CATHERWOOD, AVERY A., M.A. Loblolly Pine Traumatic Resin Ducts Serve as a Proxy for Cool-Season Storm Events at Nags Head, North Carolina, USA. (2021). Directed by Dr. Paul A. Knapp. 28 pp

I present a method for identifying and recording cool-season weather events along northern coastal North Carolina, USA using the frequency of traumatic resin ducts (TRDs) formation in loblolly pine (*Pinus taeda* L.) earlywood tree samples that occur in response to stressful events. Based on a sample of 48 cores collected at Nags Head Woods Ecological Preserve during summer 2020, I tested the viability that the occurrence TRDs in the earlywood was caused by the occurrence of late-season tropical cyclones, mid-latitude windstorms including Nor'easters, and snow and ice storms, thus served as a proxy for extreme weather during 1950–2019. The stabilized frequency of earlywood TRD formations was significantly ($p < 0.001$) related to years that had at least one documented cool-season weather event. The average number of TRDs in a non-storm year during mid-October–May is 2.80 while the average for a storm year is 3.75. Further, I found that there was no age-related bias to storm-event detection, suggesting the viability of using TRD frequency to record cool-season storms at locations where old-growth loblolly forests exist along coastal North Carolina. This method may be used to reconstruct the occurrence of cool-season weather events beyond historical records in areas where old-growth loblolly pine trees exist.

LOBLOLLY PINE TRAUMATICRESIN DUCTS SERVE AS A PROXY FOR COOL-SEASON STORM EVENTS AT NAGS HEAD, NORTH CAROLINA, USA

by

Avery A. Catherwood

A Thesis
Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Greensboro

2021

Approved by

____

Committee Chair

APPROVAL PAGE

This thesis written by Avery A. Catherwood has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair Paul A. Knapp

Committee Members Thomas W. Patterson

P. Dan Royall

3/30/2021
Date of Acceptance by Committee

6/30/2020
Date of Final Oral Examination

ACKNOWLEDGEMENTS

There are so many people that I would like to thank for their involvement in the completion of this thesis. I would first and foremost, like to acknowledge my parents, Laura Jean Healy Catherwood and Christopher Dudley Catherwood for their unconditional love and support throughout my childhood and adulthood. Without their love and support, as well as their reminders to me of what I am capable of, I would not have been able to summon the strength and courage to proceed forward towards my goals. I would also like to thank my two sisters, Marilyn Leigh Catherwood and Kelsey Marie Catherwood, and my brother, Joshua Adam Hayes, for always offering help whenever I asked for it.

I am particularly grateful for my advisor, Dr. Paul Knapp. Without his experience, insight, and continued patience when working with me, there would be no thesis to express acknowledgements on. I cannot express enough appreciation towards him for allowing me to work under him during this process. I feel as if Dr. Selima Sultana deserves a special thanks as well. Without Dr. Sultana encouraging me to apply to the Graduate School at UNCG, I do not believe I would be here today. She provided me with the confidence that I needed to put myself in a situation that I was not sure if I would succeed in. I would also like to express my gratitude towards my committee members, Dr. Dan Royall and Dr. Thomas Patterson, for providing me with insight throughout this process. Aaron McCall of The Nags Head Woods Ecological Preserve deserves my gratitude as well for allowing me to conduct my research there.

I would also like to also extend my deepest gratitude to Tyler Joseph Mitchell of the Carolina Tree Ring Science Lab for helping me through every step of this process. Without his ingenious suggestions, profound belief in my abilities, and most importantly, his friendship, this work would not have been possible.

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CHAPTER I: INTRODUCTION

High-wind events, including late-season hurricanes/tropical depressions and Nor'easters as well as snow and ice storms, are important meteorological events that affect the coastal plains of North Carolina during the cool season. Yet, detailed records of these events are limited both temporally, typically beginning in the mid-20th century, and spatially, as records beyond larger cities are incomplete. Thus, there is an impetus to determine a method that can both record these events and extend the record to allow for a historical context of cool-season storm variability. Here I detail a method that uses the presence of traumatic resin ducts (TRDs) that form in the earlywood portion of loblolly pine *(Pinus taeda* L.) as a proxy for evaluating interannual variability of cool-season weather events in northeastern coastal North Carolina, USA.

The relationship between TRD formation and winter storms has been documented by Gaglioti et al. (2019). They found that a relationship existed between the number of occurrences of TRDs and the number of recorded high-wind winter storms in southern Alaska. However, although a coniferous tree was used in their study, Alaskan hemlock (*Tsuga heterophylla*) are longer-lived than loblolly pine and reach greater heights (Gaglioti et al. 2019). The southern Alaskan climate varies greatly from the coastal North Carolina climate, which combined with the differences in climate between the two areas could cause ambiguity in results. To my knowledge, there have been no studies examining the relationship between TRD formations in loblolly pine and growing/non-growing season storms in the southeastern United States.

The purpose of this research was to 1) assess whether TRDs are an efficient proxy for non-growing season storm data in North Carolina, and 2) assess what type of systems are the main contributors to TRD formations. If the former are operative, this study would provide a new avenue to track and record cool-season storms in North Carolina beyond the historical climate records.

