Using Tree-Rings to Reconstruct Fire History Information from Forested Areas

Julián Cerano-Paredes[1], **Jose M. Iniguez**[2], **José Villanueva-Díaz**[1], **Rosalinda Cervantes-Martínez**[1], **Víctor H. Cambrón-Sandoval**[3], **Josué R. Estrada-Arellano**[4], **Gerardo Esquivel-Arriaga**[1], **Osvaldo Franco-Ramos**[5], **Lorenzo Vázquez-Selem**[5], **Gabriel F. Cardoza-Martínez**[4]

[1] CENID-RASPA, INIFAP [2] Rocky Mountain Research Station, USDA Forest Service [3] Facultad de Ciencias Naturales, Universidad Autónoma de Querétaro [4] Facultad de Ciencias Biológicas, Universidad Juárez del Estado de Durango [5] Instituto de Geografía, Universidad Nacional Autónoma de México

Corresponding Author

Julián Cerano-Paredes
cerano.julian@gmail.com

Citation

Cerano-Paredes, J., Iniguez, J.M., Villanueva-Díaz, J., Cervantes-Martínez, R., Cambrón-Sandoval, V.H., Estrada-Arellano, J.R., Esquivel-Arriaga, G., Franco-Ramos, O., Vázquez-Selem, L., Cardoza-Martínez, G.F. Using Tree-Rings to Reconstruct Fire History Information from Forested Areas. *J. Vis. Exp.* (164), e61698, doi:10.3791/61698 (2020).

Date Published

October 22, 2020

DOI

10.3791/61698

URL

jove.com/video/61698

Abstract

Annual tree-ring patterns are a source of ecological and environmental information including the history of fires in forested areas. Tree-ring based fire histories include three fundamental phases: field collection, laboratory methods (preparation and dating), and data analysis. Here we provide step-by-step instructions and issues to consider, including the process for selecting the study area, sampling sites, plus how and which fire-scarred trees to sample. In addition, we describe fire-scar sample preparation and dating which are done in the laboratory. Finally, we describe basic analysis and relevant results, including examples from studies that have reconstructed fire history patterns. These studies allow us to understand the historical fire frequency, changes in those frequencies related to anthropogenic factors, and analyzes of how climate influences fire occurrence over time. The description of these methods and techniques should provide a greater understanding of fire history studies that will benefit researchers, educators, technicians, and students interested in this field. These detailed methods will allow new researchers to this field, a resource to start their own work and achieve greater success. This resource will provide a greater integration of tree-ring aspects within other studies and lead to a better understanding of natural processes with forested ecosystems.

Introduction

Forest fires, ignited by natural or anthropogenic causes, are considered one of the most common ecological disturbance factors that influence terrestrial ecosystems[1]. For example, fire and more specifically fire regimes, influence plant species composition and structure[2]. Fire is also a fundamental process linking biogeochemical cycles and climatic variability[3,4]. In some areas, fire contributes to degradation and deforestation, while in other areas, fire is fundamental for regeneration and sustaining open forest structures[5,6]. As a result, understanding the ecological role of forest fires is essential to management and conservation programs.

Fire regimes are defined as the pattern of fire events over time characterized by the frequency and its variability in type, extent, intensity, seasonality and severity[7,8]. Forest fire regimes can be studied through direct observation, reports, satellite images, oral history, age structure and species composition, and through the use of dendrochronological methods[9]. Dendrochronology uses tree-rings, dated with annual precision, to study climatic and ecological events[10]. One of the branches of Dendrochronology is fire history reconstruction or Dendropyrochronology which uses tree-rings to determine the spatial and temporal patterns of past and contemporary fires thereby reconstructing the fire regime within a study area[11,12]. Dendrochronological methods, provide precision and resolution advantages compared to other dating methods, because they allow dating of ecological events, with annual to intra-annual (i.e., seasonal) precision, at long temporal scales, sometimes up to several thousand years[13,14].

Fire history reconstructions are also critical in understanding how general climate circulation patterns at regional scales have influenced fire spread. These analyses of the climate-fire relationship are novel because they provide insight into how climate influences fire frequencies over long periods of time, which is not possible with the modern instrumental climate records[4]. In order to facilitate reconstructing fire histories, we provide a field and laboratory protocol that describes dendrochronological methods and techniques that will allow researchers, teachers, technicians, and students interested in this field of study to initiate their own projects and studies.

In this protocol, we provide the tools to develop a greater understanding and answers to different ecological questions in the field of forest ecology such as: 1) What is the fire regime? 2) Have fire regimes changed in recent decades or have fire frequencies continued without significant change? or 3) Have there been changes attributed to anthropogenic influence? 4) How are fire frequency patterns related to climate variability?

Protocol

1. Sampling strategy

1. Determining the study area
    1. Generally, forest areas are extensive (hundreds or thousands of hectares), therefore, select a study area that will meet the objectives, which in this case, is to determine the fire history and its variability over time (**Figure 1**). Limit the study area only to the areas that contain fire-scarred trees which will be the sampling unit. Reconnaissance of the study area can often be facilitated using drones and video technologies, which provide views of the larger landscape, saving both time and money.
    2. Within a study area, identify potential sampling sites that are ideally similar in size, in order to facilitate comparisons. Sampling sites can vary in size ranging from large areas (>50 ha), to smaller sites (5–50 ha) or plots (<5 ha) depending on the study area, availability of fire-scarred trees, and study objectives. The number of sites will of course depend on the variability, but in general, more than one

site is suggested. The topography and forest type within each site should be representative of a larger ecosystem to allow extrapolation of results[9].

