

Fire History of an Acidic Barrens Complex: A Methods Assessment of Fire Return Intervals

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In

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ACADEMIC ABSTRACT

Fire-scarred trees provide an important source of data and direct evidence for understanding past fires and vegetation dynamics. Although dendrochronological fire scar records provide fine-scale temporal and spatial resolution, limitations exist in the development, analysis, and interpretation of these fire history datasets. In order to assess these limitations, we applied a systematic gridded sampling scheme to a 4-hectare study area located in the Ridge and Valley Province of northeastern Pennsylvania. We mapped and described a total of 155 fire-scarred trees within a 50-meter resolution grid, noting the species, health status, and basal scar orientation for each tree. Additionally, we cut a full or partial cross section from 58 fire-scarred pitch pine (*Pinus rigida*) for the purpose of assessing multiple “filtering” techniques and for the development of a fire interval simulation model. The simulation model randomly selected trees from each grid cell to estimate fire return intervals at multiple spatial scales. Our results indicate that fire return intervals are dependent upon the definition of “recorder” years are influenced by various filtering methods, including minimum number and minimum percentage of trees scarred.

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PUBLIC ABSTRACT

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Chapter 1: Introduction

Introduction

Fire is a natural disturbance that shapes global biomes and maintains ecosystem function of fire-prone communities (Bond and Keely, 2005). Fire varies over multiple spatial and temporal scales, and depends on three fundamental elements: ignition (natural and anthropogenic), consumable resources, and atmospheric conditions (Parisien and Moritz, 2009). Fire regimes have helped shape landscapes and ecosystems in North America since at least the late Paleozoic Era (Lorimer, 1985; Abrams and Nowacki, 1992; Pausas and Keely, 2009; Fesenmeyer and Christensen, 2010). In North America, sediment charcoal evidence suggests Native Americans regularly used fire as a tool for forest clearing, maize production, game trails, and as a strategy for warfare over the past 4000 yr. BP. (Day, 1953; Fesenmyer and Christensen, 2010).

Fire benefits forests by accelerating soil nutrient cycling, increasing mortality rates of individual trees, increasing landscape heterogeneity, and changing the physical structure of surface-soil organic layers (Whelan, 1995). High intensity crown fires reach the tree canopy and can kill trees that are not fire adapted, while less intense ground fires serve as contributors to community organization by reducing excessive amounts of fuel build-up and encouraging native vegetation to thrive (Waldrop and Goodrick, 2012). Characteristics of fire, including frequency, intensity, extent, and seasonality also depend on climatic factors and forest composition (Lafon et al., 2005; Flatley et al., 2010).

Dendrochronology, the scientific study of annual tree rings carried out with specific principals (i.e. site selection, crossdating, standardization) and field and laboratory methods (i.e. coring, sanding, statistical analysis) is a proven tool for reconstructing the timing of past fire events

and characterizing fire regimes (Grissino-Mayer, 1995; Guyette et al., 2006). Tree rings are formed from layers of cells produced by the vascular cambium during an annual growth period (Speer, 2010) and display ring-width variation that reflects environmental conditions. For example, wide rings often form during years with increased moisture availability, while narrow rings typically form during dry years. Tree rings can be crossdated and ring-width variations can be analyzed to determine specific environmental conditions to create a master chronology (Speer, 2010).

Dendrochronology is a proven tool for reconstructing the timing of past fire events and characterizing fire regimes (Grissino-Mayer et al., 1994; Guyette et al., 2006). Fire-scarred trees provide one of the most tangible sets of data for understanding past fire regimes and vegetation dynamics. A fire scar is defined as an injury left behind on a tree during a specific year and season due to the vascular cambium (a plant vesicular tissue associated with a plant's secondary growth) being physically damaged by a fire (Dieterich and Swetnam, 1984; Smith and Sutherland, 1999). Although the tree is often just wounded from the fire event, a basal scar is embedded within the growth rings and the trunk which researchers can identify as a “catface” (Arno and Sneek, 1977). Dendrochronologists can determine fire return intervals at annual resolutions, allowing for the documentation of the season and calendar year of the fire event and an examination of fire frequency (Everett, 2008). Fire-scar records can be compiled from areas showing multiple trees responding to an event, thus allowing researchers to interpret how fire regimes respond to land use change or shifts in climate.

Although fire scar records provide both temporal and spatial fine scale data of fire history, the development and interpretation of fire scar records are met with limitations. (Guyette et al., 2006). For example, sometimes trees do not exhibit a visible fire scar, even if a fire has affected it (i.e., false negative). Additionally, tree species differ in their capacity to record a fire. Those with thick bark, such as Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), do not always leave

behind evidence of fire (bark not charred or no scar visibly present). Fire-sensitive tree species (i.e., those with thin bark) that are established during long fire free intervals attain a large size that helps avoid scarring (Lafon et al., 2017). Additionally, stand-replacing fires leave no record because trees are killed (Guyette et al., 2006) and fire scars only indicate the occurrence of fires and not the ignition source. There is also a constraint on the record length as fire-scarred trees can only give insight into past fire regimes over the last few hundred years (Hart and Buchannan, 2012). Finally, topographic roughness introduces an additional factor that must be considered in a fire scar study. In rough terrain, fire spread is limited by slope and aspect, which can influence measures of fire frequency. For example, steep slopes intensify fires, channeling winds and “pre-heating” fuels as flames move upslope. In this case, slope indirectly influences the likelihood that a tree will be scarred or killed. One suggestions when reconstructing a fire history is to confine the analysis to a set of area parameters that do not exceed more than several hundred hectares (Guyette et al., 2006).

Strategies for sampling fire-scarred trees and the required number of samples collected vary among researchers. Target sampling is the most common type of sampling approach used by researchers, and it consists of traversing a study area and sampling only the oldest trees with, presumably, the longest fire records. A census sampling approach consists of sampling every fire-scarred tree within a constrained area yielding large sample sizes, many times from multiple tree species. Some researchers prefer to sample in forest stands that contain several fire scarred trees as a way to record past fire events comprehensively (Swetnam and Baisan, 2003). However, varying opinions exist with respect to how many fire scar samples are ideal for fire reconstruction. In temperate forests of Eastern North America, fire-scarred trees are not as dense or clustered as in arid and semi-arid landscapes of Western North America and therefore a target sample size of 20 should be obtained (Farris et al., 2013; Lafon et al., 2017).

One field sampling approach for estimating fire return intervals is a grid-based methodology. While this approach is uncommon, the spatial component of this methodology is advantageous when looking at how mean fire return intervals (MFI) increase, decrease, or stabilize as sampled area changes. Within the gridded area, a fire census is assembled using all fire scars from various species serving as an intensive approach to reconstruct fire history (Van Horne and Fule, 2006; Brown et al., 2008). Systematic grid cell sampling provides information on historical fire regimes, which is important for understanding the role of fire in forested ecosystems (Everett, 2008).

Fire Interval Estimation from Fire Scars

Mean fire return interval (MFI) is the arithmetic average of all intervals, in years, in a defined study area during a specific time period (Romme, 1980). It is a metric that is skewed right due to occasional longer return intervals (Sutherland et al., 2015). Therefore, scientists use a number of supporting statistics (i.e., standard deviation, Weibull distribution, and lower and upper exceedance intervals) to describe the fire regime in a given area (Grissino-Mayer, 2001). The median fire return interval can also serve as a solution to the right skewness of the (MFI). Median fire return interval is the middle value of all intervals in a series ranked from shortest to longest and is less sensitive to skewed distributions (i.e., unusually short or long intervals) (Sutherland et al., 2015). Even with questions that arise with MFI, scientists studying temperate forests of Eastern North America find the metric valuable as it allows for a better understanding of ecosystems at local scales due to succession and land history use (Thompson et al., 2013). Scientists recognize MFI as a fire regime characteristic that can be used to inform fire management and policy (Gilmore and Palik, 2006).

Additional fire interval statistics allow researchers to analyze the data using two probability distributions (normal and the Weibull). The standard deviation is the square root of the variance in a

sample and measures dispersion about the mean. The Weibull distribution smoothly distributes the associated occasionally long fire return intervals (Falk, 2004; Grissino-Mayer, 1995; Johnson, 1985). The Weibull median is the 50th percentile of the Weibull distribution. Exceedance intervals are useful for fire reconstructions as they represent the probability of a fire event. Exceedance intervals allow researchers to analyze short and long intervals. The lower and upper exceedance intervals are values that delimit unusually long or short fire intervals. (Sutherland et al. 2015).