CHAPTER II: LOBLOLLY PINE TRAUMATIC RESIN DUCTS SERVE AS A PROXY FOR COOL-SEASON WEATHER EVENTS AT NAGS HEAD, NORTH CAROLINA, USA

2.1 Abstract

I present a method for identifying and recording cool-season weather events along northern coastal North Carolina, USA, using the frequency of traumatic resin duct (TRD) formations in loblolly pine (*Pinus taeda* L.) earlywood tree samples that occur in response to stressful events. Based on a sample of 48 cores collected at Nags Head Woods Ecological Preserve during summer 2020, I tested the viability that the occurrence TRDs in the earlywood was caused by the occurrence of late-season tropical cyclones, mid-latitude windstorms including Nor'easters, and snow and ice storms served as a proxy for extreme weather during 1950–2019. The stabilized frequency of earlywood TRD formations was significantly ($p < 0.001$) related to years that had at least one documented cool-season weather event. The average number of TRDs in a non-storm year during mid-October–May is 2.80 while the average for a storm year is 3.75. Further, I found that there was no age-related bias to storm-event detection, suggesting the viability of using TRD frequency to record cool-season storms at locations where old-growth loblolly forests exist along coastal North Carolina. This method may be used to reconstruct the occurrence of cool-season weather events beyond historical records in areas where old-growth loblolly pine trees exist.

2.2 Introduction

Loblolly Pine (*Pinus taeda* L.), also referred to as North Carolina or Arkansas pine, is a species with an average life span between 100– 150 years (Borders and Bailey 1991, Schultz 1997) with the oldest documented live tree aged to 241 years old (Pederson 1997). Loblolly pine typically grow to a height of between 30–45 meters and are now the most widely dispersed pine species in the southeastern United States (Borders and Bailey 1991, Schultz 1997). In North Carolina, longleaf pine (*Pinus palustris* Mill.) was once the predominant pine species (Schultz 1997), but extensive harvesting of longleaf for lumber and naval stores in the 1800s, caused the longleaf to become an endangered species (Shultz 1997). After the longleaf was widely cleared in the 1800s, the 1900s saw a new era of land-management practices in the form of extensive fire-control measures, which reduce longleaf pine competitiveness as well as the wide-spread planting of loblolly pine (Borders and Bailey 1991). Loblolly pine has since become the second-most common tree species in the United States (Baldwin and Feduccia 1987) with extensive populations along the coastal regions of the southeastern United States (Schultz 1997), most prominently North Carolina.

Some severe meteorological events that are common along coastal regions of the Southeast can play a role in the growth patterns seen in loblolly pine (Fernandez 2008). Loblolly pine has lower wind tolerance relative to other co-occurring pine species including shortleaf (*Pinus echinata* Mill.) and longleaf pine (Johnsen 2009). Thus, high-wind events can cause structural damage to the tree itself and cause a decline in the radial growth of populations (Fernadez 2008). Any structural damage that the species would sustain from high-wind events could trigger the formation of traumatic resin ducts (TRDS) (Stoffel 2008). Similarly, the long needles (10–23 cm) of loblolly pine present extensive surface area for either snow or ice to accumulate and because of the low wood density (Michael 1985) this species is susceptible to the loss of either the branches or upper portion of the bole, which would also trigger the formation of TRDs. Here, I evaluate the fidelity between cool-season storm events and TRD frequency sampled from loblolly pine along the northeastern coast of North Carolina, USA. I address two objectives to evaluate the potential viability of this relationship as a proxy method for storm-event occurrence documentation prior to historical records. Specifically, I determine if a significant relationship exists between: 1) the occurrence of storm events and the stabilized frequency of TRDs during a 70-year period (1950–2019), and 2) tree age of the number of TRD occurrences exists.

2.2.1 Traumatic Resin Ducts (TRDs)

Resin ducts are tubular-shaped cavities/canals that secrete resin in response to environmental stresses that cause physical damage to the tree (Stoffel 2008, Gagliotti et al. 2019). These ducts are most heavily concentrated within the period of tree-ring growth that experiences the most trauma; either from storms or biotic infestations (Stoffel 2008). The resin that is secreted generally has antifungal and antiseptic qualities that facilitate the healing process within the trees (McKay *et al.* 2003). Resin ducts can be triggered to release resin when the tree has either undergone structural damage, such as loss of a limb, or has been infested with insects, which makes the resin an important feature for maintaining general health within the tree (McKay *et al.* 2003, Nagy 2008, Stoffel 2008). For example, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) is known to invest more stored carbon into producing resin ducts during a drought to help defend themselves from pine beetle infestations (Kane and

Kolb 2010). The resin can both fill and suffocate the boroughs where pine beetles have infested the tree (Kane and Kolb 2010).

TRDs are the residual pockets of resin that form within the annual growth rings of trees (Quarterman and Keever 1962, Nagy 2008). The formation of TRDs suggests that there was some sort of environmental disturbance in the time immediately before the occurrence (McKay *et al.* 2003) regardless of if the trees were actively producing new wood. Thus, tree damage during the non-growing season would be recorded as TRDs in the following earlywood growth season (Gaglioti *et al*. 2019). The environmental disturbance would have made a direct impact on the tree such as losing a limb from a windstorm or heavy snow/ice, rotting due to cambium disturbance, or biotic infestations (Luchi *et al*. 2005). TRDs will commonly form in a tangential pattern and vary in terms of amount and density depending on the type of trauma experienced and the time of year at which it occurs (Stoffel 2008).

