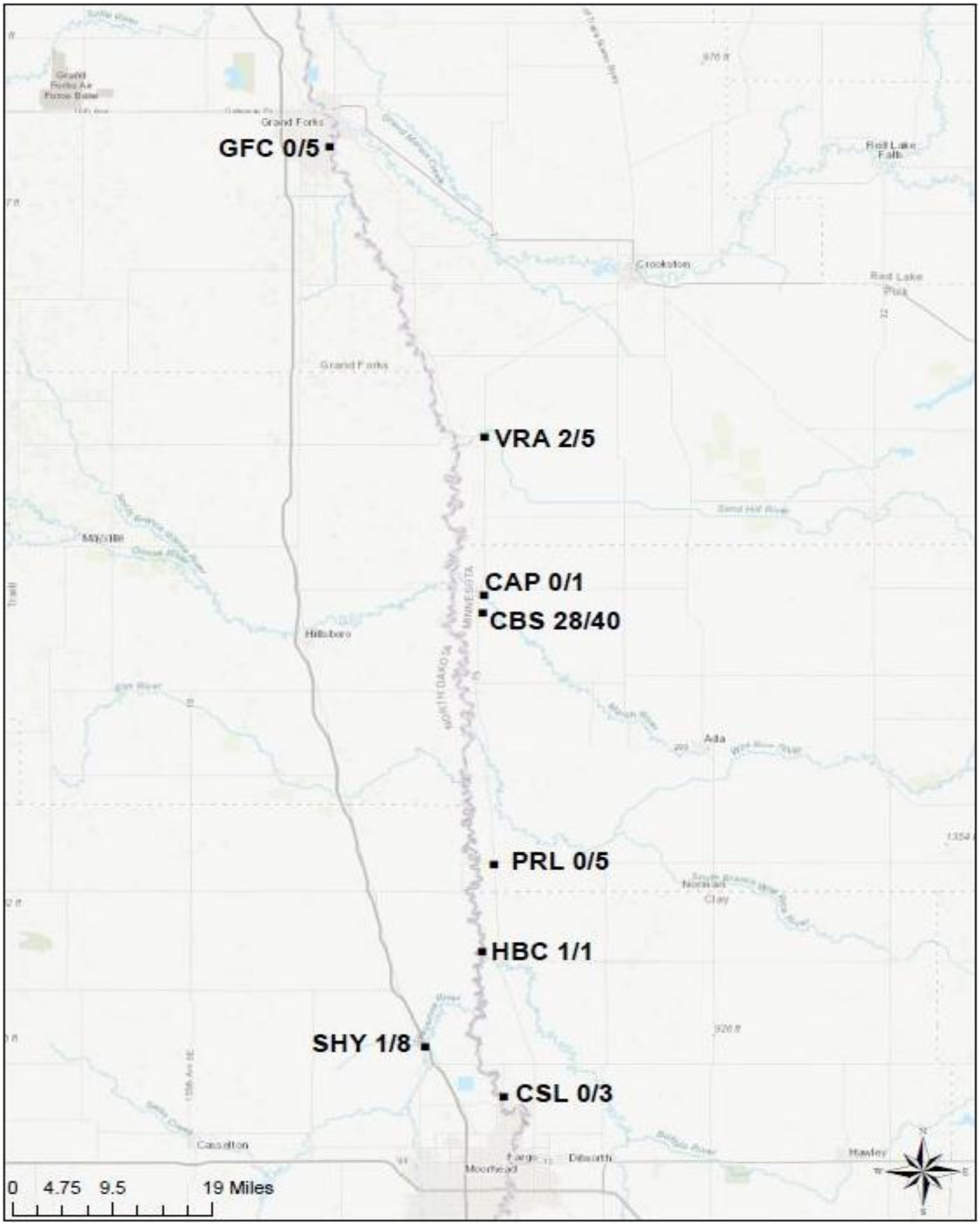

Figure 20. Sites that recorded flood rings for 1826 and nearby sites that did not. Numbers indicate the number of 1826 flood rings over the sample depth for 1826. Sites were not included if chronology did not extend to 1826.

Table 8. USGS gage sites, datum elevations, and change in slope between sites along the Red River.

Gage Site and Datum Elevation (meters)	Flood Stage (meters)	Gage Location (River Mile)	Slope (cm/km)
Pembina (227.6) **(740.7 feet)**	11.9 (39 feet)	157.5	5.8
Drayton (230.4) **(756 feet)**	9.75 (32 feet)	207.5	5.00
Oslo (235.8) **(773.7 feet)**	7.92 (26 feet)	274.5	4.91
Grand Forks (237.9) **(780.7 feet)**	8.53 (28 feet)	301.5	11.06 (Between Grand Forks and Halstad)
Thompson (radar) Datum unknown	Data not listed	322.5	Unknown
Halstad (252.2) **(827.4 feet)**	7.92 (26 feet)	381.5	11.81
Fargo (268.2) **(879.8 feet)**	5.5 (18 feet)	465.5	3.02 (Between Fargo and Enloe)
Hickson **Datum unknown**	9.14 (30 feet)	492.5	Unknown
Enloe (271) (radar) **(889.06 feet)**	Data not listed	523.5	31.1
Wahpeton (287.7) **(944.06 feet)**	3.35 (11 feet)	557	-

An equal number of flood rings (12) were found in 1997 and 1852. The flood of 1997 was recorded instrumentally and will not be discussed. However, the flood of 1852 was not recorded instrumentally. Once again, the CBS site recorded the most flood rings for 1852 with 10. The only other flood rings found for 1852 were at the BQS and BBS sites (Figure 21).

The CBS site was the farthest north site to record flood rings for 1852. Because flood rings for 1852 are present in both Canada and at the CBS site, we expected to find flood rings for 1852 in the four sites north of the CBS site. However, we only collected 10 radii north of CBS that spanned through 1852. Again, if we assume that the PEM photographs span through 1852, no flood rings appeared to be present out of an additional 54 radii.