Figure 1: *Pinus hartwegii* forests. (**A**) Topographic variability of the site in terms of slope, forest cover, orographic barriers, fuel, among others. (**B**) Broader landscape perspective on the terrain and forest conditions, variables that influence fire behavior, and the selection of study sites. Please click here to view a larger version of this figure.

2. Sampling strategy (site selection within a study area)
    1. Within the study area, select a method sampling site, either random, systematic, or selective sampling[15]. This will depend on the study objectives, availability of personnel and financial resources.
    2. Typically to reconstruct fire history, use selective sampling. That is, within the study area, select sites that are known to contain fire-scarred trees.
    3. Using this sampling strategy, select sites where there is evidence that fires have occurred and were recorded as fire scars. Areas that show signs of recent fires, such as scorched or recently fire killed trees, but have no evidence of previous fire scars are not suitable for reconstruction of fire regimes but are often confused with suitable sites (**Figure 2A**).
    NOTE: If the objective was to measure damage done by fire to the regeneration, its effect on growth rates, or to evaluate the recovery of these forests after the fire, these types of areas would undoubtedly be ideal. However, since the objective is to determine the fire history and its variability over time, it requires sites where trees show signs (scars) of previous fire damage but have begun healing (**Figure 2B**).
    4. Scout the study area and locate a site with numerous (>10) long-lived trees and evidence of fire scars (**Figure 2C**). Record the location (GPS coordinates) of all fire-scarred trees using those of points to delineate the limit of the study site.
    5. Map the spatially surface of the site in a Geographic Information System or other mapping software to ensure sites are of similar size.
    6. In particular, within each site, locate the longest-lived fire-scarred trees to allow for reconstructive the fire history of the site as far back in time as possible (one or several centuries in the past), and greater

understanding of fire frequency variability over that time period.

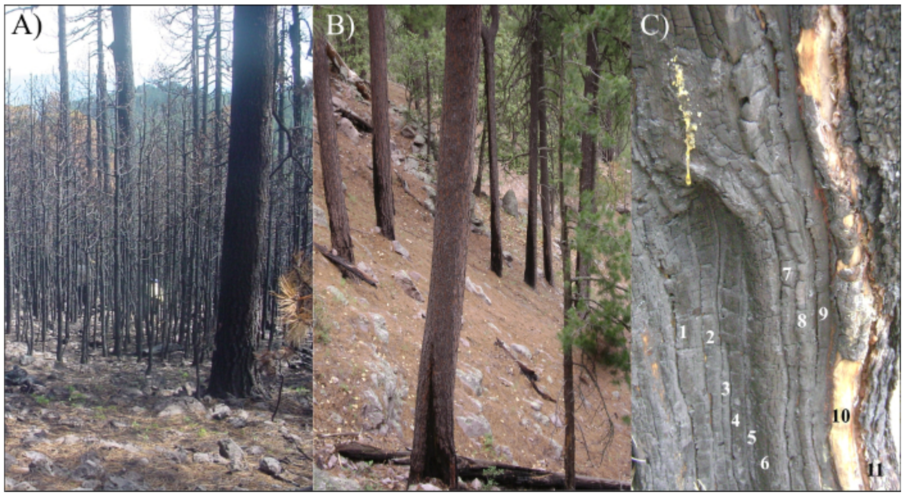

Figure 2: Study sites with and without potential for fire history reconstruction. (**A**) Pine forest that has been affected (scorched) by a recent fire, but trees show no evidence of scarring; such sites are not useful for this type of study because they lack fire-scarred trees. (**B**) Pine forest with evidence of past fires, the trees have visible charred section at the base of the trunk in the shape of a triangle, known as “cat face”, formed as the tree heals after repeated fire events. Such sites are considered to have potential for fire history reconstruction. (**C**) Close-up view of the base of a fire-scarred tree that appears to have recorded numerous fires. Each of the different layers represent a fire scar. In this case, 11 fire scars are visible. Please click here to view a larger version of this figure.

3. General considerations for sampling (selecting tree samples within sites)

   NOTE: The collection of fire-scarred trees is one of the most important steps in this type of study.

   1. Once the study area and site boundaries have been determined, start scouting the selected site from a known point, progress gradually until covering the entire site. The objective of the scouting is to take as complete of an inventory as possible of all fire-scarred trees noting their condition (live tree, snag, or log), the number of fire scars, locations and accessibility (difficulty in extracting the fire-scar sample from the tree). (**Figure 3A,B**).
   2. Based on this information, determine which trees would best contribute to reconstructing the longest and most complete fire history for that site. Collect as least 10 fire-scarred trees from each site, giving the highest priority to trees with the most number and best-preserved fire scars[9] (**Figure 3B,D**). Note that not all fire-scarred trees within a site need to be sampled. In most cases, the number of recorded fires increases with increasing sample size (number of

trees); however, this relationship typically asymptotes past 10–15 trees[16].