TRDs can be classified based on their location within the annual ring-width growth (i.e., either earlywood and latewood growth rings) to better understand which TRDs could be potentially caused by specific storms (Figures 1 and 2). Phases of ring growth include: **EEW—**early earlywood, found within the first half of the earlywood; **LEW--**late earlywood, found within the second half of the earlywood; **ELW--**early latewood: found within the first half of the latewood; **LLW--** late latewood, found within the second half of the latewood. The number of TRDs is suggestive of the severity of the event (Figure 1) while the placement within the ring growth reflects the timing of the event as TRDs typically form either days or weeks following the initial damage (Gaglioti *et al*. 2019) except for traumatic events that occur during the dormant season, which would be expressed in the early part of the earlywood **(EEW**) the following growth year.

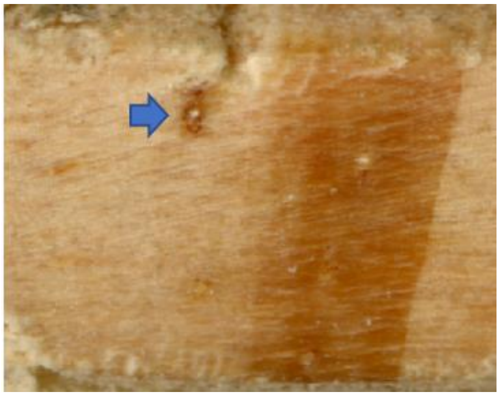

Figure 1: View of TRDs occurring in the latewood bands of a loblolly pine

Figure 2: View of an earlywood TRD in the annual growth ring of a loblolly pine

2.2.2 Coastal North Carolina Storm Events

Nor'easters

A Nor'easter is a macro-scale, cyclonic meteorological event with climatological importance that typically forms in the western North Atlantic Ocean and impacts the eastern coast of North America (Davis and Dolan 1993). Much like a tropical cyclone, Nor'easters can cause detrimental environmental and economic damages to the affected area (Davis and Dolan 1993). For a Nor'easter to form, warm air originating from the Gulf of Mexico needs to encounter cold air masses originating from Canada. The collision of two differing air masses creates an unstable and low-pressure system (Karvetski 2009). As the system travels along the east coast, it will meet more warm and moist air. This process causes the air pressure to drop to even lower levels which in turn, causes the air mass to become more unstable. The moister air that the system encounters, the more precipitation it will produce in the affected area (Davis and Dolan 1993, Karvetski 2009). Nor'easters can typically form the largest and most intense storms during October–April as without both warm and cold air masses, Nor'easters cannot thrive (Davis and Dolan 1993). Nor'easters can produce gale-force winds, flooding, and large amounts of either rain or snow to the affected area (Gagloti et al. 2019). In more northerly latitudes, Nor'easters can bring blizzard-like conditions while southern latitudes as far down as North Carolina will experience more hurricane-like conditions (Karvetski 2009).

Nor'easters characteristically form and gain strength off the coast of North Carolina (Davis and Dolan 1993) causing damage from coastal regions of North Carolina to areas north of New England (Davis and Dolan 1993). The Outer Banks of North

Carolina act as a buffer between the storm itself and the mainland of the state (Patrick 2019). When Nor'easters impact North Carolina, they first encounter the Outer Banks. As the storm affects the area, it begins losing moisture and strength. If the Nor'easter has the strength to reach the mainland, it will not be as powerful as it was when it affected the Outer Banks and thus not cause as much damage as it could if North Carolina did not have these Barrier Islands. However, the damage that Nor'easters cause to the Outer Banks can be substantial as these islands are getting the full force of the storm (Patrick 2019). Areas in the Outer Banks can experience storm surges during these storms that will cause the dunes along the coast to erode and spread sand in the inland areas of the island. This causes homes to be completely exposed to floodwaters. In 2019, the Outer Banks experienced a Nor'easter that caused the complete erosion of the dunes on Nags Head (Patrick 2019). Thousands of homes were flooded, and many residents of the area were left displaced. The economy of the Outer Banks suffered loss as the tourist industry was forced to close to make way for the repair process.

Tropical Cyclones: Hurricanes and Tropical Storms

Tropical storms and Atlantic hurricanes are tropical cyclones that form in the north Atlantic Ocean and are typically the most violent storms that affect the Atlantic coast (Elsner 1999). Tropical cyclones that have a one-minute sustained maximum wind of at least 34 knots (kt) are considered tropical storms while those with a one-minute sustained maximum wind of at least 64 kt are considered hurricanes (NHC 2021). Tropical cyclone season is from June 1st– November 30th, with the highest storm frequency occurring from mid-August through mid-October (NHC 2021). Storm lifespans range from 1-30 days and affect coastal North Carolina from a few hours to several days (Landsea 1992).

Tropical cyclones begin as areas of low-pressure, known as “tropical waves” that begin off the western coast of Africa and continue westward toward the Tropics (NHC 2021). As the tropical wave moves over the warm and moisture-rich air of the southern Atlantic, the low-pressure area directly under the storm system will cause an increase in the air-flow supplying the moisture within the system (Landsea *et al.* 2008). As the amount of moisture and heat within the system increases, the energy that powers the system will also increase, causing the system to become more powerful (NOAA 2021).