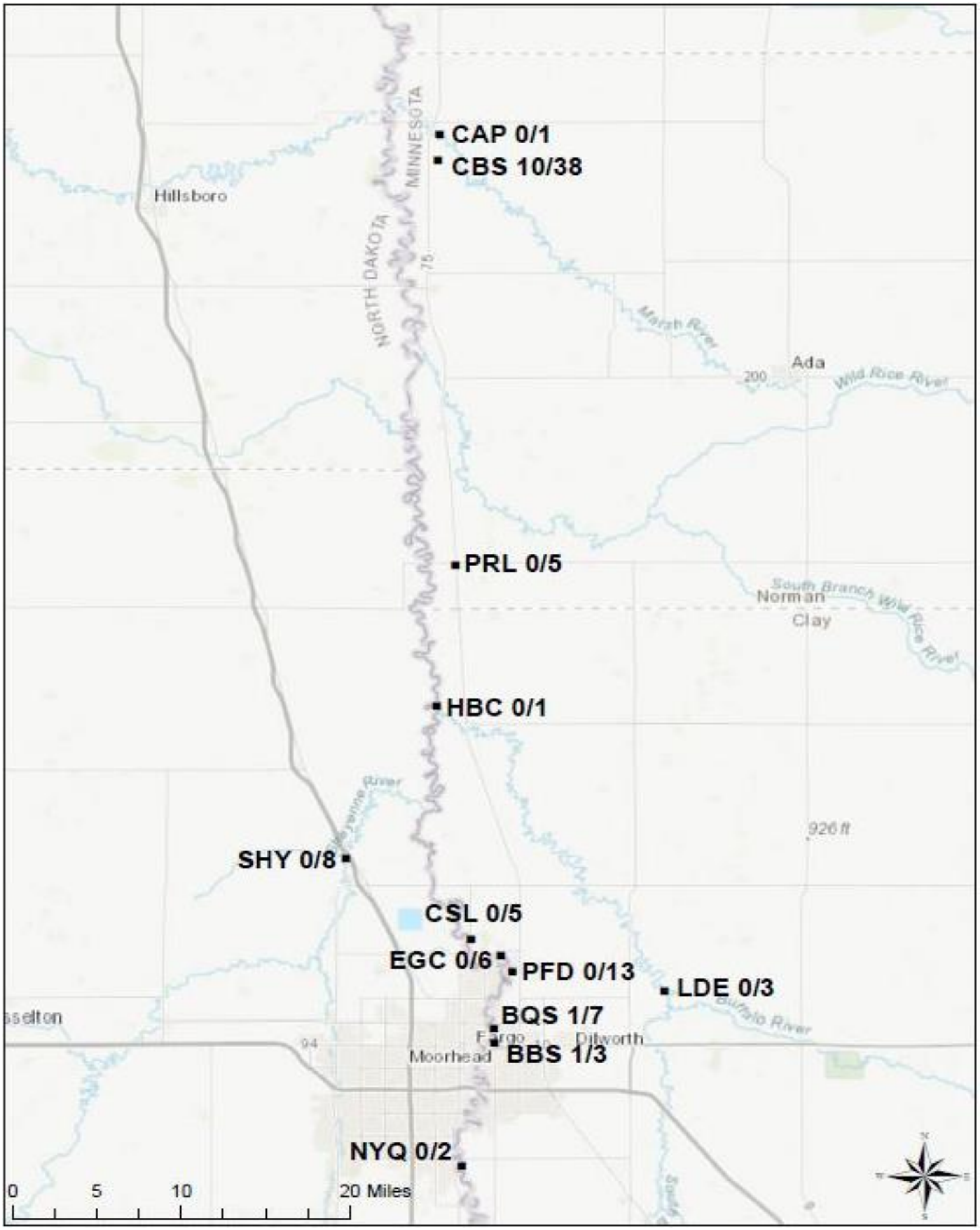

Figure 21. Sites that recorded flood rings for 1852 and nearby sites that did not. Numbers indicate the number of 1852 flood rings over the sample depth. Sites were not included if chronology did not extend to 1852.

The flood of 1852 was not recorded south of the BBS site (Figure 21). Like the flood of 1826, we had a large gap between sites that did not show flood rings for 1852. While the CBS site near Shelly, MN, recorded 10 flood rings for 1852, no other sites within 60 kilometers showed flood rings for the year, even though 41 radii were collected in this section that spanned through 1852 between the CBS and BQS sites.

Ring-width chronology

We created an extended ring-width chronology for the United States portion of the Red River that has not been documented before. Live trees and log buildings were both beneficial for starting and extending the chronology. This ring-width chronology provides a solid foundation for ring widths in the United States portion of the Red River Valley. Sample size is above 25 from 1713 to 2019 (Figure 22). The correlation of all ring widths in the master chronology compared against itself is 0.587 (see supplemental files). The ring-width chronology may be helpful for climatology studies along this portion of the Red River if future studies exist.

All the photograph samples from PEM, two photograph samples from GFC, three photos from PFD, one photo from HRC, and the subfossil log (which will be discussed further below) were unable to be crossdated. This was unexpected. Most likely, the logs used to build PEM follow a slightly different chronology than the one centered around the Fargo-Moorhead area. If we were more familiar with the chronology and marker years from Manitoba (which contains some marker years similar to those in our chronology), we might have a better chance at visually crossdating the samples from this building. If physical samples were taken from PEM and the two logs at GFC that could not be crossdated, the samples could be statistically crossdated to determine years of growth. However, it did not appear there were any visual characteristics of flood rings from either of these sites, so there may not be much benefit in taking physical samples. The photo samples from PFD that were unable to be visually crossdated had extremely narrow ring widths. Even though the photo from HRC contained 103 annual rings, it was unable to be crossdated.