3. In order to have the greatest sample depth possible over time, make efforts to collect fire-scarred logs and snags, which are more likely to contain the oldest fire-scars, as well as live trees which will have scars from more recent fires.
4. Avoid collecting loose or highly deteriorated fire-scar samples that, when cut, could be lost and nearly impossible to re-assemble.
5. When the selected trees have the same number of scars and sturdiness, consider sampling the species with the clearest growth rings, which will facilitate the dating of the scars[9].
6. Before collecting any sample, develop a field data sheet that allows gathering the most relevant information from each sample and site including the following information[17].
    1. Use field data sheets that include general information such as: study area name and code (preferably three letters, for example, Cuenca Río Nazas, CRN), site number, sample number, condition of the sample (solid, sectioned, rotten), collection date, and collector.
    2. Determine the microsite description(dry, wet, intermediate), slope and aspect.
    3. Determine tree attributes: Species, diameter, height, condition (live, snag, log, stump).
    4. Determine the geographical location: Coordinates (UTM and in degrees), elevation.
    5. Determine the sample description: Height and side of the sample on the trunk, number of samples taken, number of pieces/sample, number of visible scars/sample, exposure of the scars.
    6. Take field sample photos and/or drawing: This information will document the shape of the fire scar sample and the number of sections in case parts of the sample are dislodged and will need to be re-assembled later. This will assist in its restoration (glued and prepared) in the laboratory. Drawing within the datasheet is often helpful because it allows for annotations.

4. Sampling collection (collecting fire-scarred trees)
    1. After determining which trees will be sampled, but prior to initiating the extraction of the fire scar sample, examine the area surrounding the tree. This examination may reveal branches, loose rocks, or other safety issues that may need to be addresses prior to chainsaw ignition, in order to provide a safe working environment.
    2. To extract fire scars from stumps or logs, take full cross-sections (**Figure 3C**). However, to extract samples from standing snags and live trees, it may be necessary to cut out partial cross-sections (**Figure 3A,D**). When possible, emphasize sampling dead trees to minimize damage to live trees[18]. The main tool for sampling is a chainsaw, with at least a 20-inches bar (for example: 18 to 24-inch bar) to allow the extraction of samples from both small trees and large trees. It is also recommended to have extra equipment parts when samplings so that field sampling is not delayed if mechanical failure occurs.
    3. When choosing the side and height of the fire scar sample to be extracted, consider the side and/or

height with the most number and best preserved visible fire scars. Often, the number of fire scar is greater closer to the ground[12] (**Figure 3A,B**). Fire-scars can often be up to several meters in height and scars that are observed in the upper part may not occur at the base of the trunk (**Figure 3B**). In such cases, it will be necessary to collect multiple samples from a single tree, including samples from both the base and higher up in order to capture as complete a fire history record as possible, from that tree. However, collecting fire-scars at the base is often more difficult and dangerous particularly when cutting cross-section using a heavy chainsaw. In addition, cutting lower on the tree may require kneeling, which may hamper a quick evacuation of the site, if necessary.

4. Prior to starting with cutting the tree, be sure to take all the necessary safety precautions including proper protective equipment such as gloves, helmet, hearing protection, chaps, and proper shoes.
5. Once the fire-scarred tree has been selected along with the height and side where the sample will be extracted from, have an additional person nearby keeping a close watch on the tree, ready to alert the sawyer in case the tree begins to fall. Make sure this additional person and the sawyer have a non-verbal/non-visual way to communicate, such as a tap on the shoulder, in case of such an emergency. In addition, make sure both persons have a pre-determined evacuation strategy and safety zone prior to initiating any cutting.
6. After selecting the tree and the side with the best record, and necessary safety precautions, extract the fire scar sample from a living or dead tree standing.

1. First, cut a partial cross-section from the tree[9,19]. To do this, make a horizontal cut along the cross-section on one side of the fire-scarred trunk (Catface) that extends from the bark to the center of the tree and cuts across all the scars that need to be extracted (**Figure 3D**).
2. After making the first horizontal cut, make a second horizontal parallel cut 2 to 3 cm above or below the first cut (**Figure 3D**). The thinner the cut, the less damage it will do to the tree; however, the thickness will depend on how solid the tree is. If the tree is highly deteriorated, the sample should be thicker (>3 cm) to provide greater stability.
3. After making the two horizontal cuts across the trunk, make two plunge cuts, one from the back and another from the front of the tree toward the center of the tree in order to remove the cross-section from the tree. Make the plunge cut using the tip of the saw blade to enter the tree at the point where the two parallel horizontal cuts end. The plunge cuts should cut any wood that is holding the cross-section to the tree thereby allowing the cross-section to be extracted (**Figure 3E,F**).

   NOTE: Start the plunge cut by placing the chainsaw bar at a 45° angle from the tree trunk (**Figure 3E**), at the end of the two parallel horizontal cuts. Start the cut with the upper most tip of the bar, cutting slowly into the tree using an upward motion to avoid the saw from kicking-back. Once the cut is initiated and the blade has penetrated the tree, the bar can be brought to a horizontal position (**Figure 3F**) to penetrate deeper into the tree. Starting at a 45-degree angle allows a safer start of the cut. If the start of the cut is attempted from a position that is horizontal to the trunk, the chainsaw blade will bounce away from the tree with great force and could cause injury.