In North Carolina, there are approximately two tropical cyclones every year that make landfall and directly impact the state, with the Coastal Plains region being the most heavily affected (NCSU 2021). One of those tropical cyclones every two years will evolve into a named hurricane that will affect the Outer Banks of North Carolina (Blevins 2017). The Outer Banks serve as North Carolina’s barrier islands. Barrier islands act as a protective barricade for an area’s mainland by absorbing energy from storm systems before they reach the mainland, slowing the systems’ progress and decreasing the potential impact they can have in an area (Blevins 2017). The Outer Banks often receive the most severe damage from tropical cyclones (Blevins 2017).

Snow and Ice Storms

Nags Head has a humid subtropical climate featuring warm and humid summers with mildly cold and drier winters and is typically not heavily affected by classic winter-storm events (Johnson 2007) as the Pamlico Sound to the west and the Atlantic Ocean to the east moderate temperatures. During the cool season, Nags Head receives less than 5 cm of snow/ice. Any system that produces more than 3 cm of snow or 0.64 cm ice during a single event would be considered extreme winter weather events for Nags Head (OBX 2021). Snow and ice storms that affect Nags Head typically form in the Gulf of Mexico and travel through the southeastern United States and absorb excess moisture from the warmer waters of the Atlantic Ocean.

2.3 Materials and Methods

2.3.1 Study Site

Tree-ring data were collected from adult loblolly pine at Nags Head Woods Ecological Preserve (NHW) in the Outer Banks of North Carolina, USA, 35° 59' 5.604'' N and 75° 39' 54.63'' W. NHW lies on the Barrier Islands of North Carolina (Figure 3), making it particularly susceptible to the high-wind events associated with tropical depressions, hurricanes, and Nor'easters. It also receives heavy winds stemming from the Atlantic Ocean on the east and the Pamlico Sound on the west. The specific field site within NHW that was used is known as the maritime deciduous forest portion of the location (Johnson 2007), which is a mixed pine-hardwood forest comprised of hickory, oak, beech, and loblolly and longleaf pine. This portion of the preserve is in the most coastal-facing area of the site and is the most affected by coastal weather events. Trees growing at this site, including loblolly, are situated on sandy dunes rising approximately 3–10 meters above the surrounding terrain, which lies at 1 m asl. NHW was extensively logged in the 1920s and 1930s, effectively clearing the land of any longleaf pine. Thus, the lack of native longleaf pines at NHW excludes the need for controlled burns for their regeneration and there are few signs of fire within the Preserve. The site was designated a Natural Landmark in 1974 and has undergone little change since then.

NHW is characterized by well-drained sandy soils (Fripp fine sand-80.2%, Newhan fine sand-2.3%, Osier find sand-8.3%) with the remaining 8.4% consisting of Conaby muck, a poorly drained found in the depressions of NHW (USDA 2021). The island of Nags Head, which is 3 km south of NHW, has a humid subtropical climate (Cfa based on the Köppen-Geiger classification), featuring humid summers and mild, dry winters (Johnson 2007, Peel et al. 2007). The average high and low temperatures for summer (June–September) range between 25–35℃ while average winter temperature ranges between 2–15℃ and rarely fall below 0℃. Nags Head receives approximately 140 cm of rain annually, with 65% of the rainfall occurring during July–December (NCDC 2021).

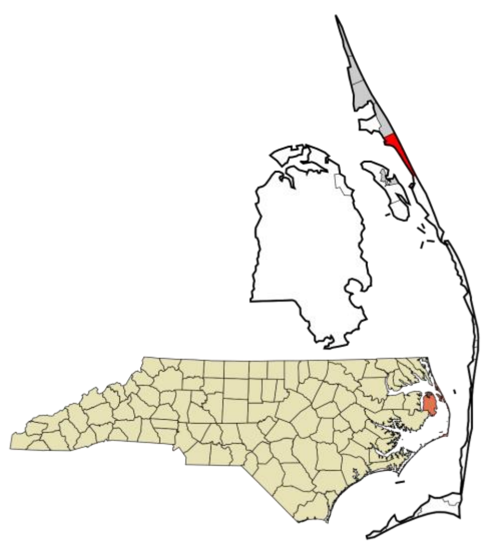

Figure 3: Field Collection Site-
NHW highlighted in red

Figure 4: NHW trees along
sandy dunes

2.3.2 Loblolly Pine Tree-Ring Data

During summer 2020, I sampled 24 loblolly pine on the eastern side of NHW that is closest to the Atlantic to increase the odds that the trees were receiving the maximum wind damage during a wind-event. I obtained two core samples from each tree, totaling 48 core samples using a 5.15 mm diameter increment borer and non-destructively sampling from each tree following standard dendrochronological procedures (Stokes and Smiley 1996). I recorded the geographic location of the samples as well as the crown height and stem diameter (at 1.3 m) of each tree. Any unusual observations about the tree also were recorded, including any substantial limb loss and location relative to down trees. After collecting the samples, the cores were dried for two weeks and then glued and mounted to wooden strips. The mounted cores were sanded with progressively finer sandpaper beginning with 200 *u*m and ending with 800 *u*m to reveal as much of the cellular structure as possible. The sanded samples were scanned at a high resolution (DPI > 1200) and earlywood, latewood, and totalwood ring widths of each core were measured using WinDENDRO™. Once measured, the annual ring dates were confirmed using the crossdating accuracy software COFECHA. Any sample that could not be correlated with a master chronology was removed.