. Once of the most crucial components in fire history analysis is the role of recorder years (Sutherland et al., 2015), which indicate when tree rings are in recording status. Recorder years influence percentage of trees scarred (i.e., fire extent) and are recognized in two ways. Some researchers recognize recorder years as those years after the initial scar, thus making the tree more susceptible to scarring due to bark falling off and the wood being exposed (Sutherland et al., 2015). Other researchers, however, recognize recorder years as when a tree is living (Saladyga, 2017; Marschall et al., 2016; Stambaugh et al., 2014).

Filtering techniques with different criteria can be applied in Fire History Analysis and Exploration System (FHAES) to create an output of fire history statistics. The objective of the minimum percentage filter is to apply a percentage that characterizes fire on a particular landscape. Further, using a percentage filter allows for comparison between sites with different sample sizes and sample areas, as well as a comparison between time periods with different sizes within one site. For instance, in Northern Arizona, fire-scarred trees were collected from a confined area of 247 acres by the means of a census, and a 25 percent filter was used to show fire return estimates (Van Horne and Fule, 2006). The composite information is important to assess changes in fire frequencies both spatially and temporally. Applying a variety of filters that are commonly found in traditional dendrochronological fire history studies can help identify fires and allows interpretations regarding particular fire years that might be considered widespread across the study site.

Study Objectives

The purpose of this research was to develop a fire-scar chronology for a globally rare pitch pine (*Pinus rigida* Mill.)-scrub oak (*Quercus ilicifolia* Wangenh.) community in northeastern Pennsylvania. We used a grid-based method for sampling fire-scarred trees, which we then used to model fire return intervals. Pitch pine-scrub oak barrens are globally rare ecosystems that depend on frequent disturbances to maintain unique habitat structure (PGC, 2017). Without periodic fire, the ecosystem will transition from early successional to closed canopy forests becoming overgrown by taller hardwoods such as black oak (*Quercus velutina* Lam.) and white oak (*Quercus alba* L.) (PGC, 2017).

Implementing a grid-based methodology will allow for a census of fire-scarred trees on multiple species in the pitch pine-scrub oak barren, and allowed us to assess how fire activity varies spatially. Grid-based field methodologies have not been used in any comprehensive, peer-reviewed fire history studies in Eastern Temperate Forests. To date, the method has been used primarily in semi-arid landscapes of Western North America (Van Horne and Fule 2006; Everett, 2008).

We followed field sampling with the application of a simulation model that simulated mean fire return intervals over space. The overall goal of this model was to understand how randomly selected sampling statistics per grid cell are compared to the overall sites MFI. The model will allow for a broad application by future researchers to recognize sampling limitations as well as provide fire managers information regarding fire frequency and extent.

Specifically, my research objectives are to: 1) characterize fire scarred species composition, 2) develop a fire-scar chronology for a globally rare pitch pine-scrub oak community in northeastern Pennsylvania, 3) apply a grid-based method for sampling fire-scarred trees and modeling fire return

intervals, 4) compare simulated target sampling with census sampling, and 5) use fire-scar data from nearby sites to compare mean fire return interval filtering techniques.

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Chapter 2: Manuscript

Fire History of an Acidic Barrens Complex: A Methods Assessment of Fire Return Intervals

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To be submitted to: Tree-ring Research

Abstract

Fire-scarred trees provide a valuable source of data and direct evidence for understanding past fires and vegetation dynamics. Although dendrochronological fire scar records provide fine-scale temporal and spatial resolution, limitations exist in the development, analysis, and interpretation of these fire history datasets. In order to assess these limitations, we applied a systematic gridded sampling scheme to a 4-hectare study area located in the Ridge and Valley Province of Northeastern Pennsylvania. We mapped and described a total of 155 fire-scarred trees within a 50-meter resolution grid, noting the species, health status, and basal scar orientation for each tree. Additionally, we cut a full or partial cross section from 58 fire-scarred pitch pine (*Pinus rigida*) for the purpose of assessing multiple “filtering” techniques and for the development of a fire interval simulation model. The simulation model randomly selected trees from each grid cell to estimate fire return intervals at multiple spatial scales. Our results indicate that fire return intervals are dependent upon the definition of “recorder” years are influenced by various filtering methods, including minimum number and minimum percentage of trees scarred at local and landscape scale. For example, the number and length of fire intervals was greater when years prior to the initial scar were considered “non-recording” vs. “recording” and when a percentage scarred filter was applied. The simulation model provides an additional range of fire interval estimations that can be used by land managers to guide forest restoration and fire management objectives.

Keywords: dendrochronology; fire history; modeling; Pennsylvania

Introduction

Fire is a natural disturbance that shapes global biomes and maintains ecosystem function of fire-prone communities (Bond and Keely, 2005) in numerous ways, depending on spatial extent and intensity. Fire accelerates soil nutrient cycling, increases landscape heterogeneity and biodiversity, and changes the physical structure of surface-soil organic layers because organic matter becomes rapidly combusted (Whelan, 1995; Trumborn et al., 2015; McDowell et al., 2018). High intensity crown fires reach the tree canopy and can kill trees that are not fire adaptive, while less intense ground fires serve as contributors to community organization by reducing excessive amounts of fuel build up and encouraging growth of native vegetation (Waldrop and Goodrick, 2012). Characteristics of a fire regime, such as frequency, intensity, size, and seasonality also depend on climatic factors, patterns of ignition, and forest composition (Lafon et al., 2005; Flatley et al., 2010).

Dendrochronology, the scientific study of annual tree rings carried out with specific principals (i.e. site selection, crossdating, standardization) and field and laboratory methods (i.e. coring, sanding, statistical analysis) is a proven tool for reconstructing the timing of past fire events and characterizing fire regimes (Grissino-Mayer, 1995; Guyette et al., 2006). Specifically, fire-scarred trees provide one of the most tangible sets of data for understanding past fire regimes and vegetation dynamics. A fire scar forms when the vascular cambium of a tree is damaged during a fire event (Dieterich and Swetnam, 1984; Smith and Sutherland, 1999). The wound leaves behind a basal scar recorded within annual growth rings that researchers can identify as a “catface” (Arno and Sneek, 1977).

The season and year of fires can be documented at a fine-scale resolution based on the position of a scar relative to annual growth rings (e.g., Everett, 2008). Dendrochronologists have

determined fire return intervals at annual resolutions, allowing for examination of fire frequency with consideration to short-term driving factors that influence ring-width variation (Everett, 2008). Examples of these driving factors include: climate, insect outbreaks, logging, and other disturbances (Silver et al., 2013; Stambaugh et al., 2014; Saladyga, 2017; Copenheaver et al., 2017). Fire-scar records can be compiled for areas with multiple trees responding to an event, allowing researchers to interpret how fire intervals respond to land use change or shifts in climate.

Researchers use a number of metrics to measure fire frequency. Mean fire return interval (MFI) is the arithmetic average of all intervals, in years, in a defined study area during a specific time period (Romme, 1980). Mean fire return interval is a metric that is skewed right due to occasional longer intervals (Sutherland et al., 2015). Median fire return interval is the middle value of all intervals in a series ranked by fire interval length, and is less sensitive to skewed distributions (i.e., unusually short or long intervals) (Sutherland et al., 2015). The MFI is a valuable metric for a better understanding of ecosystems at local scales due to succession and land history use (Thompson et al., 2013). Point fire intervals allow researchers to analyze fire history based on individual trees. Point fire intervals are not compiled into time series, which makes it an unreliable metric in larger geographic areas as the fire return lengths can be overestimated (Lafon et al., 2017). Composite fire intervals are a more reliable metric in more confined smaller areas, as the intervals compile all samples into one series which lowers the likelihood of a missing fire (Dieterich, 1980; Lafon et al., 2017).

Fire history analysis provides information about variations in fire occurrence from past decades or centuries. One of the most crucial components in fire history analysis is the designation of recorder years (Sutherland et al., 2015), which indicate when tree rings are in

recording status (Figure 1). Recorder years have a direct effect on analysis statistics and are recognized in two ways. Some researchers recognize recorder years as those years after the initial scar, thus making the tree more susceptible to scarring due to bark falling off and the wood being exposed (Sutherland et al., 2015). Other researchers, however, recognize recorder years as when a tree is living (Saladyga, 2017; Marschall et al., 2016; Stambaugh et al., 2014).