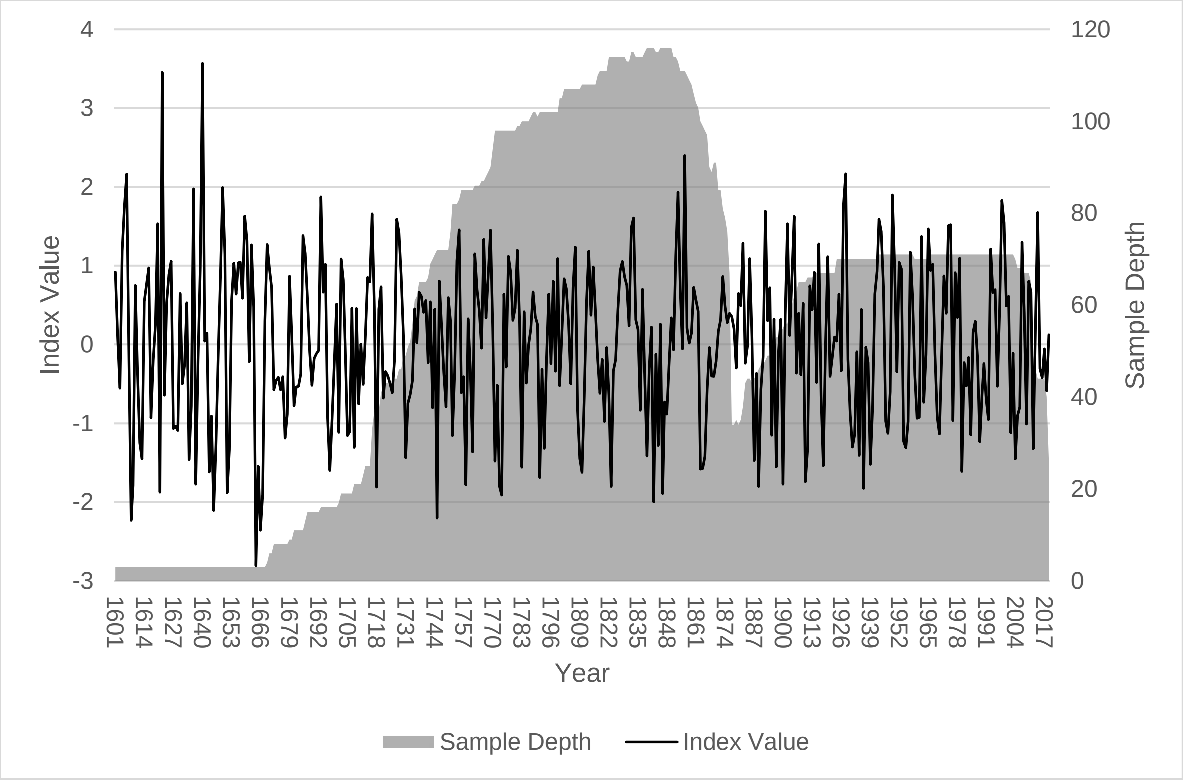

Figure 22. Index values and sample depth from ring width measurements of physical samples in the master chronology. Index values created using default values in COFECHA.

Individual site results

There were several sites that stood out for this project. The LDX site was not discovered until fall of 2020. Even then, getting in contact with the landowner and getting permission to sample did not happen until December of 2020. Additional samples should be collected from this building. If the building was found earlier in the study, more samples would have been taken.

The HBC site also holds potential for additional sampling. We have permission to resample this building, but coring would be the only method to use since the ends of the logs are not exposed. A flood ring was also found for 1826 at this site, making it even more important to collect additional samples here to determine if more flood rings for 1826 are present.

Sample BQS01B needs to be discussed as well. The BQS building is one that has had reconstruction work in the past, and there is a lack of documentation of replacement logs. BQS01B is one that may have been a replacement log due to its lower correlation with the master chronology (0.32). However, we have mixed results with this sample. BQS01A has a much higher correlation with the master chronology (0.49). Therefore, it is unclear if this log is a replacement or original log. It is also possible the BQS01B was dated improperly. Or perhaps BQS01B was dated properly, and it is an anomaly. Mark Peihl, Senior Archivist at the Historical and Cultural Society of Clay County, suggested that replacement logs on the BQS building may have come from the areas near Pelican Rapids, MN. However, there is no physical evidence to support or refute this statement. If BQS01 is a replacement log, that violates our third assumption listed at the beginning of the Discussion.

We were able to collect a large number of cross-sections from the DAN site. We expected the site to have more than two flood rings present because of the large number of samples collected (36 radii from 26 samples). However, that was not the case. Future sampling from the DAN site could be beneficial, specifically for adding to the ring-width chronology. However, due to the large number of samples already collected, this site should not have a heavy focus if the purpose is to identify flood rings.

If future studies exist, there are several areas that should be targeted to determine the extent of the 1826 flood, as well as the flood of 1852. First, more sampling should be conducted within the large gap between the GFC site and the United States-Canada border. We have permission to sample a second log building at the GFC site, but it is covered with modern siding.

The logs are accessible on the inside of the building so taking cores is the only sampling method available. Heritage Village in East Grand Forks, MN, is a site that was not visited but holds several log buildings. We visited another forested site (KNG – not listed for sites) and received permission to sample trees. However, very few trees fit the description we wanted. Collecting several samples from standing trees at this site could help specifically in building on the ring-width chronology for this area, but the chronology may not extend much past the 1870s. There is also another log building in Pembina, ND, but we know very little about it. More information is needed to determine if this building could be beneficial to the study. Finally, we could also collect more samples from the LDX site, since permission to sample was not received until late in the study.