4. Extract the sample (**Figure 3G**).
5. Label the sample using the site code, tree number, and sample number (For example, the first sample from site CRN would be labeled CRN-01-a. Tree number (1, 2, 3, …) and sample number, the latter is indicated by letters, a, b, c, etc.) (**Figure 3H**).
6. Take a photo of the sample in the field; this allows capturing the physical state of the sample at the time of extraction, including the shape, number of pieces (if it has split into multiple pieces), condition of the sample, sample label in case it is erased, etc. If the sample splits into several pieces when extracted, reconstruct the sample as best as possible including all the pieces and mark each piece with a marker.
7. To facilitate reconstructing the sample, mark where the pieces join by drawing perpendicular lines through adjacent pieces. Each of these pieces should be individually labeled with the site and tree ID plus a unique number for each individual piece. Therefore, if the pieces from the sample are mixed, this information will complement the photo and facilitate determining how each piece within the sample is arranged[17]. A drawing in the field at the time of extraction can also facilitate this reconstruction. The advantage of a drawing is that it allows for annotation and thus labeling individual pieces within the drawing.
8. Finally, use electrical tape or plastic wrap to secure the fire scar sample and all the individual pieces as close as possible to the original arrangement. This is particularly important for fire-scar sample with a certain degree of deterioration or rot. Firmly wrapping the sample will also protect the sample while it is transported to the laboratory[17] (**Figure 3I**).
9. Although most fire reconstruction studies use partial or complete cross-sections, it is important to mention that another alternative, although not widely used, is to use increment cores. This type of sampling is possible only in living or solid dead trees and taking into account the extraction considerations indicated in **Figure 4**.

Figure 3: Fire scar sampling process. (**A**) A tree with a fire scars is selected and (**B**) a close-up view of the cat face (areas with exposed fire scars at the base of the tree) shows numerous fire-scars and would be an example of a tree that could be selected for sampling. (**C**) Extraction of a fire-scarred sample from a log. In the case of logs, extraction of partial or complete section is easier because cutting can be done vertically. In the case of live trees and snag, the process is more difficult and includes the following steps: (**D**) to extract fire scars from live trees, the first step is to select the face with the clearest records, and make two horizontal cuts at the base of the tree trunk. (**E,F**) To extract the sample, perform an plunge cut, where the tip of the chainsaw is pushed vertically along the back end of the two horizontal cuts, from the bark toward the center of the tree to break off the sample, (**G**) the sample is then extracted and (**H**) labeled (study area, site and tree number, sample number, coordinates), and finally (**I**) the sample is wrapped in plastic to avoid damage while it is transported to the laboratory. Please click here to view a larger version of this figure.

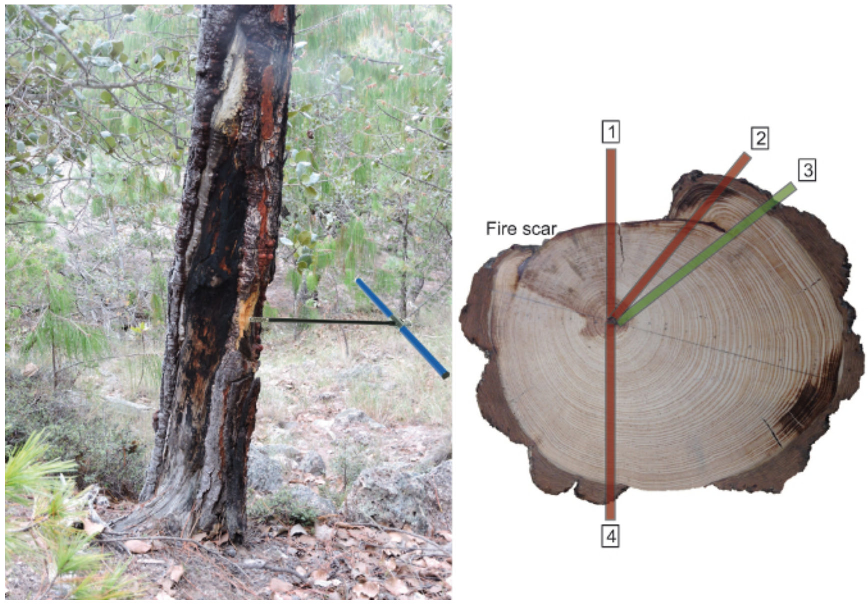

Figure 4: Sampling fire-scarred trees by extracting growth cores (increment cores) with a Pressler drill. To successfully execute this sampling technique, it is important to consider the angle of the extraction in relation to the scar. 1) The sample core that crosses the fire scar will be incomplete because all the rings after the scar will be missing, 2) in the second core the first rings after the scar will may also be missing, but 3) ideally a third core will have all the growth rings and will allow the identification and dating of the fire scar to the exact year and 4) a fourth core far from the fire scar, therefore, with all the growth rings will be obtained, but it will not serve to identify and date of the fire. However, the latter can serve as a reference chronology for the tree. Please click here to view a larger version of this figure.

2. Sample preparation in the laboratory

1. Once the fire-scar samples arrive at the lab, carefully unpack them, separating one-piece cross-sections from those that consist of multiple pieces.
2. Restore samples with multiple pieces. This procedure consists of identifying all the pieces that are part of the sample, and gluing the different pieces together (using white glue for wood). If needed, use the photographs taken in the field to determine the arrangement of each individual piece.
3. In samples that are highly deteriorated due to rot, the application of glue may not be enough to create the required sturdiness that will be needed in the sanding/polishing and dating processes. To create the stability needed, mount these samples. That is, after assembling all the parts of these samples, mount all the individual pieces of the sample onto a wooden surface (for example, plywood), adhere all the sample pieces using a mechanical stapler during the gluing process, if needed[17].
4. After the preparation process is complete, dry the samples outdoors in the shade for 3–5 days. Do not dry

the samples directly in the sun, as the sudden loss of moisture can cause the sample to split and break.