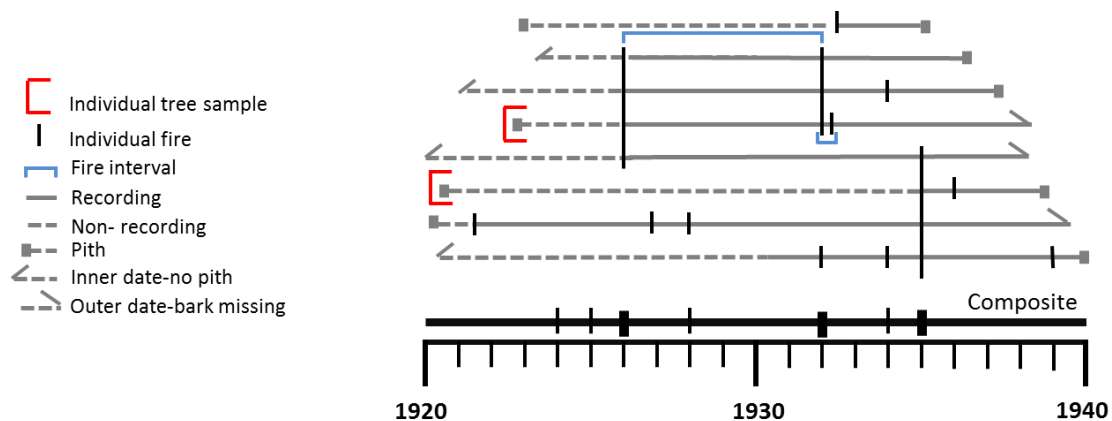


Figure 1: Example of fire history chart after Lafon et.al 2017. Each horizontal grey line represents an individual tree sample. Non recording status is represented by the dotted grey line and recording status is represented after an individual fire scar year (bold vertical black line). The grey slanted or vertical lines at the earliest year shown represent the inner-most ring or pith date, a slanted line indicates the outer-most ring present, a vertical line indicates bark year. The black line located at the bottom is the “composite”. The composite MFI is calculated by average of intervals between fires. Major fires are located at the bottom and are indicated by thick vertical black lines. Major fires are including the following filters: 3 samples minimum, and recording after initial scar.

Although fire-scar records provide fine scale temporal and spatial fire history data, the development and interpretation of fire-scar records have limitations (Guyette et al., 2006). For example, sometimes trees do not exhibit a visible fire scar even if a fire has affected it. Additionally, tree species differ in their capacity to record a fire. Those with thick bark, such as Ponderosa pine (*Pinus ponderosa*), do not always leave behind evidence of fire if the bark is not

charred or no scar is visibly present. Fire-sensitive tree species (i.e., those with thin bark) that are established during long fire free intervals attain a large size that helps avoid scarring (Lafon et al., 2017). Then there are stand-replacing fires, where trees are killed by fire and leave no record (Guyette et al., 2006). Some ecosystems within the landscape may be influenced by topography. For example, in topographically rough terrain, fire spread is limited by slope and aspect (Guyette et al., 2006). For example, steep slopes intensify fires, channeling winds and “pre-heating” fuels as flames move upslope. In this case, slope indirectly influences the likelihood that a tree will be scarred or killed. One suggestion to the topographical roughness issue the reconstructing a fire history is to confine the analysis to a set of area parameters that do not exceed more than several hundred hectares (Guyette et al., 2006). Additionally, fire scars only record the occurrence of fires, and not the ignition source. There is also a constraint on the record length as fire-scarred trees can only give insight into past landscapes over the last few hundred years (Hart and Buchannan, 2012).

Sampling strategies of fire-scarred trees, including sampling approach (target vs. census) and number of samples collected, vary depending on research objectives and, often, site permissions (Table 1). Target sampling is the most common type of sampling approach used by researchers and consists of traversing a study area examining the old fire-scarred trees with, presumably, the longest fire records. Some researchers prefer to sample in forest stands that contain several fire-scarred trees as a way to record past fire events comprehensively (Swetnam and Baisan, 2003). A census sampling approach consists of sampling every fire-scarred tree within a constrained area yielding large sample sizes, many times from multiple tree species.

Table 1: Example of fire-scar analysis methods in Eastern Temperate Forests organized by published study.

Author	Recording Status	Filter Method
Schuler and McClain, 2003	Recording after initial scar	Two or more trees scarred during single year, One or more trees scarred during a single year
Guyette et al., 2006	Recording if tree is live	Minimum of three samples during single year
McEwan et al., 2007	Recording after initial scar	Time periods of two fire injuries considered
Maxwell and Hicks, 2010	Recording if tree is live	Two or more trees scarred during single year, One or more trees scarred during a single year
Hessl et al., 2011	Recording if tree is live	$\geq 10\%$ of samples and at least two trees showing fire.
Silver et al., 2013	Recording after initial scar	Minimum two trees scarred and at least 25% of the recorder trees
Stambaugh et al., 2013	Recording if tree is live	Minimum of three samples during single year
Flatley et al., 2013	Recording after initial scar	Point fire interval, composite fire interval, 25% filter composite fire interval, area-wide fire interval, regional fire interval
White and Harley, 2014	Recording after initial scar	At least one sample, $\geq 25\%$, and $\geq 50\%$
Brose et al., 2015	Recording if tree is live	Minimum of three samples during single year
Marschall et al., 2016	Recording if tree is live	Minimum of three samples during single year
Saladyga, 2017	Recording if tree is live	Minimum of three samples during single year

Systematic gridded design is a field sampling approach for estimating fire return intervals, which allows for assessment of fire regimes over space. Systematic grid cell sampling can provide information on historical fire regimes, which is important for understanding the role of fire in forested ecosystems (Everett, 2008). Grid cell sampling can allow researchers to see how fire return intervals change spatially—knowledge that is useful for management practices,

specifically for prescribed burns, which are useful for fuel reductions, species composition, forest regeneration, and other ecosystem processes (Brose et al., 2002). Grid-based field methodologies have not been recorded in any comprehensive, peer-reviewed mean fire return interval (MFI) literature in eastern United States. To date, the method has been used primarily in the western United States (Van Horne and Fule, 2006; Everett, 2008).

Specifically, my research objectives are to: 1) characterize fire-scarred species composition, 2) develop a fire-scar chronology for a globally rare pitch pine-scrub oak community in northeastern Pennsylvania, 3) apply a grid-based method for sampling fire-scarred trees and modeling fire return intervals, 4) compare simulated target sampling with census sampling, and 5) use fire-scar data from nearby sites to compare mean fire return interval filtering techniques.

Study Area

The study area, Waste House Run East (WHE), is situated on Locust Mountain, which is located in the ridge and valley section of northeastern Pennsylvania. (40-50'40" N, 076-10'16" W) (Figure 1B). The site is a ridgetop acidic barrens complex with an elevation range from 365 m to 650 m. This globally rare plant community complex is comprised of pitch pine-scrub oak (*Quercus ilicifolia* Wangenh.) forest, mixed hardwood woodland, and scrub oak scrubland. The vegetation is adapted to dry acidic shallow soils, fire, and high winds (Fike, 1999). Disturbances, such as insect outbreaks and fire, have helped shape and maintain communities in the barrens; in particular, frequent fires place constraints on tree growth. The ridgetops of these acidic barrens are comprised of dwarf-stature pitch pine, scrub oak, chestnut oak (*Quercus montana* Willd.), scarlet oak (*Q. coccinea* Munchh.), white oak (*Q. alba* L.), black gum (*Nyssa sylvatica*

Marshall.), gray birch (*Betula populifolia* Rhodora.) and sassafras (*Sassafras albidum* Nutt.). Dwarfed trees are usually accompanied by a thick undergrowth of blueberry species (*Vaccinium* spp.), huckleberry species (*Gaylussacia* spp.), mountain laurel (*Kalmia latifolia* L.) and black chokeberry (*Aronia melanocarpa* Michx.) (Fike, 1999). The regional climate has an average annual temperature of 13.7 °C and monthly temperatures ranging from −3.7 °C in January to 23.2 °C in July (Pennsylvania Climate Division 2; National Oceanic and Atmospheric Administration [NOAA], 2017).