2.3.3 Traumatic Resin Duct Count per Year

Each core was analyzed for the presence of TRDs in the earlywood (**EW**) growth. (Figure 5) and all the TRDs for the sample were counted and recorded starting from the earliest recorded complete ring through the year 2019. I did not make a distinction

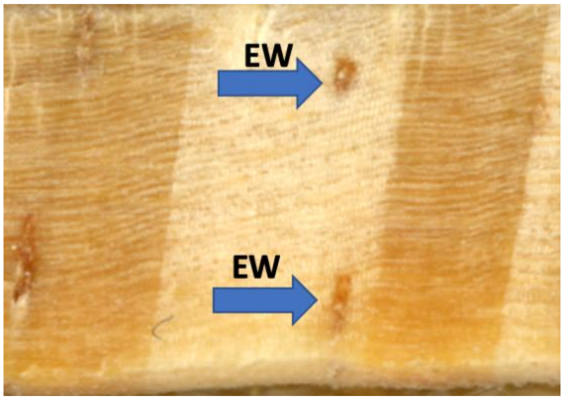

Figure 5: Location of two earlywood TRDs in a loblolly pine

between early earlywood and late earlywood as no clear division existed in the samples. Further, because the raw number of TRDs per year is affected by the sample size, a sample size that varies through time introduces a potential bias that dilutes the efficacy of the data (Osborn et al. 1997). Thus, I created a stabilized frequency using *f=Fn^0.5* where N is the raw number of TRD formations per year while n is the total number of available samples for the given year and F is the standardized Frequency (Osborn et al. 1997).

2.3.4 Weather Data

I used multiple sources to identify weather events at NHW that may have triggered TRD production during 1950-2019 including the North Carolina State Climate Office (NCSU 2021) Winter Storm Database covering January 1, 1965–July 31, 2017, the WeberWeather Winter Weather Database (Webb 2021), and NOAA's "Historical Hurricane Tracks" (Knapp *et al.* 2010), with the latter two complete from 1940 through 2019. Storms were listed as one of four categories: Tropical cyclone (hurricanes and tropical storms), windstorm (including Nor'easters), snowstorm, and ice storm. Tropical cyclones and windstorms were included in the database if wind speeds at NHW likely exceeded 33 kt based on a review of Daily Weather Maps from NOAA's National Climate Data Center. Additionally, because quantification of the extremeness of all the weather events was not possible, I treated events by either their presence or absence for a year and did not differentiate between years with one or more events.

I associated the date of the storm to the subsequent TRD formation assigning all events during October 15th–May 31st (hereafter "Cool Season") with earlywood radial growth. Nearly all cool-season events occurred during mid-October through March, thus the formation of TRDs would likely be captured in the **EW** formation, which typically extends until approximately the end of May (Rother *et al* 2018). Few storm events occur at NHW during April and May as the strength of mid-latitude storms is considerably weakened, snow, and ice are rare, and it is prior to the onset of tropical cyclone season. Thus, it is highly likely that EW TRDs were initiated during the cool season even though EW formation occurs until the end of May. Finally, TRDs that are recorded during the cool season are unlikely to have been formed due to a pine beetle infestation (Bentz 2014) or other biological agents, which could cause an increase in years with a high TRDs without storm events.

2.3.5 Analyses

To determine the differences in the number of TRDs for storm years and non-storm years, I used an independent samples test, which included the significance level for the difference. Additionally, I tested the significance that each samples' age in 2019 had on the number of TRDs using correlation and a simple linear regression model. The number of TRDs per year was analyzed using the stabilized frequency of TRDs from 1950–2019. To determine if the age of the trees had a relationship with TRD formation, I ran a simple linear regression for the age of the trees in 2019, and the total number of **EW** TRDs formed in the common period of 1970-2019 (i.e., the period when all samples were complete). I tested correlations between stabilized TRD frequency in the **EW** with the total number of storms per year and the four individual storm types. The differentiation of the **EW** storms did not show significance. Thus, **EW** storms were categorized together.

I also tested for presence of false positives and false negatives using the z-scores associated with the TRD **EW** stabilized frequency for each year. A false positive was characterized by a year with a high z-score (>0.5) for stabilized frequency with no recorded storm event (i.e., the presence of TRDs not associated with storms), while a false negative was characterized by a low z-score (<0.5) with one or more recorded storm events (i.e., few to no TRDs during a year with storm events). The FP/FN rates were calculated using the formula $\frac{FP(N)}{FP(N)+TP(N)}$, where FP(N) is equal to the number of FPs or FNs and TP(N) is the true number of positives/negatives.

2.4 Results and Discussion

The final sample that met the criteria for inclusion (i.e., clear, continuous ring-width pattern) in the chronology consisted of 24 trees and 48 cores from NHW. These samples were used for TRD analysis. The annual number of TRDs for the earlywood per year in each sample ranged from 1–17. Tree age ranged from 54–107 with the median age of 93. The cores crossdated well with an interseries correlation of 0.454 and a mean sensitivity for the earlywood of 0.381.