5. Once the samples have dried, cut thicker samples (>3 cm) to a thickness of 2 to 3 cm to facilitate handling under the microscope and measurement system.
6. Sand/polish all the samples using different sandpaper grains, from 40 to 1,200 grit. Start with the smallest number (coarsest) grain to remove the roughest cut parts and continue sanding with progressively higher number grits (finer) until a uniform surface is achieved and the tree-ring cell structures are clearly visible under a microscope. This will allow for identification of fire scar position within the annual ring (**Figure 5**).

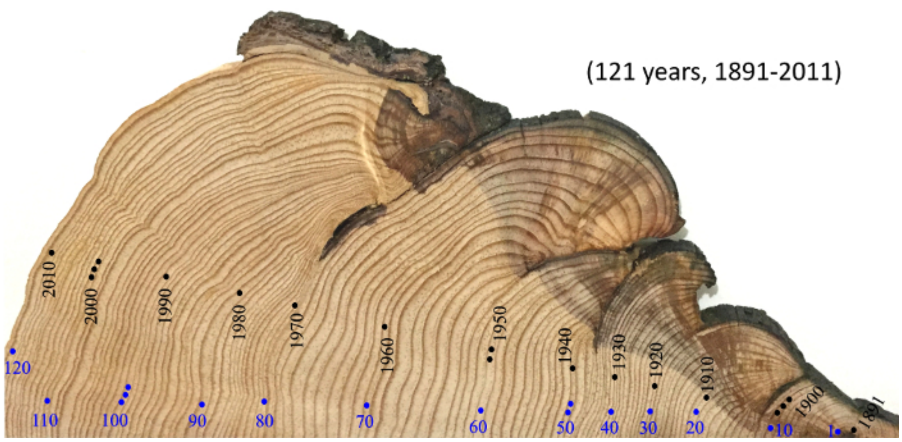

Figure 5: Fire-scarred *Pinus hartwegii* sample after preparation or sanding. The initial tree-ring count marked in by blue dots indicates the age of the sample (121 years). The dated annual rings are shown in black (1891–2011). Direct dating is possible in samples collected from live trees where the year of the outermost ring is known (2011 in this case), the rings are clear, and there are no growth problems (missing and false rings) or such problems can be easily distinguished. Please click here to view a larger version of this figure.

3. Tree-ring dating

1. Count the growth rings on each sample to determine the age, starting from the center toward the bark. Mark every 10-year period with one dot, 50 years with two dots, and three dots to indicate every 100 years[20].
2. Determine the exact year of formation of each of the annual rings by comparing growth patterns[20].
3. In samples from young live trees, the date of the outermost ring (adjacent to the bark) is known because it is the year in which the sample was collected. In this case, date directly on the sample by counting the rings from the outside (bark) toward the center of the sample. For example, if the sample was collected in the last months of 2011, that year's growth will already be almost entirely complete, therefore, the date of this last outer ring will be 2011. Start counting down from this ring and mark the date of the subsequent rings down to the innermost ring

(**Figure 5**). As mentioned before, mark the start of every decade using one dot, two dots for the fiftieth year and three dots for every century.

4. For longest-lived live trees, develop a growth graph or Skeleton Plots for each sample and compare the growth patterns between trees. For more details on how to create a skeleton plot, please see Stokes and Smiley[20]. Synchrony (of thin and wide rings) between different trees is an indication that there are no growth problems (false or missing rings). Therefore, it is feasible to assign dates (calendar years) to the rings in the same way as was done with the living trees.
5. Some fire scar samples may not show synchronous growth patterns with other trees, this is due to growth suppressions (very small rings) that can lead to missing rings (i.e., calendar years when the tree did not add wood to that portion of the tree) in specific years and which were not considered in the count. Conversely, it is possible to have “false rings”. A false ring is a tree-ring that appears as two-rings but is really associated with a single calendar year. This is caused when the tree is stressed due to season drought and begins laying down latewood in preparation for shutting down growth only to re-start regular growth after receiving sufficient moisture. Determine which of these two issues is preventing the lack of synchrony by comparing each individual ring between the non-synchronized sample and a sample that did not register growth problems.
6. Once the problem has been identified, correct the tree-ring count in the non-synchronized sample and its growth graph. Repeat this procedure for all samples that are non-synchronized.
7. To date all live trees, develop an average graph commonly called the “Master chronology,” which is the average of all individual skeleton plots and indicates the growth pattern of the site. For more details on how to create a Master chronology, please see Stokes and Smiley[20].
8. After the live trees with a known outermost tree-ring have been dated, start dating dead trees, where the outermost ring is unknown. To do this, start by creating a skeleton plot for each dead-tree sample, compare the skeleton plot from each dead tree to the master chronology derived from live trees (cross-dated)[20]. The key to matching the tree-ring growth patterns between the dead trees and the master chronology is matching the pattern of years with suppressed growth (small tree-rings). By definition, small tree-rings are due to a climate pattern resulting in a lack of moisture. Because droughts are experienced and recorded by all trees, this communal pattern will be reflected in the tree-ring patterns of all trees in the study area.
9. When the growth pattern of the dead tree is matched perfectly with the master chronology graph, determine the calendar year when the tree died. That is, the outermost ring of the sample will correspond to the years when the tree died but only if the bark is still present. Without the bark, it is impossible to know the year when the tree died although it is still possible to date the rest of the tree-rings in the sample.
10. In cases where the dead trees are not perfectly synchronized with the master chronology, identify the problem (identify missing and/or false rings) and make appropriate adjustments, following the same procedure used for live trees.