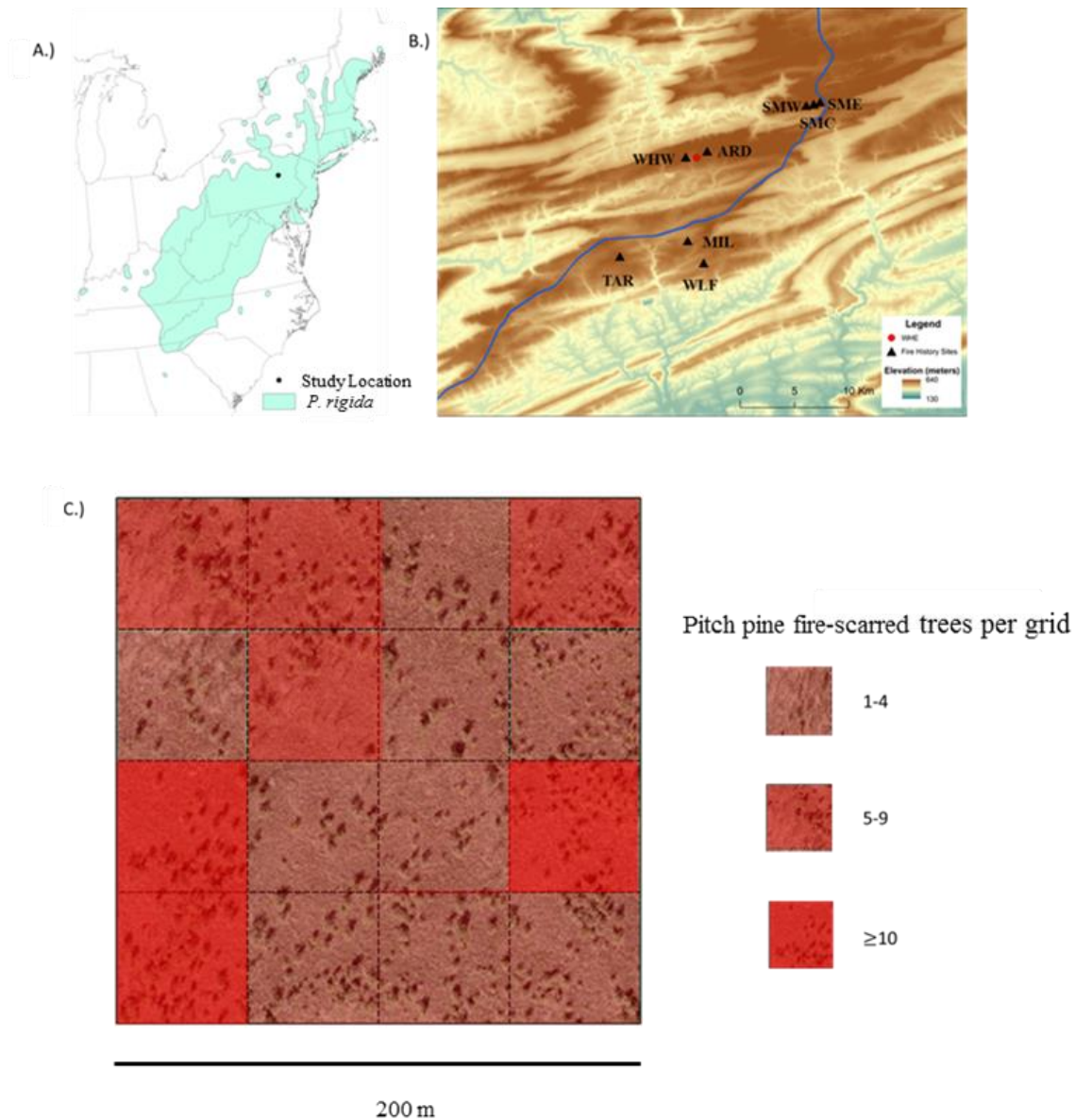


Figure 2 A-C: A) Pitch pine species range. The black dot represents the study site while the green shows the range of *Pinus rigida*. B) Fire history sites (black triangles) in Schuylkill County, Pennsylvania, USA that are compared to Waste House East (WHE, red dot). Fire history sites (black triangles) in Schuylkill County, Pennsylvania, USA: Abandoned Road (ARD), Mill Creek (MIL), Spring Mountain East (SME), Spring Mountain Central (SMC), Spring Mountain West (SMW), Tar Run (TAR), Waste House Run East (WHE), Waste House Run West (WHW), and Wolf Creek (WLF). C) Four hectare, 50-meter resolution grid sampling area located on Locust Mountain. The choropleth map represents the number of fire-scarred pitch pine in each grid cell.

Data and Methods

Field Methods

Fieldwork was conducted in May 2017. We used a four hectare, 50-meter resolution grid sampling area (Figure 2C) to reconstruct fire history at the WHE site. Each grid cell was surveyed for living and dead fire-scarred trees. The location of each tree was recorded using a Garmin GPS and the following attributes were noted: species, live/dead status, diameter at breast height (DBH), basal scar orientation, and elevation. We focused our fire reconstruction analysis on pitch pine since it was the most abundant species throughout the grid cells and because many of the chestnut oak samples had center rot. We cut samples from 66 living pitch pine trees with visible basal fire scars with a chainsaw and assigned each sample an identification number.

Laboratory Methods

Standard dendrochronological methods were used to process the pitch pine samples (Orvis and Grissino-Mayer, 2002; Speer, 2010). Samples were air-dried and then smoothed with a belt sander and electrical orbital sander with progressively finer sandpaper (40 to 800 grit) to create a smooth surface capable of revealing annual rings and fire scars under magnification. The cross sections were visually crossdated against a nearby reference chronology (i.e., Spring Mountain). Marker years, defined as rings with unique widths, were skeleton plotted and recorded on graph paper for each cross section (Schweingruber et al., 1990). Under magnification, tree rings were dated to the appropriate year and fire events were identified by callus tissue along with other cambial injuries (Figure 3). The season of occurrence (dormant, earlywood, or latewood) was assigned for each fire scar based on its position in relation to

annual growth rings. Fire scar data was saved in FHX2 format and analyzed in Fire History Analysis and Exploration System (FHAES; Brewer et al., 2015; Grissino-Mayer, 2001).

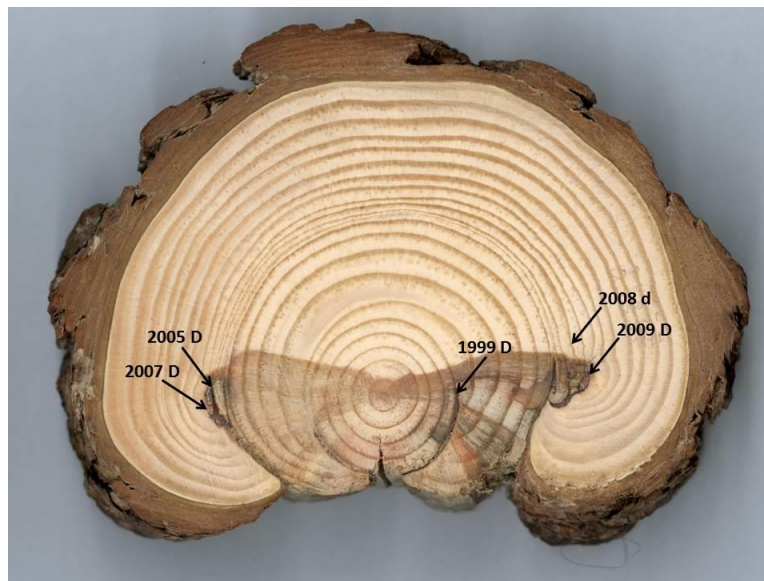


Figure 3: Example of fire-scarred section collected on Locust Mountain, Schuylkill County, Pennsylvania in May 2017. The sample has a total of 5 scars since 2009.

Multiple fire history charts and summary statistics were produced including composite fire intervals with recorder status “live” and “after the initial scar” (Figure 3). We measured the Importance Value to characterize the species composition of fire-scarred trees at the WHE study site. Importance is a standard tool used by foresters to inventory an ecosystem (Bello et al., 2007). The importance value was calculated by dividing relative frequency by basal area. We compared Filter 1 (Table 2) was a three sample minimum (Guyette et al., 2006; Stambaugh et al., 2013; Marschall et al., 2016; Saladyga, 2017), Filter 2 was a minimum of two trees scarred per fire, while being considered in recording status after the initial scar (Grissino-Mayer, 1995; Swetnam and Baisan, 2003; Schuler and McClain, 2003), and Filter 3 was limited to $\geq 10\%$ of samples scarred while being considered recording status after the initial scar (Grissino-Mayer, 1995; Swetnam and Baisan, 2003; Van Horne and Fule, 2006).