Storm-type frequency ranged from 14–21 events each year from 1950 to 2019 and the number of events per year ranged from 0–7 (Figures 6 and 7). The average number of TRDs in a non-storm year for the **EW** is 2.80 while the average for a storm year is 3.75 per sample (p <0.001, Figure 7). This finding suggests that there is a significant relationship between the formation of TRDs triggered by weather events during the months of mid-October–May. These results agree with the findings from Gaglioti et al. (2019) who found that TRD frequency in earlywood growth was correlated with high-wind exposed mountain hemlock in southeastern Alaska. I also tested the correlation between the stabilized frequency of TRDs with the four individual storm types. The stabilized frequency was not significantly related with any individual storm type (Table 1).

Table 1: Relationship between TRDs and the 4 storm types

	Tropical Cyclones	Ice Storms	Snowstorms	Windstorms
Correlation	0.037	0.332	0.381	0.081
P-value	0.379	0.181	0.285	0.283

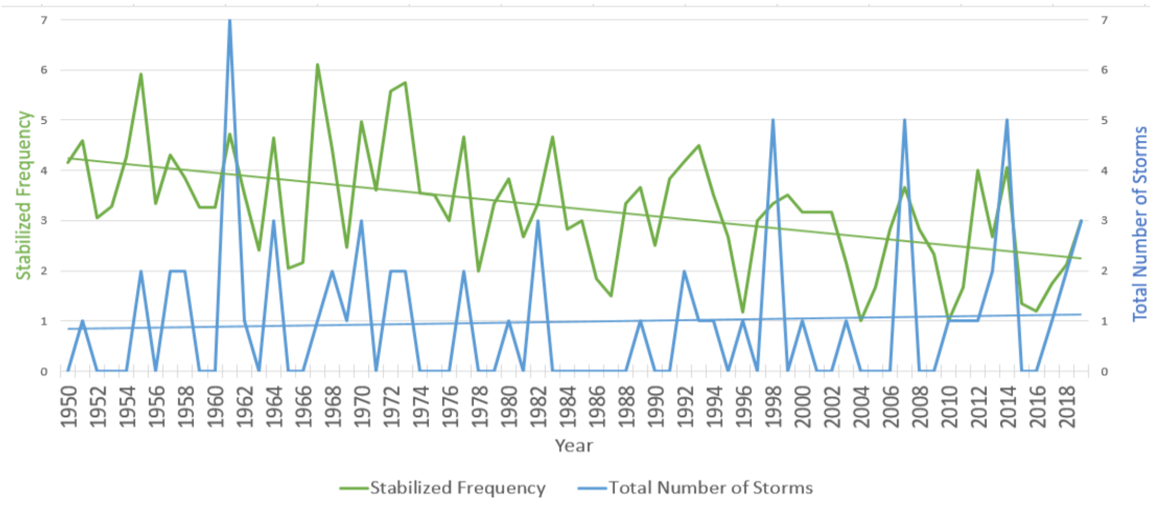

Figure 6: Number of cool-season storm events by type 1950-2019.

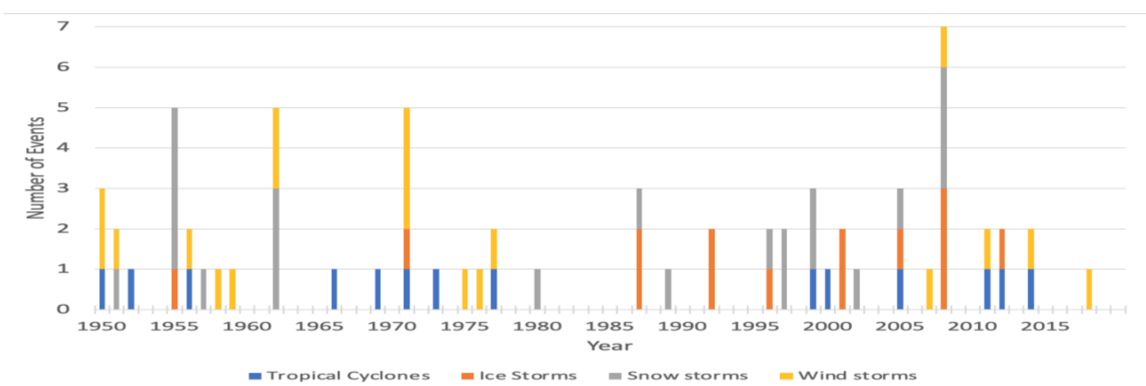

Figure 7: **EW** Stabilized frequency (with trendline): Storm R=0.225 *p*-value<0.001
Storm total: R=0.003, *p*-value=0.541

The **EW** TRD stabilized frequency during 1950–2019 significantly decreased (Figure 7) suggesting that there has been: 1) a decrease in cool-season traumatic events from 1950-2019, 2) an age-related trend as trees may be less-likely to record storm events through TRDs, or 3) a combination of these. However, there was no significant trend in storm frequency (Figure 7). Rather the correlation between the **EW** stabilized frequency and the total number of storms that occurred per year (Figure 7) is significantly related ($r = 0.40$, $p < 0.001$) indicating that the downward trend in TRD stabilized frequency captures the decrease in cool-season traumatic events that affect NHW. Further, to test whether stabilized TRD frequency was affected by tree age, I plotted mean stabilized frequency during the 1970–2019 common period with tree age (Figure 8). As trees age, changes in morphology (i.e., DBH, height) and local environments (i.e., development of wind-buffering trees and changes in forest productivity) may alter their sensitivity to storm events (Ryan *et al*. 1997) and TRD formation. That said, this relationship was not significant suggesting that there is not an age-related change in TRD formation witthese data so the variability in TRD can be compared from the earliest to latest periods of record.