11. Once each fire scar sample has been pre-dated (preliminary dated), measure the width of each individual tree-ring along a perpendicular line across the cross-section using a measurement system (for example, Velmex with a precision of 0.001 mm)[21]. Those who do not have a Velmex, can use a high-resolution scanner. That is, tree-ring-measurements and dating can also be done using scanned images of the cross-sections and a software such as CDendro/CooRecorder. Measurements of the tree-ring widths will be used to verify the quality of dating statistically with the COFECHA program[22]. This is recommended to validate the quality of the dating.

12. If there is a previous chronology developed in the study region based on the annual tree-rings which has been statistically verified, then use that chronology or master series to support the dating of fire scar samples.

4. Fire scar dating

1. After the tree-ring dating has been completed within each sample, identify all fire scars within the sample and determine the year in which the fire occurred (**Figure 6A**).

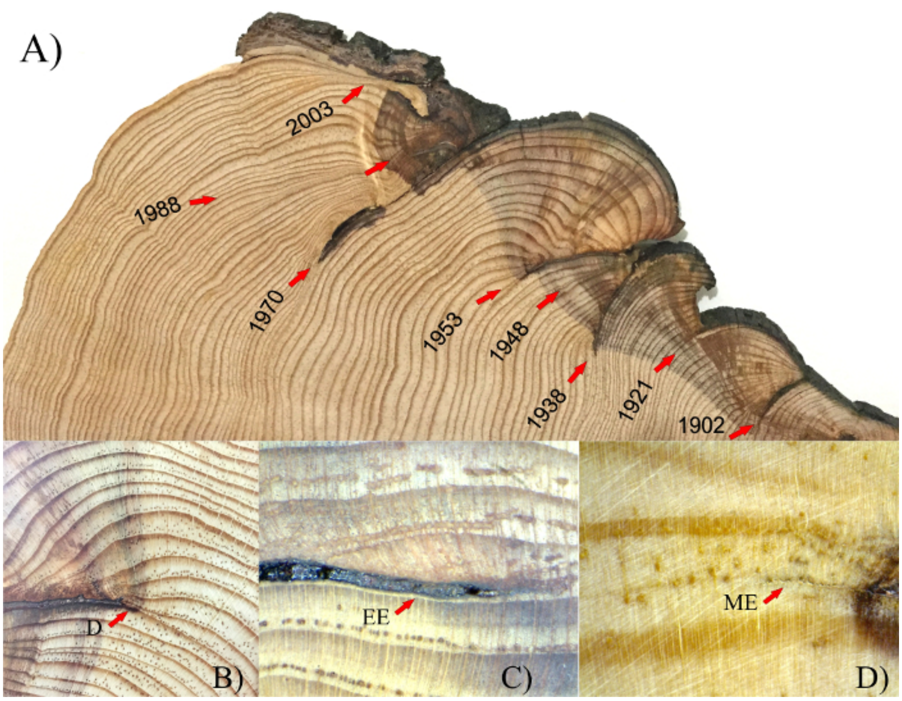

Figure 6: Fire scar position and seasonality within the tree-ring and corresponding calendar year. Panel A is an example of a fire-scarred cross-section with individual fire scars indicated by the red arrow and preceded by the year in which each fire occurred between 1902 and 2003. Panels B, C and D show magnified examples of fire scars in the dormant (D), early-earlywood (EE) and middle-earlywood (ME) within the annual tree-ring, respectively. Please click here to view a larger version of this figure.

5. Determining fire scar seasonality

1. Use the position of the fire scar within the annual tree-ring to determine the season in which the fire occurred. In general, assign the location of each fire scar into one of the following categories (**Figure 6B**) within the tree-ring: EE (early part of the early wood), ME (middle part of the early wood), LM (end part of the early wood), L (late wood), and D (dormancy or ring boundary)[23,18].
2. Assign fire-scars that occur during the dormancy period (between ring boundaries), to the beginning of the next year's early wood (spring fires) unless other samples have fire scars in the latewood section of the tree-ring[24,25,26]. The seasonality categories can also be grouped into spring (D + EE) and summer seasons (ME + LE + L)[11].
NOTE: The grouping of these categories may vary according to the geographic region and forest type.