The area between the Fargo-Moorhead community and the CBS site should also be sampled more. If permission is granted, the BQS site would be beneficial to sample more. The log ends for this building are exposed, so any of the three sampling methods could be used. There was also a flood ring found for 1852 at this site, making collecting additional samples more interesting.

There are also log buildings in Hillsboro, ND. One building on the south side of town appeared to be mainly American elm, but a few bur oak logs might have been used in its construction. However, the log building located in Woodland Park was mainly bur oak and sampling it could benefit the project. These buildings were identified and visited earlier in the study but were not sampled because they were located along the Goose River, nearly 20 kilometers southwest of its confluence with the Red River. Finally, one more cabin that could be sampled is the Newland Cabin in Ada, MN. The original location of this building is near Hendrum, MN, between the Wild Rice River and the Red River.

Even though we did not find any flood rings for either 1826 or 1852 south of the Fargo-Moorhead community, the area should still be sampled more. Specifically, additional samples should be collected between the DAN site and the community of Wahpeton-Breckenridge, since only two samples were collected along this stretch of river. The FTA site could be a start. There are multiple historic buildings on site, however, permission would be needed to sample. However, this is a site that has had reconstruction and once again, documentation is poor. The sanding and photograph method would most likely be the only option given the historical importance of the site. Additionally, NES is not much farther north than DAN and could provide more samples. As mentioned earlier, we believe that the NES structure was salvaged from one of the structures originally at Ft. Abercrombie.

Sampling methods

There are pros and cons for each sampling method in relation to historic log buildings. Collecting cross-sections by chainsaw is the most destructive method used in the study. While this is a very quick process, the ends of the logs must stick out beyond the joinery. In some log buildings, this method is not even possible due to the logs not sticking out far enough.

Taking core samples from the logs is minimally destructive and it results in only a small hole on the outside of the log, which can be filled with a wood putty and/or wooden dowel if needed. However, we faced issues with our tools properly driving into the wood to collect samples. This method is also time consuming since the archaeo borer drives into the wood slowly.

Sampling log buildings by sanding and photographing was the least destructive method used for the study. This method removes only a small amount of the log end, making the annual rings visible. However, this method is the most time consuming of the three since two separate sanders are needed and at least three different grit sandpapers are needed for each sander. Once the sanding was completed, multiple photos must be taken for each radius and each photo requires moving the base of the tripod slightly, as well as raising or lowering the camera.

The methods we used for each building ultimately depended on what the building owner preferred or allowed. Most times, the sampling method we used related to the condition the building was in. For instance, for the CBS and DTN sites, we were able to collect a large number of cross-sections and we could use whatever method we wanted. Because the CBS building was falling apart and the DTN logs were sitting on a trailer, the owners did not mind if we used a destructive method to collect samples. Core samples were collected from buildings when we couldn’t use a chainsaw. We collected only core samples from the HBC site since the logs at the site were either standing upright as posts or horizontally as beams. The sanding and photographing method was used at the PEM and GFC sites because both buildings were well preserved.

I believe the best method used for sampling log buildings in our study was by chainsaw. In most cases, using a chainsaw allowed us to collect two radii per sample. The method was quick and resulted in a physical sample. I also believe that collecting samples by coring can be beneficial if the tools work properly. This method is not as time consuming as the sanding and photographing technique and it also results in a physical sample. The sanding and photographing technique is time consuming and can be ineffective. Some of the photos taken at the PEM were slightly out-of-focus, making it difficult to identify every annual ring. Some of those logs also needed a bit more sanding since they still had scratches from the lower grit sandpaper that weren’t sanded out. These were not recognized until after the pictures were taken and uploaded to the shared drive. The sanding and photographing method also does not result in a physical sample, making visual crossdating the only way to identify the years of growth.

Subfossil log search

The search for subfossil logs did not go as planned. The main issue we faced was high water levels. While we never determined an ideal river height to search for subfossil logs, the river always seemed to be too high. The Red River does not drop much below 15 feet in Fargo (Figure 23), which is only three feet below flood stage (Table 8). The river tends to drop farther below flood stage at other sites compared to the Fargo-Moorhead area. Nonetheless, more than four trips needed to be taken on the Red River to collect subfossil logs.

I believe the best method we used to find subfossil logs is by taking a boat on the river and visually scanning the banks. This was an effective method used by St. George and Nielsen (2003) and it worked when we used it. Using fish finders to find subfossil logs was ineffective for our study. A proper method for retrieving logs beneath the surface of the river was never identified. Another method that could be beneficial for locating potential target logs is by flying a drone, equipped with video camera along the river corridor. This could save time if two or more drones are used, each scanning a different section of river. Once potential logs are identified, the researchers would still need to get on the river and collect samples by hand.