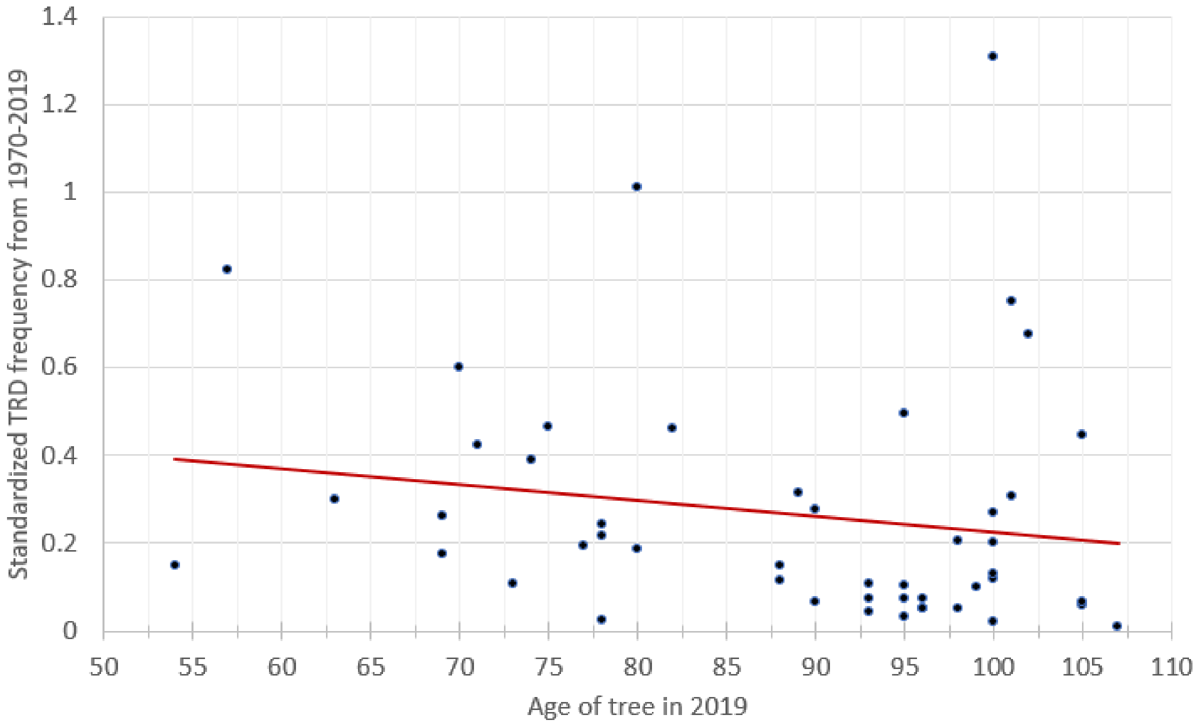

Figure 8: Relationship between standardized TRD frequency during the common period of 1970-2019 and tree age with red trendline. No significant (R^2=0.001, p=0.21) relationship exists suggesting TRD frequency is not affected by tree age.

Twenty years during the 70-year time series were classified as having either an FP (n = 4) or FN (n = 16). Within the FN dataset, the most common types of recorded storms were Nor'easters and other cool-season high wind events (43.3 %), and tropical cyclones (26.6%) (Figure 9). The high frequency of tropical cyclones and cool-season high wind events in FN years suggest that these systems might not cause as much damage to loblolly pines as snow and ice-storms as wind direction in addition to wind speed may affect the production of TRDs. However, loblolly pines are also known to have a moderate wind-resistance and will show little damage after a windstorm (Frederickson 1993, Gardiner 2016). The little damage that is caused by a windstorm in the late warm-season can be exacerbated by an early-cool season event, such as an early freeze. Because of this, it is possible that the damage that a Nor'easter or tropical cyclone, particularly if it occurred during the non-growing season, has on a loblolly pine may not be noted in the TRDs until the following growing-season.

The false positivity rate was calculated to be 0.125, meaning that using a similar dataset in NHW to reconstruct wind-events using TRDs would result in falsely recording a wind-event in a year with a high stabilized frequency in 12.5% of the years recorded. The false negative rate was calculated to be 0.20, meaning there is a 20% probability of falsely accepting the null hypothesis and rejecting the true hypothesis. These results confirm that having a large amount of TRDs present within the **EW** is unlikely to occur without some sort of storm event. Conversely, not all storm events contribute to the formation of TRDs and it is also possible that TRDs do not have uniformity throughout the tree, meaning some TRDs can be concentrated within an area of the tree that was not cored.. This is expected because storm timing, wind direction, and storm intensity are not recorded at the exact time the event affects the tree. Studies on conifers have shown that after each traumatic event, conifers are more likely to release an increased amount of resin for each subsequent similar traumatic event (Casteller 2007), which could lead to an increased amount of FP years during events that do not cause as much damage to the trees. False positives and negatives are important in the discussion on whether TRDs should be referred to as "traumatic" because one cannot differentiate between the various causes of TRDs (Fahn and Zamski 1970, Wu and Hu 1997). Although it is unlikely that specific storm events can be differentiated from one another, TRDs in loblolly pines are unlikely to occur in years without some sort of traumatic event.