6. Data analysis

1. To analyze fire-scar data, first build a fire history database using a spreadsheet, where each sample is a row and each column is a variable associated to that sample. Consider including the following fields for each sample.
    1. Include the scientific tree name: genus and species.
    2. Include the sample number: The number designated to the sample during field collection, for example, CRN01a (Cuenca Río Nazas, tree 01, sample a).
    3. Include the year: This section includes two dates, year of the innermost (or center) ring and outermost (closest to the bark) ring. It is important to indicate when the first ring corresponds to pith and whether the outermost ring is adjacent to the bark, which indicates the date on which the sample died or stopped recording. This information is required by most programs used for the fire history analysis.
    4. Include the inner most ring date.
    5. Include the outer most ring date.
    6. Include the pith (Yes or No).
    7. List of all fire-scar years and seasons. For example: 1902EE, would indicate a fire was recorded in the early part of the earlywood within the year 1902 (**Figure 6C**).
2. Upload the fire history file into the Fire History Analysis and Exploration System (FHAES) Version 2.0.0-SNAPSHOT[27]. If the program is not available, download it using this link: https://www.frames.gov/partner-sites/fhaes/fhaes-home/.
    1. Open the program. There will be three options: Create a New FHX File, Load Existing FHX File(s) and Run Superposed Epoch Analysis.
    2. Select the first option: **Create a New FHX File**. A new window called **Fire History Recorder** will open, and will provide the following options: Data, Metadata, Summary, and Graphs.
    3. Select **Data**, to select the samples currently loaded, and click on the green cross sign to add a new sample to this data set.
    4. A new window will open asking for: Sample name, First year (does the inner most ring correspond to the pith or not?), Last year (does the year correspond to the bark or not?). Once this general information has been provided, click **OK** to continue.
    5. The window with the general information that was added is now activated and includes three fields: Event Type, Event Season, and Event Year. Start

adding the specific information, including each fire event, to the first sample. Click **Add Event** to add information for each of the three fields.

6. The information required for each of the fields is: In **Event Type** select **Fire Scar**, in **Event Season** select the position of the fire scar within the tree-ring, and in the **Event Year** include the calendar year in which the fire occurred. Start from the oldest to the most recent record.
7. Within **Add Event**, add the next fire event until the last fire within that sample has been added.
8. After finishing the sample, save the file according to the site name and the FHX extension (for example: CRN.FHX), preferably in the same folder as the FHAES program, when given the option to save. You will then be notified that the file was successfully saved unless there was a problem with the file in which case that message will not appear. In that case, the problem will need to be corrected before continuing.
9. To add the information for the new sample click on **Add a New Sample to This Data Set** and provide the information for the new sample.
10. Click on **Ok** to continue.
11. This activates a new window to add information regarding each fire within the sample. Follow the same procedure to add all fire scar samples to the file. Save the information each time a new sample is added and verify that it was saved correctly by noting the message that the FHX file was successfully saved.
12. If unable to add all the information within one session, continue working on the database later. To do this, open the FHAES program, and click on **Load Existing FHX File(s)**. Select the file to continue working on. Click **Open**, and a new window should open with the data for the sample. Select **Edit File** located in the menu above, which should open a new window Fire History Recorder-CRN.FHX with the file; from here, continue entering the information that is still needed.
13. To finalize the file, add the information that may be important as part of the Metadata. This information could include Summary and Graphs, which were generated with that file. Another option for fire history analysis and graphics is the new software "burnr in R"[28].

3. **Generating a fire history graph.** Open the FHAES program and open the file created using the database described above (CRN.FHX). Select the **Chart** option and the history of the fire can be seen graphically.
4. **Generate fire history descriptive statistics** based on the year and season in which the fires occurred. Similar to the processes used to create the graphs, open the file in FHAES and select **Analysis** > **Run Analysis** > **Apply**. On the right side of the program screen, a new window will open (FHAES analysis result) displaying both the Interval Analysis Summary and the Seasonality Summary. The most important descriptive statistics are: mean fire interval (MFI), minimum and maximum intervals, mean fire interval per sample and the Weibull median probability interval (WMPI) or fire recurrence. The latter is a measure of central distribution used to model the asymmetric distribution of fire intervals and to express recurrence intervals in probabilistic terms[29,30].

5. For each statistic, consider three filters: 1) all scars, 2) 10% filter, which are fire years recorded as scars by 10% or more of the samples, and 3) 25% filter, which are fire years recorded as scars by 25% or more of the samples. The last filter allows in determining the intervals of the most extensive fires[30].
6. Regarding the seasonality of the fire, different parameters are displayed, the most important being the number and percentage of scars recorded for each intra-ring category. Likewise, the number and percentage of fires recorded in the spring and summer seasons is provided[11].

7. Climate-fire analysis

1. Open the FHAES program and select Run Superposed Epoch Analysis (SEA).
2. For this analysis, use two files: 1) Continuous time series file and 2) Event list file. The first file refers to the climatic data ordered in column (for example: Precipitation, Temperature, PDSI, ENSO, etc.) and the second file lists the reconstructed fires ordered within a column, both files must be in text format (.txt).
3. Load each of these files in their appropriate formats.
4. When running the SEA analysis, it is possible to modify the number of years prior to and after the fire years in the Simulation and statistics window. However, it is highly recommended to keep the default parameters.
5. At the bottom click **Run** to execute the analysis.
6. This generates the summary information; from there click on **Chart** to create the results that are automatically displayed as bar graphs.
7. Interpret these graphs: on the X-axis “0” represents the fire year, negative and positive values indicate years before the fires and after the fire. Confidence intervals at 95, 99 and 99.9% are shown in the form of lines above and below the average axis, expressing the significance of the analysis.
8. Save the output in either PNG or PDF format.
9. Based on this analysis, it is possible to assess the influence of climate variability on fire occurrence over time, including climate conditions during the years before, during, and after the fires included in the analysis. For further support in the execution and interpretation of results with FHAES, consult the user manual[31].