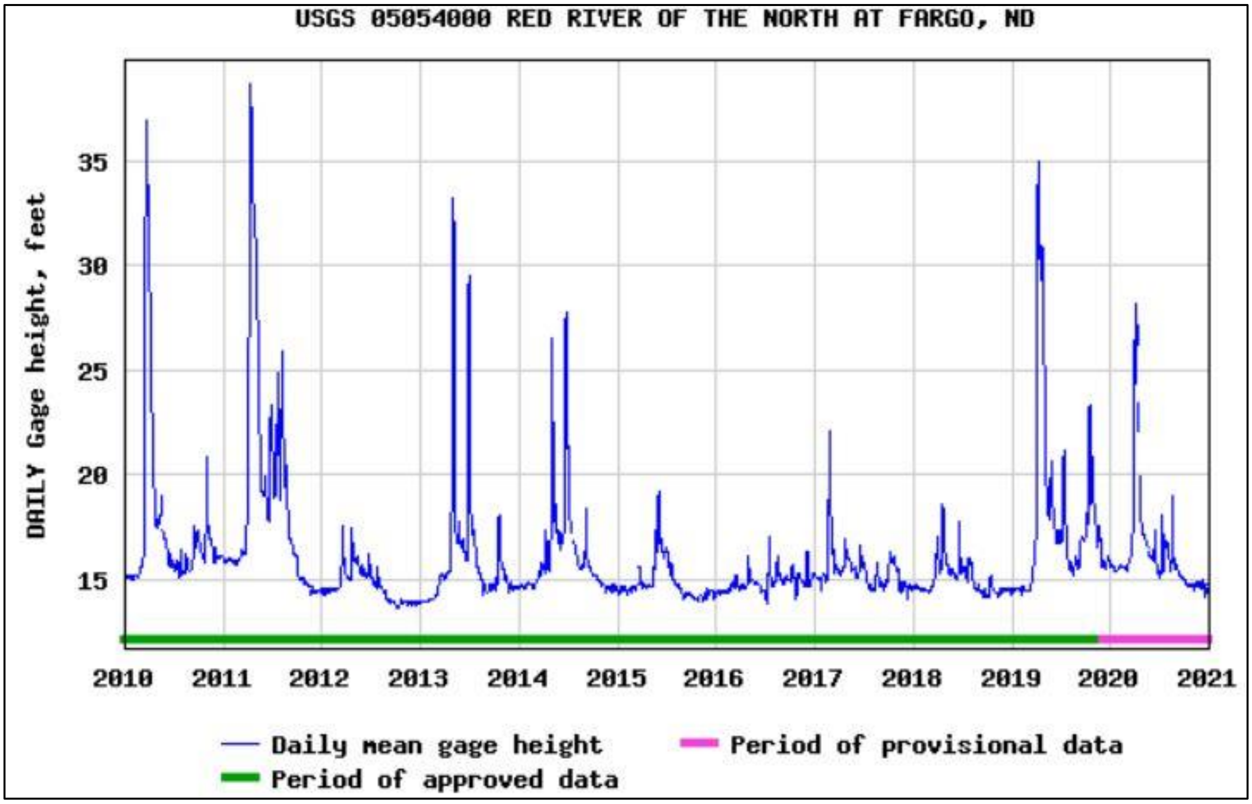

Figure 23. Daily gauge heights from the Red River in Fargo from January 1, 2010 through December 31, 2020. Graph is representative of average low periods since 1980s. Stream data and graphic courtesy of U.S. Geological Survey from (https://waterdata.usgs.gov/usa/nwis/uv?05054000) (public domain).

It is unclear whether the Red River in Manitoba holds subfossil logs that have a higher ring count than those in the United States portion. While it seems unlikely, we were unable to find subfossil logs that had over 100 years of growth as in St. George and Nielsen (2003). The average ring count for subfossil logs in St. George and Nielsen (2003) was nearly 100 years and the highest ring count of any subfossil log collected from the Red River was 249 years. All the logs collected for our study appeared to be from modern trees and did not have more than 70 years of growth (Figure 24). At most, three samples were collected from what appeared to be the bottom of the tree (RED14, RED17, and RED25).

We attempted to dig up two or three samples, however, it was very time consuming without much progress. Sampling from the base of these trees would likely have led to higher ring counts. We believed these trees were modern because they did not have the dark color seen in logs that have been buried for a long time. We assumed we might have more luck searching near Pembina since St. George and Nielsen (2003) found most of their subfossil logs within 40 kilometers of the U.S.-Canada border.

Figure 24. Subfossil logs collected from Red River searches. Does not include sample RED10. Metal yardstick located in upper left portion of the tarp, for scale.

Landowner visits

The landowner visits went poorly. To have any success, more households must be visited or a different approach must be taken. The time of day for a visit may be better in the evening. Nobody was home to speak with me roughly 10 separate occasions during the household visits. If these visits occurred later in the day or on the weekend, we might not run into this issue. It would also be important not to limit visits to households as close to the river as possible. We assumed that visiting households close to the Red River would result in finding log buildings because typically, the buildings weren't built far from where the logs were cut. However, there is no hard evidence proving that individuals living along the river have a better awareness of where these log building are located. In fact, we had better luck at finding log buildings by talking with local individuals about our project. Therefore, I believe there is a lot of luck involved with these visits and talking to the right people.

Giving a presentation at public meetings may also provide some guidance for finding more log buildings. Dr. Zeleznik gave a presentation in the spring of 2019 at the Red River Basin Commission, and while it did not result in any leads for finding log buildings, it led to a handful of individuals giving us leads on large bur oak trees. I believe if we gave more presentations and if the COVID-19 pandemic would not have occurred during our project, public presentations would have led to finding individuals having leads on log buildings. We also contacted the 12 county-level historical societies in Minnesota and North Dakota along the Red River (Table 9) with some success.

Table 9. County-level historical societies along the Red River and information received on log buildings in those counties.

County	Community, State	Notes
Pembina	Cavalier, ND	Directed us to the Ox-Cart Trails Historical Society, which led to DTN. No log buildings on site.
Kittson	Lake Bronson, MN	One log building on site but logs were not oak.
Walsh	Minto, ND	Log building on site but permission was never granted to sample. Also, unsure if the cabin was from near the Red River.
Marshall	Warren, MN	Three cabins on site but they did not come from near the Red River.
Grand Forks	Grand Forks, ND	Two log buildings on site. One was sampled (GFC), the other can be sampled by coring.
Polk	Crookston, MN	One cabin on site but logs were not believed to come from the Red River.
Traill	Hillsboro, ND	Two log cabins in Hillsboro. Did not sample since logs were most likely harvested from along the Goose River.
Norman	Ada, MN	NEW (Newland) log building on site.
Cass	Fargo, ND	Two log buildings on grounds of Bonanzaville. One from Red River and one from Sheyenne River.
Clay	Moorhead, MN	One log building (BQS) managed by the society. Also helped lead to PFD, LDE, BBS, and BHH/BHC. Also, one more that was never sampled.
Richland	Wahpeton, ND	No information on log buildings. Possible logs from Hellendale Township from previous log building but lost contact with Historical Society.
Wilkin	Breckenridge, MN	No information on log buildings.