2.5 Conclusion

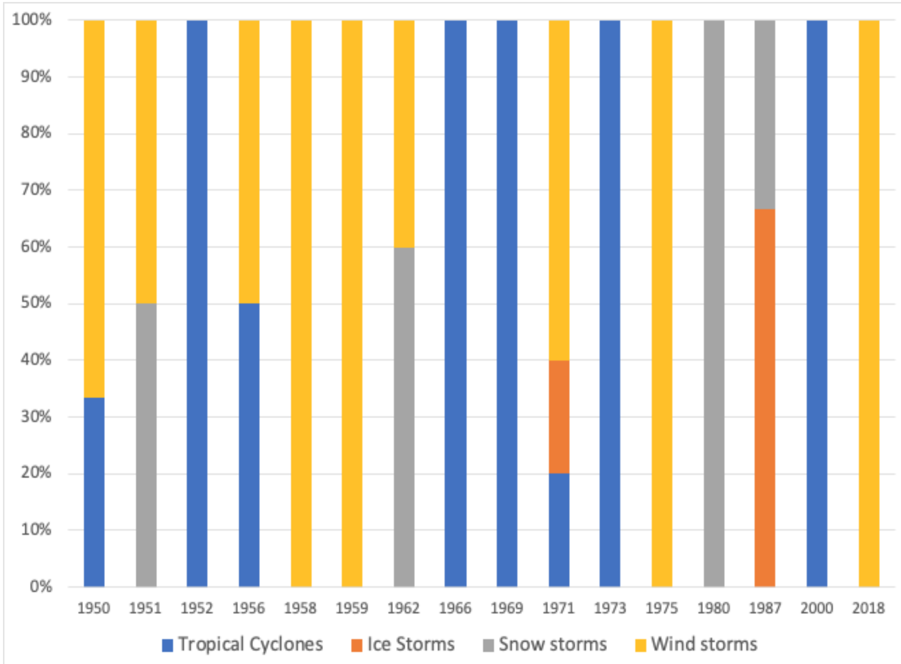

Figure 9: The frequency of each storm event during FN years

These results indicate that storm events that occur during the cool-season are likely to promote the formation of TRDs in adult loblolly pine. In turn, the findings produce a viable method that can be used to extend the record of storm frequency with annual precision and which provides context for interannual variability beyond historical records when old-growth samples are available. The first question asked in this study was if TRDs can be used to reconstruct Nor'easters in the southeastern United States. It was found that years with Nor'easters do influence the formation of TRDS, though it was not possible to separate and analyze each specific wind-event from one another. In any given year that had both a Nor'easter and a tropical cyclone, it was not possible to differentiate each individual TRDs that were caused by the Nor'easter and which were caused by the tropical cyclone. However, it is important to note that Nor'easters were the most prominent storms in years that were marked as FN. The low stabilized frequency of TRDs during these FN years could mean that Nor'easters are not causing as much damage to the loblolly pine in the NHW as other cool-season storm events. This could be because the forest itself is so densely populated that the trees are protected from wind-damage caused by strong storms.

To further investigate the relationship between TRDs and cool-season events, it would be beneficial either to sample from old-growth loblolly pine or from a co-occurring pine species that is longer-lived than loblolly pine such as longleaf pine or coastal pitch pine. More sampling from different sites, both inland and along the coast, would add a means of comparison between sites that are more exposed to wind and sites that are more protected and would test the fidelity of the relationship under a variety of scenarios. It would also be useful to obtain core samples from a different species altogether because although *Pinus* are likely to form TRDs after a traumatic event, there is no anatomy differences between the TRDs that are formed in response to physical trauma to the tree and those that form from high temperature fluctuations. There are no differences between the anatomy of the TRDs caused by different types of events other than their location relative to one another with the methods I used (Wu and Hu 1997).

CHAPTER III: CONCLUSION

There are several key findings from these analyses. First, the stabilized frequency of TRD formations in the **EW** of loblolly pines in NHW is significantly ($p<0.004$) related to storm-events that occur during mid-October through May, suggesting that TRD analysis is an effective way to examine cool-season storm events in North Carolina. This argument was further strengthened after finding that the age of the tree and the TRD stabilized frequency are not significantly related (p-value > 0.05), meaning that early years in the chronology can be analyzed the same as the recent years. The analysis of the TRD stabilized frequency shows that there has been a downward trend in the amount of TRDs per year. This finding suggests that there has been a decrease in cool-season traumatic events that affect NHW over the past 70 years. Although this research had originally sought to relate TRD formations with Nor'easter occurrences, it was found that it can be used to record 4 different storm types that cause trauma to loblolly pines. With that said, this method cannot differentiate between storm types, only the time of year by which the storms occurred. The significant relationships in these findings allow for a better and more accurate understanding of historical wind-events in North Carolina.

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