Grid Cell Simulation Model Development

For the purpose of assessing a grid-based method for field-based sampling and modeling fire return intervals at our study site, we generated a model to simulate three common filtering approaches (Table 2) to determine fire events and intervals. The fire scar filters included: 1) a minimum of three samples; 2) a minimum of two trees scarred; and 3) $\geq 10\%$ of samples scarred. With these filters, the MFI can be estimated within a 95 % confidence interval. The confidence interval will provide a range that will serve as an informative tool to land managers to employ controlled burns.

First, we calculated fire return intervals using FHAES. All functions in FHAES are open source (Brewer et al., 2015), so we were able to determine, from examining the code, how calculations of mean fire return intervals are performed in FHAES. We then recreated the FHAES analysis method inside R program version 3.5.1 to incorporate both common dendrochronology filtering methods and recording status mentioned earlier (Grissino-Mayer, 1995; Swetnam and Baisan, 2003; Schuler and Mcclain, 2003; Van Horne and Fule, 2006; Stambaugh et al., 2013; Marschall et al., 2016; Saladyga, 2017). A bootstrap sampler allowed us to randomly select between 4 and 16 grids (with and without replacement) for analysis. The basis of bootstrapping is that the same probability of individual samples selected exists for each simulation run because the covariance between each sample is zero. Sampling without replacement enabled us to assess how quickly the mean fire return interval converged to the mean of the 16 grids. Sampling with replacement, on the other hand, gives a much more accurate picture of the actual population distribution, which serves as an approximation of what we would see if we were to replicate our model in the same forest. Simulating fire intervals offers insight into fire return intervals change over space. This information is important as it can inform land

managers when to initiate controlled burns. Each filtering method (described above) was simulated for 10,000 iterations in order to calculate the MFI for each number of grids, as well as bootstrapped upper and lower 95% confidence bounds.

We then assessed the statistical differences of mean fire return intervals among the grid cells using bootstrapped samples of each fire-scarred pitch pine. We used Tukey's Honest Significant Difference (HSD) Test to assess differences in MFI as the total number of grid cells increased. More specifically, Tukey's HSD allowed us to determine where the differences of mean fire return intervals among the grid cells lay statistically within a 95% confidence interval.

Comparing Target vs Census Sampling

We compared target sampling MFI's to the models' MFI (with and without replacement). Target sampling is the most common sampling approach used by dendroecologists. The idea of target sampling is to find the oldest trees with multiple fire-scars (Swetnam and Baisan, 2003; Grissino-Mayer et al., 2004). We selected 20 trees with the largest DBH and calculated the MFI with filter 1, 2, and 3 (Table 2) in preparation for the comparison.

Subsequently, we calculated the simulation model's overall mean of each filter's MFI. We did this by adding the mean from each grid from each filtered model. This calculation was performed for both with and without replacement. The standard deviation and mean of each data set were compared to the target sample's MFI. Comparing the sampling techniques offers insights into MFI's variability. We hypothesized that the simulated target sampling approach would have an MFI within the range of simulated modeled MFI with and without replacement.

Analysis of Fire-scar Data from Multiple Ridgetop Barrens

We compared common filtering techniques (Table 2) with WHE and existing fire history records at eight nearby sites also located in Schuylkill County, Pennsylvania. Each nearby site used target sampling for sample collection and was processed for a separate research objective (Saladyga and Standlee, 2018). The comparison allows for us to have a better understanding of MFI common filtering methods and calculations (Grissino-Mayer, 1995; Swetnam and Baisan, 2003; Schuler and McClain, 2003; Van Horne and Fule, 2006; Stambaugh et al., 2013; Marschall et al., 2016; Saladyga, 2017) at a landscape scale.

The filters were selected with respect to common filtering methods used in traditional fire reconstructions. The selected filters incorporated both recording statuses to better demonstrate how mean fire return intervals can be interpreted and influenced based on the definition of recording status. We then analyzed the fire intervals using each filter for all sites. We did this by adding all intervals from each site and doing a comparison of Filter 1, Filter 2, and Filter 3. We reported the total number of intervals, mean, median and range.

Table 2: Filters used in fire-scar analysis

Filter ID	Filter Method	Recording Status
Filter 1	3-sample minimum	Recording if tree is live
Filter 2	2-scar minimum	Recording after initial scar
Filter 3	$\geq 10\%$ of samples scarred	Recording after initial scar

Results

Importance Value of Fire-scarred Species Distribution

The pitch pine-scrub oak ecosystem is dominated by fire-scarred trees, specifically, pitch pine and chestnut oak, followed by sassafras (Figure 4). The largest importance value for *P.*

rigida was due to the high frequency. Chestnut oak had the second highest importance value indicating it is well-represented in the stand compared to red maple, elm, and black gum.

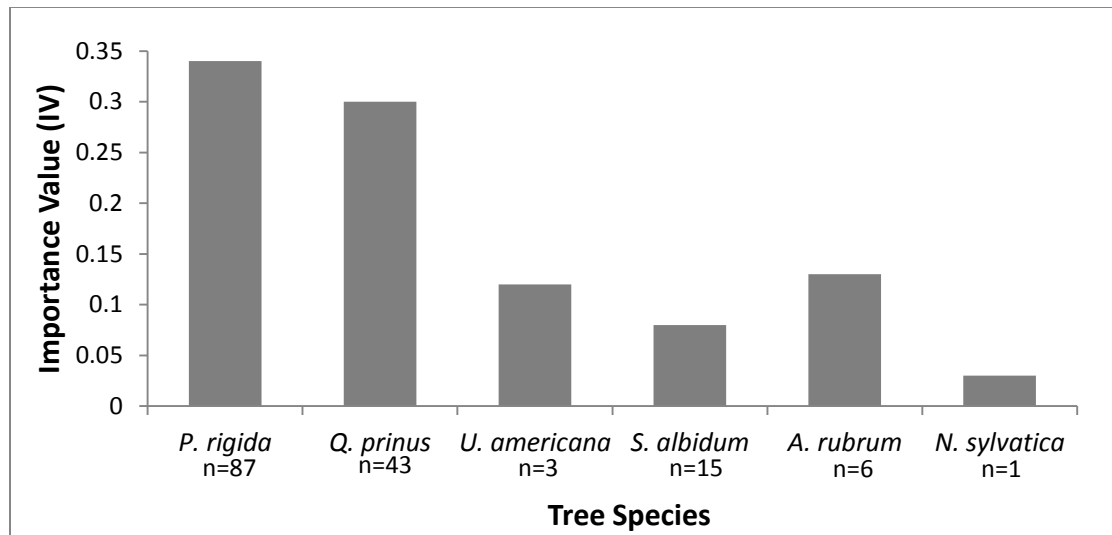


Figure 4: Importance value of fire-scarred trees within the gridded sample area showing the relative frequency, density, and basal area of species per throughout the sampled area.

Waste House Run East (WHE) Fire History

The pitch pine fire history (Figure 5A) extends 80 years (1939-2016), with the fire interval analysis restricted to common filtering methods (Table 2). The pitch pine samples recorded 88 total fire scars from 1939-2017 (Table 3) with 22 intervals which is double Filter 2 and three times the number of filter 3.. The composite fire intervals for all filters had a mean fire return interval of 2.1-3.1 years. The lower exceedance interval for Filter 1 was 2.1 years while the upper exceedance interval was 3.7 years meaning that 75% of the 22 fire intervals are between 2.1 and 3.7 years. We reported 100% of all scars occurred between annual rings during the dormant season, which is the early spring and late fall of scarred years. Notable years that had the highest percentage responding to fires as defined as recording if the tree is live, were 1992, 1993, and 1994, being the highest. In contrast, percentage of recorder samples (5B), defined as

recording after the initial scar, had a significantly higher percentages than total number of samples scarred, specifically in 1972, 1974, 1978, and 1982. Further 1993 had the highest percentage of recorder trees scarred with over 60 percent of recorder samples.