Conclusion

Based on our results, I do not believe the flood of 1826 was as severe in the United States as it was on the Canadian side of the border. Lack of flood rings across multiple sites is the main issue. If the flood of 1826 was as severe as it was in Manitoba, a higher percentage of flood rings should have shown up like they did in St. George and Nielsen (2003). Rannie (2002) believes the Assiniboine River played a large role in the massive flood of 1826. This is possible given our lack of flood rings for 1826 from multiple sites along our stretch of river. However, the Assiniboine River is not the focus of this paper. I believe the influence of tributaries of the Red River are what caused flood rings to appear for 1826 in the United States. Every site that recorded flood rings for 1826 was near a tributary of the Red. It appears the Red River may have flooded moderately that year and tributaries may have also flooded, which led to flood rings for those individual sites.

OAK GROVE PROJECT

Introduction

During earlywood growth, bur oak trees create flood rings at or below flood waters when they have been inundated for a certain amount of time (St. George & Nielsen, 2002). However, the start of earlywood growth varies from year to year and it is unknown if the same stand of trees begins earlywood growth at the same time or if there is any variation among trees.

A project at Oak Grove Park in Fargo, ND, was conducted during the early months of 2020. The goal of this project was to analyze earlywood vessels from three bur oak trees to determine at what elevations flood waters produced flood rings. We expected to identify flood rings within the lowest sampled cores and for flood rings to disappear as the height increased, demonstrating a relationship between flood ring formation and the start of earlywood growth. We also wanted to compare our results to those of Wertz et al. (2013), who had sampled different trees in Oak Grove Park. An additional, smaller project involved phenological observations of budbreak and earlywood formation.

Methods

Oak Grove Park is located along the Red River in Fargo, ND, about 2.4 kilometers southeast of NDSU. Three bur oak trees that were low on the landscape were identified and four cores were taken from each tree at varying heights using an increment borer. Core 1 was always taken 0.5-0.6 meters above ground level. Three more cores were taken from each tree in 0.6-meter intervals. A ladder was used to retrieve the final cores from each tree, which was always 1.8 meters above where the initial cores were taken.

Trees were labeled with tags as part of the Fargo Park District’s forest inventory. The trees sampled were numbers 4809, 4813, and 5152 (Figure 25). The elevation at the base of the tree and core elevations were also determined (Table 10). In Fargo, ND, minor flood level is reached when the waters from the Red River rise above 5.48 meters (18 feet, 879.6 feet elevation). Once the elevation of each core was determined, the USGS website was used to determine how long each core was inundated for. Each core was mounted and prepared as described earlier. Cores were visually analyzed for flood rings with a focus on the large flood years of 2019, 2011, 2009, 2006, 1997, and 1996.

Figure 25. Aerial view of Oak Grove Park with locations of the three trees. Retrieved from Google Earth Pro.

Table 10. Tree numbers and elevation (meters) of each core.

Tree Number	**4809**	**4813**	**5152**
Elevation (meters)			
Base of tree	268.5 (881 feet)	268.8 (882 feet)	269.1 (883 feet)
Core #1	269 (882.5 feet)	269.3 (883.5 feet)	269.7 (885 feet)
Core #2	269.6 (884.5 feet)	269.9 (885.5 feet)	270.4 (887 feet)
Core #3	270.2 (886.5 feet)	270.5 (887.5 feet)	271 (889 feet)
Core #4	270.8 (888.5 feet)	271.1 (889.5 feet)	271.6 (891 feet)

Observations were made of the dates of bud break and earlywood vessel formation in 2019 and 2020 on a different group of 14 bur oak trees in Oak Grove Park. The site was visited twice per week. Binoculars were used to examine branches to determine when trees changed phenophases as defined by (Copini et al. 2016). An increment borer was used to retrieve five-centimeter cores at breast height on each tree. Cores were observed under a microscope to determine if earlywood vessels were present.

Results

Only seven flood rings were identified within the 12 cores (Table 11). Each of the seven flood rings was found in core 1 – the lowest elevation core – in the different trees. The flood of 1996 was recognized only once in tree 4813. The floods of 1997, 2009, and 2011 were seen in both trees 4809 and 4813. There were no flood rings found in tree 5152. Tree 4813 had ‘delayed earlywood’ in the second lowest elevation core during the spring flood of 1997, but no flood characteristics were identified in that ring.

Dates of inundation for each core from each tree is found in Table 12. Core 1 for tree 4813 created a flood ring for 1996, while it was flooded for 13 days (April 9 – April 22) (Table

11). Core 1 for tree 4809 was flooded for a longer duration of 15 days (April 8 – April 23) during 1996 but did not create a flood ring, even though it is at a lower elevation. Trees 4809 and 4813 both contained flood rings for 1997 with inundation periods for the first cores of 40 days (April 4 – May 14) and 39 days (April 4 – May 13), respectively.

The lowest elevation cores in 2009 for trees 4809 and 4813 exhibited flood rings and were inundated for 48 days (March 22 – May 9) and 47 days (March 22 – May 8), respectively. The lowest elevation cores in 2011 for trees 4809 and 4813 exhibited flood rings and were inundated for 45 days (April 2 – May 17) and 42 days (April 3 – May 15), respectively. Tree 5152 did not show any flood characteristics throughout any core, even though times of inundation were similar.

No flood rings were identified in 2019 or 2006. The flood of 2019 peaked on April 8, one day earlier than the peak date of the 2011 flood, at 10.7 meters (35 feet, 3.7 feet lower than 2011 peak). All cores for 2019 were flooded for 22 days or more. The lowest cores in all trees were flooded for at least 30 days, and core 1 for tree 4809 was flooded for 35 days (April 1 – May 6) in 2019. The flood of 2006 peaked on April 5, three days earlier than the peak of the 2011 flood, at 37 feet (1.7 feet lower than 2011 peak). All cores were flooded at least 12 days, and core 1 for tree 4809 was flooded for 17 days (March 30 – April 16) in 2006.

Table 11. Tree numbers, years of floods, observations, dates of inundation (month/day), and length of inundation (number of days) of core 1.

Tree #	**Year**					
	1996	**1997**	**2006**	**2009**	**2011**	**2019**
4809	No flood ring	Shrunken vessels	No flood ring	Shrunken/extended vessels	Extended vessels	No flood ring
Inundation dates	4/8 – 4/23	4/4 – 5/14	3/30 – 4/16	3/22 – 5/9	4/2 – 5/17	4/1 – 5/6
Inundation time	15 days	40 days	17 days	48 days	45 days	35 days
4813	Shrunken vessels	Shrunken vessels	No flood ring	Shrunken/extended vessels	Extended vessels	No flood ring
Inundation dates	4/9 – 4/22	4/4 – 5/13	3/31 – 4/16	3/22 – 5/8	4/3 – 5/15	4/2 – 5/4
Inundation time	13 days	39 days	16 days	47 days	43 days	34 days
5152	No flood ring	No flood ring	No flood ring	No flood ring	No flood ring	No flood ring
Inundation dates	4/10 – 4/21	4/5 – 5/10	3/31 – 4/14	3/22 – 5/6	4/3 – 5/13	4/3 – 5/3
Inundation time	11 days	35 days	14 days	45 days	41 days	30 days

Table 12. Inundation dates (months/dates) for every core from all six floods. Data retrieved from https://waterdata.usgs.gov/nd/nwis/uv/%3Fsite_no=?station=05054000.

Tree #	**Dates Flooded**					
4809	**1996**	**1997**	**2006**	**2009**	**2011**	**2019**
Core 1	4/8 – 4/23	4/4 - 5/14	3/30 – 4/16	3/22 – 5/9	4/2 –5/17	4/1 – 5/6
Core 2	4/10 – 4/21	4/4 – 5/12	3/31 – 4/15	3/22 – 5/6	4/3 – 5/14	4/2 – 5/3
Core 3	4/12 – 4/20	4/5 – 5/10	3/31 – 4/13	3/23 – 5/4	4/4 – 5/11	4/3 – 5/1
Core 4	4/14 - 4/18	4/5 – 5/8	4/1 – 4/13	3/23 – 5/2	4/5 – 5/8	4/4 – 4/29
4813						
Core 1	4/9 – 4/22	4/4 – 5/13	3/31 – 4/16	3/22 – 5/8	4/3 – 5/15	4/2 – 5/4
Core 2	4/11 – 4/20	4/5 – 5/11	3/31 – 4/15	3/23 – 5/5	4/3 – 5/12	4/3 – 5/2
Core 3	4/12 – 4/19	4/5 – 5/9	3/31 – 4/14	3/23 – 5/3	4/4 – 5/9	4/3 – 4/30
Core 4	4/14 – 4/17	4/6 – 5/7	4/1 – 4/13	3/23 – 4/30	4/5 – 5/6	4/4 – 4/27
5152						
Core 1	4/10 – 4/21	4/5 – 5/11	3/31 – 4/15	3/22 – 5/6	4/3 – 5/13	4/3 – 5/3
Core 2	4/13 – 4/19	4/5 – 5/10	3/31 – 4/14	3/23 – 5/3	4/4 – 5/10	4/3 – 5/1
Core 3	4/14 – 4/18	4/6 – 5/8	4/1 – 4/13	3/23 – 5/1	4/5 – 5/7	4/4 – 4/28
Core 4	Did not flood	4/6 – 5/5	4/1 – 4/12	3/24 – 4/29	4/5 – 5/4	4/4 – 4/26

Phenological observations were also conducted during 2019 (Table 13) and 2020 (Table 14) at Oak Grove Park. In 2019, bud swell was first seen on April 26 in 5/14 trees. Five days later on May 1, all trees were in bud swell. Earlywood growth (vessels) were not seen in any of the cores until May 13. Only when all trees were in internode expansion (May 20) was earlywood growth observed in all cores.

In 2020, bud swell was first observed on April 29 in 8/14 trees. On May 4, 13/14 trees were in internode expansion and one tree was still dormant. May 1 was also the first date when new earlywood vessels were observed in a single tree. On May 7, all trees were in internode expansion and new earlywood vessels were seen in all cores.

The number of days between bud swell and internode expansion initiating in trees differed between years. In 2019, it took 10 days between the first tree to start bud swell and the first tree to start internode expansion. In 2020, it took only five days for this to happen. In 2019, it took seven days after internode expansion had initiated to see new earlywood vessels. In 2020, this occurred on the same day. It took seven days in 2019 between the first tree showing new earlywood vessels and for all trees to show new earlywood vessels. This took only three days in 2020.

Table 13. Phenological observations of shoot development and earlywood growth in 14 trees at Oak Grove Park in 2019

Date	**Twig and Leaf Development (Number of trees)**	**Vessel Development (Number of trees)**
4/26	Dormancy (9). Bud swell (5).	-
4/29	Dormancy (6). Bud swell (8).	-
5/1	Bud swell (14).	-
5/3	Bud swell (14).	-
5/6	Internode expansion (14).	-
5/8	Internode expansion (14).	-
5/13	Leaves clearly distinct (14).	Vessel development (1).
5/17	Leaves clearly distinct (14).	Vessel development (11).
5/20	Leaves clearly distinct (14).	Vessel development (14)

Table 14. Phenological observations of shoot development and earlywood growth in 14 trees at Oak Grove Park in 2020.