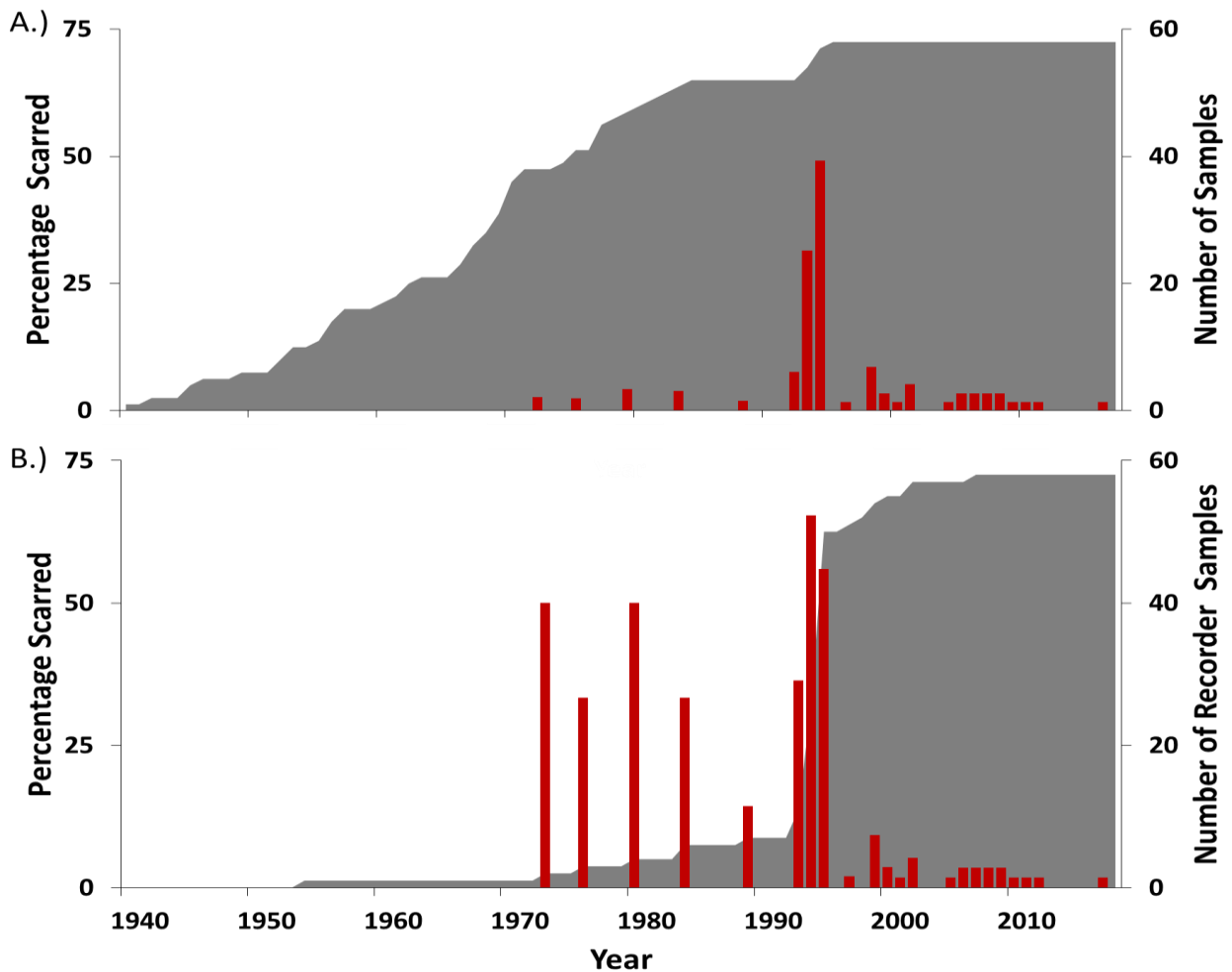


Figure 5 : 5A, time series of the percentage of trees scarred and sample depth for pitch pine (*P. rigida*) collected on Locust Mountain, Schuylkill County, Pennsylvania: (n = 58), Sample depth is represented by the grey area and the percentage of trees scarred is indicated by the red vertical bars. 5B, time series of percentage of recorder trees scarred represented by red bars and sample depth for pitch pine represented by grey area (n=58)

Table 3: Fire interval statistics for Waste House East study site, 1939-2016

Fire Interval Statistics	Filter 1	Filter 2	Filter 3
Number of trees	58	58	58
Number of scars/injuries	81/0	81/0	81/0
Intervals	21	11	7
MFI (years)	2.1	2.64	3.1
Standard Deviation	2.1	2.5	1.5
WMFI	2	2.1	3
LEI	2.1	.5	1.5
UEI	3.8	5.5	4.8

Fire Interval Simulation Model

With Replacement

Bootstrapping with replacement for Filter 1 and Filter 3 show that the MFI steadily decreases over space as more samples are considered (Figure 6). Most of the resampled MFIs were consistent with the actual MFI. Filter 3's resampled MFI estimate not only steadily decreased, but dropped below the actual MFI. The overall 95% confidence interval ranges were relatively consistent (2-7 years) with Filter 1, and Filter 3. For Filter 2, the actual MFI was almost one year less than the resampled estimate. Filter 2 shows fluctuation across space and has an overall 95% confidence interval range from 2 - 8.5 years.

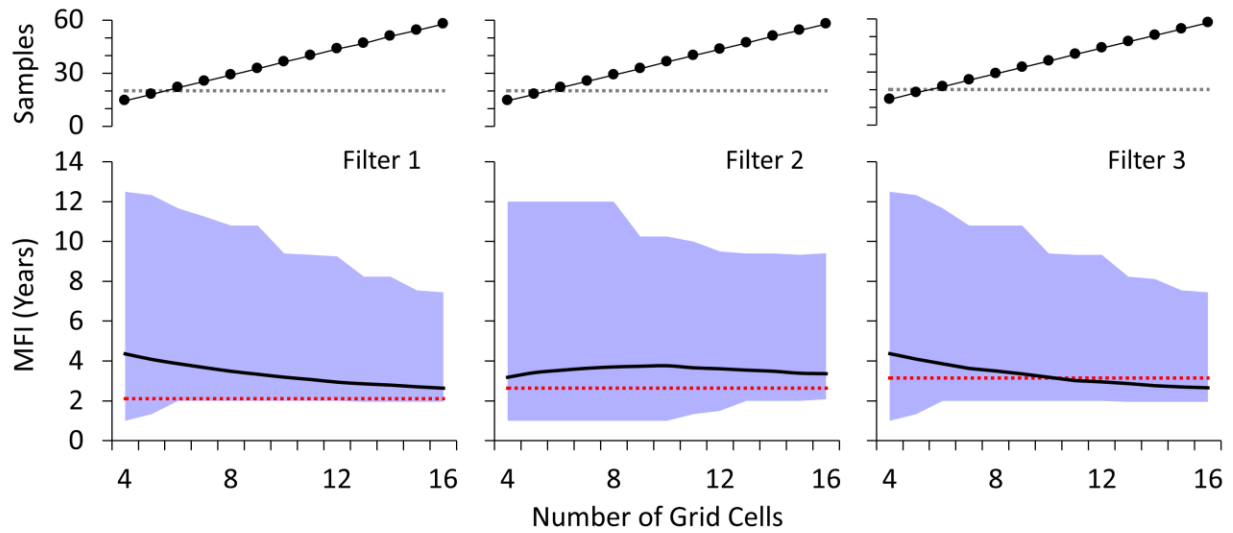


Figure 6: Bootstrap MFI simulation model with replacement. Each value on the solid black line shows the resampled MFI with R. The dotted red line indicates the MFI produced by FHAES. The dotted black line shows a 20 sample threshold, while the black dots indicate number of sample across the grid.

Without replacement

For all filters, (Figure 7) resampled MFI estimates decreased to the actual MFI when all 16 grid cells were included in the model. Filter 2 fluctuated more across space than all filtering methods. The 95% confidence interval showed a little more variation than bootstrapping with replacement. The overall 95% confidence interval for all filters was 1.7-12.

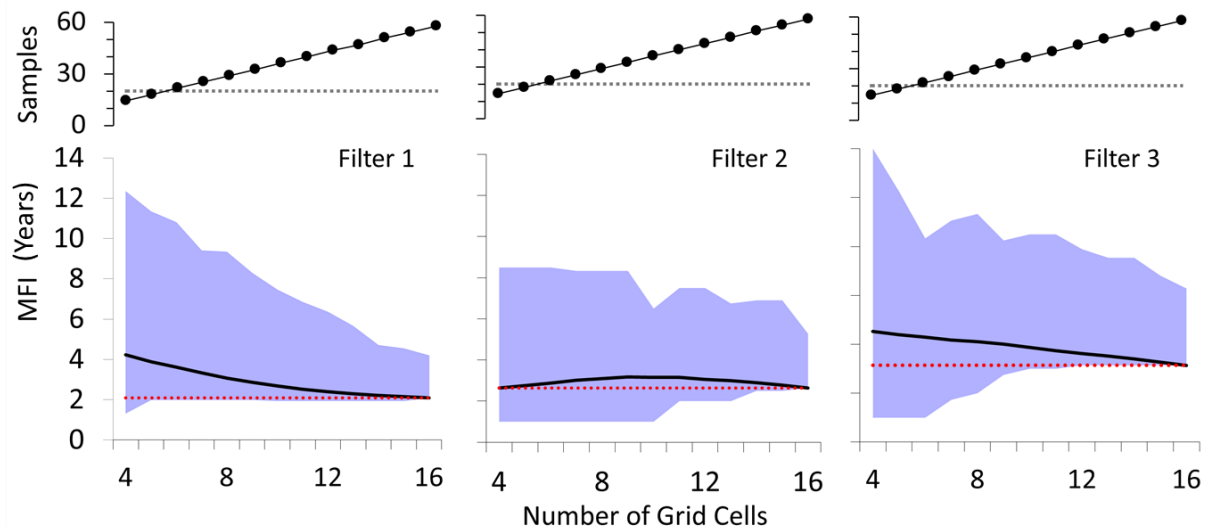


Figure 7: Bootstrap MFI simulation model without replacement. Each value on the solid black line shows the resampled MFI with R. The dotted red line indicates the MFI produced by FHAES. The dotted black line shows a 20 sample threshold, while the black dots indicate number of sample across the grid.

Simulated Target Sampling vs Census Sampling MFI

Target sampling with Filter 1 had an MFI of 6.1 which is nearly double the “with replacement” MFI (8A). Filter 3 had less variation with a MFI of 5. Both filters’ MFI were unexpectedly not within the range of the model’s MFI. Simulating with replacement had a mean from all filters ranging from 2.92 to 3.84. The simulation model mean of all filters without replacement had a range from 2.56-3.88 (8B). Sample sizes varied with 20 trees for the target sample and 39 samples for with replacement and without. Filter 2 did not have enough fire intervals to calculate a mean fire return interval.

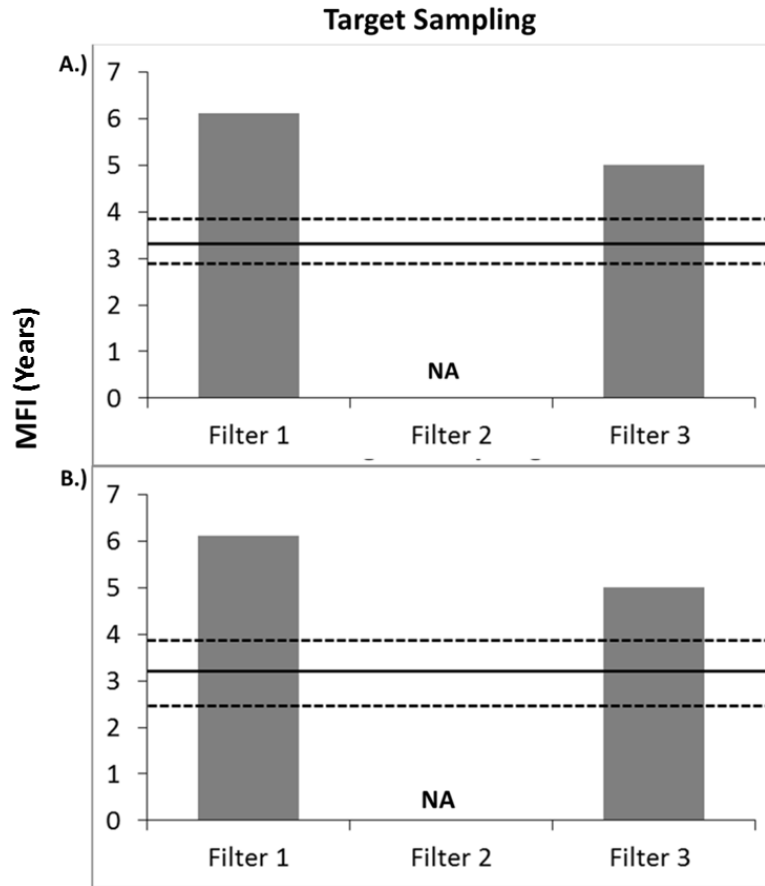


Figure 8 A and B: Simulated target sampling mean of filters 1,2,3 compared to overall mean of modeling with replacement (7A) and without replacement (7B). Bars indicate the MFI of the target sampling approach. The black line shows the mean sample of each simulated filter grid (n=39). The dotted lines show the standard deviation of each model's overall mean. NA indicates there were not enough intervals to calculate a MFI.

Comparing Mean Fire Return Interval of Nearby Sites

For Filter 1 (9A), the MFI ranged from 2.1 years to 11.5 years. For Filter 2, the MFI shows slightly more variance ranging from 2.65 years to 15.2 years. Over half the sites (MIL, SMC, SMW, WHW, and WLF) did not register a MFI due to lack of samples being able to calculate fire return intervals, so they were identified as undetermined. Filter 3 (8C) was considered in recording status after the initial scar. For Filter 3, the MFI ranges from 3.14 years to 15.71 years. MIL was the only site that did not register a MFI therefore, it was referenced as undetermined.

Filter 1 appears to be the most liberal filter as it had the most combined intervals of all sites.

Filter 2 was a more conservative filter thus having double the MFI as the Filter 1. Filter 2 had considerable fewer intervals than all sites and had a longer range. Filter 3 served as an intermediate filtering approach as the range was similar to Filter 1 and MFI was 7.5 for all site intervals.

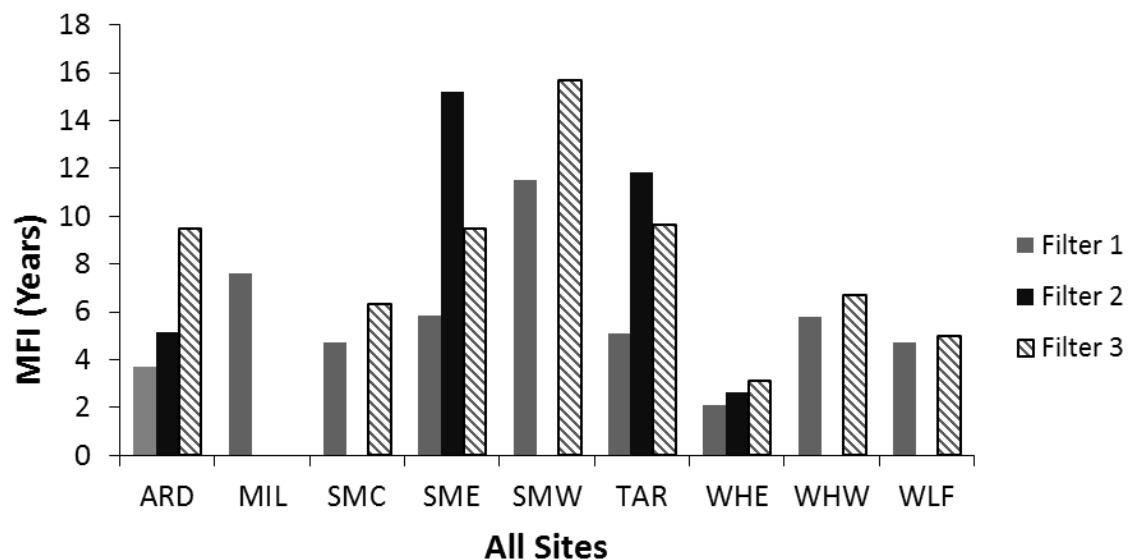


Figure 9: MFI's for nearby sites located in Schuylkill County, Pennsylvania. Please note, filters not shown at sites indicate insufficient number of intervals to calculate fire interval statistics.

Table 4: Descriptive statistics for total number of intervals for all sites

Filter	Number of Intervals	Mean ($\geq .1$)	Median	Range
Filter 1	144	5.1	3	1-45
Filter 2	35	10.3	4	1-71
Filter 3	80	7.5	5	1-45

Discussion

Overall, the findings of this research are: 1) Fire occurrence at WHE peaked in the 1990s, but is difficult to assess prior to the 1950s due to decreasing sample depth 2) MFI's decrease over space as more samples are considered, 3) target sampling leads to higher MFI variability than census sampling, and 4) mean fire intervals are influenced by the definition of "recorder" years and filtering techniques.