Date	**Twig and Leaf Development (Number of trees)**	**Vessel Development (Number of trees)**
4/29	Dormancy (6). Bud swell (8).	-
5/4	Bud swell (1). Internode expansion (13).	Vessel development (1).
5/7	Leave clearly distinct (14).	Vessel development (14).

Discussion

The results for this project were inconsistent and unexpected. We expected to find flood rings within the first two or three cores and have them disappear within the last one or two. The lack of flood rings was a surprise. Even though the dates of inundation at adjacent core heights differed by only a few days, it appears those days were critical. While the exact amount of time a tree needs to be flooded during earlywood growth to create a flood ring is unknown, Therrell and Bialecki (2015) found it took only 10 days of inundation during a spring flood to create flood rings in overcup oak and bur oak. While they do not specifically state these 10 days have to be during earlywood growth, the authors say that the trees cannot be dormant to create a flood ring. Similarly, Copini et al. (2016) determined it took only 14 days of flooding once internode expansion initiated to create flood rings in English oak.

In theory, tree 4809 should have exhibited the most flood rings since it was the lowest on the landscape and it would be the first and last tree to be flooded at all core heights. However, that was not the case. While the dates of inundation for the first cores for all three trees during 1996 were similar, only tree 4813 created a flood ring. Tree 4813 might have started earlywood growth prior to the other trees in 1996.

The flood rings of 1997 in trees 4809 and 4813 were expected. The inundation times of core 1 from both trees were 40 days and 39 days, respectively (Table 11). However, the lowest core from tree 5152 was flooded for 36 days and it did not exhibit any flood rings. While each core height from each tree was flooded for 29 days or more during the 1997 flood, flood rings were found only in the lowest core. Since two of the criteria for creating a flood ring were met (inundation period and sampling below the water level), it appears that these trees were dormant for most of the dates inundated. The only cores that created a flood ring for 1997 were inundated until at least May 13. If we assume that 10 days of inundation during earlywood growth is the minimum amount of time to create a flood ring, then it appears these trees did not begin earlywood growth until May 3, one day earlier than the first earlywood growth in 2020.

The only cores that were flooded past May 6 in 2009 created flood rings. If we again assume that at least 10 days of flooding are needed to produce a flood ring, then the trees did not start earlywood growth until at least April 27, earlier than in 2019 and 2020. The only trees that were flooded past May 13 created flood rings in 2011. Similarly, if we assume the 10-day mark, it appears that earlywood growth did not start for these trees until May 3 in 2011.

The flood of 2019 inundated the bottom cores for each tree for a similar length of time compared to other years that created flood rings. However, since the last day of inundation for all cores was on May 6, it appears that cambial growth did not start until April 27 at the earliest. However, our phenological observations on the other group of trees show that earlywood growth did not begin until May 13, two weeks later.

The flood of 2006 was short-lived. While the flood had a large peak, the waters went down rapidly after that. Since the last core to be inundated was on April 16, it is estimated that cambial growth did not start until April 7 at the earliest. This date would be over one month earlier than observations for earlywood growth for Oak Grove Park in 2019 and three weeks earlier than in 2020.

Wertz et al. (2019) found only a single flood ring in 2006 (Table 15), where we did not find any. They also found a higher percentage of flood rings for 1996 than we did. It is difficult to explain these differences. Timing of earlywood growth is important. It appears that a difference of only a day or two may be enough to create – or not create – a flood ring. Our observational results of 2019 and 2020 show that not every tree within a stand begins earlywood growth at the same time. Comparing temperatures in 2019 to 2020, both years were similar prior to bud swell. However, one week after bud swell occurred in both years, the highs in 2020 averaged 5.1° Celsius warmer than in 2019. Similarly, the lows in 2020 were on average 3.6° Celsius warmer than in 2019.

The trees in Wertz et al. (2013) also may have begun earlywood growth a day or two before the trees we sampled for our study. This could be the reason why tree 5152 lacks any flood rings; i.e., tree 5152 may have begun cambial growth later than the other trees. Flood waters may also have inhibited tree 5152 to initiate earlywood growth beneath the water level (Copini et al. 2016) (Figure 6).

Table 15. Comparison of flood rings found in Oak Grove Park between our project and Wertz et al. (2013).

	Number of flood rings/Total number of trees	
Year	**This project**	**Wertz et al. (2013)**
2019	0/3	n/a
2011	2/3	n/a
2009	2/3	10/20
2006	0/3	1/20
1997	2/3	9/20
1996	1/3	7/20

Differences in sample size is also an issue when comparing these two projects. Wertz et al. (2013) sampled nearly seven times the number of trees as we did. We wanted to sample only the lowest trees on the landscape. If a larger number of trees were to be sampled, the results could have been compared more fairly.

Prior to the study, we believed that the lowest trees on the landscape would show the most flood rings, which is why we chose these specific trees. This still holds some truth. When earlywood growth starts before or during the flood, these lower elevation trees are more likely to show flood rings since they are inundated for a longer duration than trees at a higher elevation. However, this study suggests that timing of earlywood growth in relation to flooding is critical in creating a flood ring. So, the trees we sampled that are lower on the landscape may not be the best at recording floods if the trees started of earlywood growth later than the trees sampled by Wertz et al. (2013). However, in order to prove this, both groups of trees would need to be sampled simultaneously.

The best way to demonstrate support that timing of earlywood growth in relation to flooding is the most important factor in creating flood rings is by conducting another controlled experiment, similar to Copini et al. (2016). Controlled experiments are precise and limit the number of variables, which can impact the results of the study. They also offer better support for explaining or demonstrating physiological or ecological mechanisms.

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