Waste House Run East (WHE) Fire History

Contrary to our findings, some researchers (Marschall et al., 2016) suggest fire has been virtually nonexistent in the region since 1914 with a few exceptions. Thus, our site can be considered a contribution to fire history studies in Pennsylvania's Ridge and Valley Province since the data support fire as an active disturbance process, since the early 1990's. Agreement exists among researchers that most of the fires are anthropogenic in origin (Marschall et al., 2016; Saladyga and Standlee 2018; Stambaugh, 2018). In fact, qualitative data suggests the general perception is that anthropogenic fires occur due to carelessness and negligence (Saladyga and Standlee, 2018).

One of the notable limitations of our results originated from our sampling approach. Most researchers in this ecosystem use a target approach to look for larger, older, and tree with multiple scars. Target sampling can lead to small sample sizes in some cases, but is advantageous for historical fire reconstructions. However, although an exhaustive approach, the systematic gridded design allows for fire-scarred trees to be documented and there is a less of likelihood to have small sample sizes. Our grid cell size, at 50 x50 m, was ideal for the development of a simulation model because each sample had an equal chance of being randomly selected, which is important for the validity of statistical estimates (Reed and Johnson, 2004).

With that said, researchers may find they need to increase the size of the grid cells, possibly to represent 16 hectares, to find older and multi-scarred trees that would be more meaningful for a fire history reconstruction. Further, the issue of “recorder” status arises in terms of how scientists present their data. While the recorder status of a tree has been acknowledged (Lafon et al., 2017), there has been no attempt to show the differences of recorder status. We offer a comparison of each recording status and the results indicate less sample depth for recording after initial scar with a higher percentage of trees scarred.

Randomly Simulating MFI's

The development of the bootstrapped simulation model was important for two primary reasons. First, it provided a baseline for assessing how MFI is influenced by number of samples, filtering techniques, and number of grid cells. Second, the use of two bootstrapped approaches (with and without replacement) offered a glimpse into an alternative route to observe MFI over space from various scales. Although our study area was quite small (4 hectares), we analyzed more than 50 samples—enough to account for potential misinterpreting of “outlier” fires.

Both bootstrapped approaches revealed that sample size and area sampled are related. Similar studies have shown that MFIs decrease over space with the addition of more samples (Van Horne and Fule, 2006). Specifically, Van Horne and Fule (2006) found MFI decreased from 3.49 to 2.79 years over 4 and 8 hectares, respectively. Our findings show as more samples were added to the simulation model, the MFI decreased, with the exception of filter 2. For instance, the maximum MFI range of bootstrapped without replacement resampled estimate began at 2.64 and gradually rose to 3.17 as grid cells and samples increased. One reason for the noticeable fluctuation of fire return intervals is because the filtering option is dependent on having two scars on one tree. For this filtering method, our sample size decreased, which

exemplifies the idea that small sample sizes can influence study areas MFI (Lafon et al., 2017).

Bootstrapping our model with and without replacement allowed assessing MFI in two ways. Our resampled estimates without replacement show the rate at which MFI decreases over space and as sample size increases. The bootstrapped model with replacement provides insight into potential results if the study area were to be tripled or quadrupled. Our results show that our resampled estimate with noticeable increase in MFI for that reason. The bootstrapped with replacement attempts to answer what we could find with a study site encompassing multiple landscapes while addressing limitations of area size (Guyette et al., 2006).

Whereas new fire history software packages are programmed with demography charts, creative plotting, mapping and seasonality statistics (Malevich et al., 2018), there has been little research developing models to identify the shortcomings associated with sampling. Our simulation models identify changes in sample size MFI over space. One of the limitations with this approach is a primary focus on MFI. While MFI is an important metric that is always reported, scientists tend to use supporting metrics to better represent landscape fire activity (Brewer et al., 2015; Grissino-Mayer, 2001). An additional limitation is that the simulation was only site-level. Ideally, a grid cell-based sampling approach over multiple sites would be beneficial to give scientists and land managers a better understanding of fire activity from a landscape perspective.

Analyzing Sampling Techniques

Target sampling, as compared to census sampling, provides researchers the longest fire return intervals (Swetnam and Baisan, 2003). In our case, target sampling enabled us to capture the largest trees in our study area, but results revealed an MFI that was nearly twice as long as census sampling with and without replacement. The question of accuracy arises when comparing

target sampling to census sampling. Simulated census samples for filters 1, 2, and 3 had MFIs closer to FHAES reported MFI. The number of samples seems to play a role in this variability. For instance, simulated target samples of 20 trees were used for Filter 1 and 3 resulting in a standard deviation of 6.1 and 6.7. The simulated target samples relatively high standard deviation showing most fires have longer intervals than the mean. Due to the smaller sample size, the MFI and associated supporting statistics may not be a correct depiction of fire activity at WHE. The simulated census filters had a mean of 58 samples for each filter showing a standard variation under 0.5 showing less variability amongst fire frequency, thus suggesting most samples MFI are clustered towards the mean. If more samples were added to the target sampling, the MFI would slowly decrease, however, adding more samples would remove one of the main goals of target sampling - finding old, large, multi-scarred trees.

Target sampling would not be an appropriate sampling method at this particular landscape due to the high MFI and variance. More specifically, target sampling and the application of Filter 2 would not be an appropriate sampling technique as the filter registered a NA due to insufficient fire interval calculations. Another concern of target sampling at this specific site would be the age of the WHE. WHE fire occurrence peaked in the 1990s but uncertainty arises when estimating fire before the 1950s because of diminishing sample size. Ideally, target sampling would not be applied to a young site as our findings indicate.

Comparison of Common Fire Scar Filtering Techniques

We were interested in assessing to what extent filtering techniques have an influence on MFIs at a landscape level. Most fire history reconstructions conducted in Eastern Temperate Forests have used target sampling as the primary sampling approach, defining the recorder status as recording after the initial scar (Schuler and McClain, 2003; Schuler and McClain, 2003;

Flatley et al., 2013; White and Harley, 2014). There has been research to suggest the MFI can be reduced significantly by a target sampling approach (Baker and Ehle, 2001), however, our data demonstrate that definition of “recorder” status could play a larger role.

To better understand fire activity within the Ridge and Valley Province, we looked at nearby sites. The sites that were considered “NA” had sample sizes too small to calculate the MFI. If more samples were included, bias associated with the filtering technique would have been reduced. Considering this filtering technique aligns with a tree only being in recorder status after the initial scar, it seems apparent that target sampling is the best approach in Eastern Temperate Forests considering some scientists have described grid sampling as exhaustive (Lafon et al., 2017). With respect to filtering thresholds, filter 1 results (Guyette et al., 2006; Marshall et al., 2016; Saladyga, 2017; Stambaugh et al., 2018) suggest it is a consistent indicator of fire activity as all nearby sites registered an MFI.

The nearby sites ARD, SME, TAR and WHE had Filter 1, 2 and 3 register a MFI. WHE specifically stands out as it was confined to a grid sampling approach, which allowed for more samples. WHE had the most samples of all nearby sites. The large sample size ensured confidence in the MFI with all filtering methods. Fire was not recorded at WHE until 1971, then was more severe in the early 1990s. The other eight sites, in comparison, had a longer record of fire activity but with fewer samples. Each filtering technique seems highly dependent on sample size and total number of intervals

Conclusions

In this study, we have used a 78-year old fire history to simulate fire return intervals to better understand how MFI's change over space. We have demonstrated that MFI's are dependent based on the definition of recorder status and filtering thresholds. We confirmed that simulations models can help address how MFI's change over space as more samples are considered. The model provided a range of possible MFI's associated by common filtering techniques, which leads to a realistic and new approach to describing fire activity over space.

This is one of the first studies to use a grid cell approach in the temperate forests of Eastern United States. While it is not expected for scientists to implement this approach as a primary sampling strategy, the census is thorough and can answer questions related to MFI. Although this type of approach is not constrained to a specific location, researchers in the Ridge and Valley Province might find this as a promising approach to better inform land managers on site-level MFIs. Additionally, it can be used as a benchmark to better understand the limitations associated with fire history reconstructions.

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