Representative Results

When a surface fire burns in a forest, the tree trunks of some trees are often damaged, causing injury that subsequently heals (**Figure 7A**). These scars form when the fire is intense enough or has a long enough residence time to penetrate the bark and kill part of the cambium. Historically, such fires occurred often enough to prevent the accumulation of fuels; therefore, most of these fires would not be able to reach the tree canopies. As a result, most mature trees survived and continued growing, allowing the damaged portion to partially heal before the next fire (**Figure 7B**). This recurring process resulted in the recording of a fire-scar within the tree-rings (**Figure 7C**). The open wound facilitates scarring by future fires and thus the history of past fire events can be reconstructed by selecting the best individuals and making an appropriate collection of the samples, as suggested in section 1.

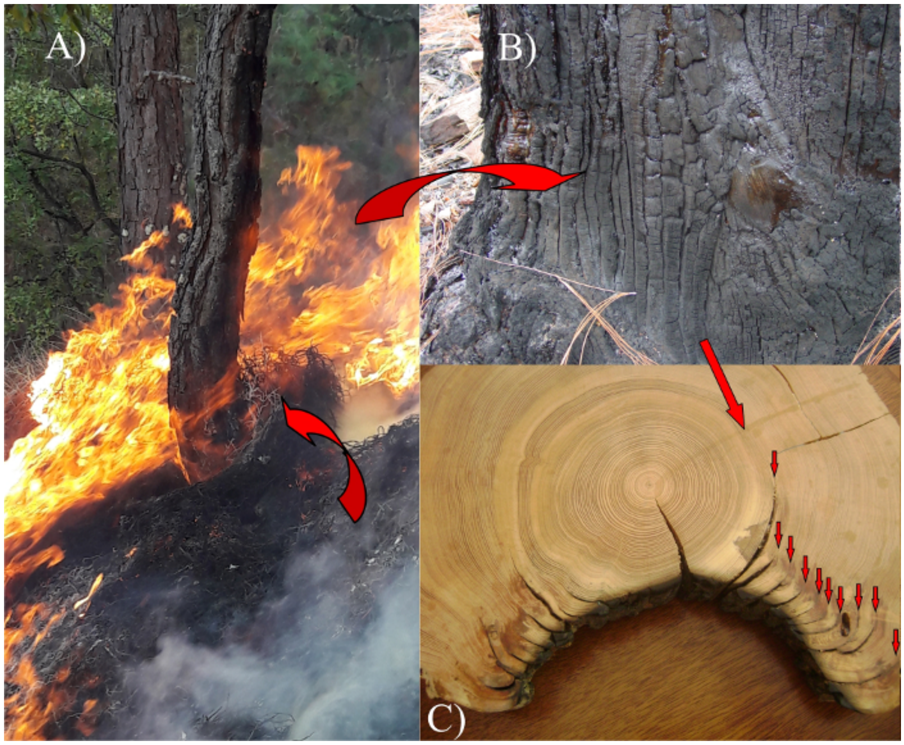

Figure 7: Fire scar formation within a tree. (**A**) As a fire burns at the base of a tree, it damages the bark and part of the cambium on the upslope of the tree, where there is greater fuel accumulation and the fire is protected from the wind. The longer residence time allows the heat to penetrate the bark and damage the cambium (Photo taken by Dante A. Rodríguez-Trejo), (**B**) As a result of the heat, that portion of the tree is no longer functional, creating a scar, (**C**) In time the scar is incrementally covered by growth for areas adjacent to the scar. However, recurring fires create new scars at the base of the tree stem. The correct extraction of the sample, the dating of the annual growth tree-rings and fire scars (indicated by the arrows in red), allow the reconstruction of the historical fire frequency in forested areas. Please click here to view a larger version of this figure.

Using these same methods here, we provide an example of a fire history study conducted within a watershed. The forests in the upper part of the watershed were divided into lower part (LP) and upper part (UP). A total of 68 fire-scar samples were collected from the following species: *Pinus arizonica* Engel., *Pinus strobiformis* Engelm., *Pinus theocote* Schlecht. & Cham., *and Pseudotsuga menziesii* (Mirb.) Franco. Of the 68 fire scar trees, 46 were collected in LP and 22 in UP, using section 1 (steps 1.4.6.1–1.4.6.7). Most samples (74%) were taken from dead trees (snags or logs) and the rest (26%) from live trees (**Table 1**). Following sections 2 and 3, it was possible to date 50 samples (74%) and using section 4, it was possible to identify 596 scars. It was not possible to date 18 samples (26%) due to deterioration or insufficient number of rings to allow reliable dating.

Site	Samples collected	Used in the study	Living	Snag or log	Cut stump	Species	Average diameter
Lower	46	33	10	16	7	Par, Pst, Pte, Psm	45.9
Upper	22	17	0	7	10	Par, Pst	46.4
Note: Tree species are *Pinus arizonica* (Par), *Pinus strobiformis* (Pst), P*inus teocote* (Pte) and *Psedotsuga menziesii* (Psm).							

Table 1: Characteristics of sampled trees. This table has been modified from Cerano-Paredes et al., 2019[30].

Of the 596 scars dated, it was possible to determine the fire-scar position (seasonality) within the tree-ring on 560 scars (94%), based on sections 5 and 6 (steps 6.4 and 6.5). The most common intra-ring position was EE (91.0% and 97.8%), followed by ME (8.7% and 1.8%) and less than 1% (0.3% and 0.4%) in LE for the LP site (**Figure 8B**) and UP (**Figure 8A**), respectively. No scars were found in D and L portions of the tree-rings. Of all the fire scars, 91% and 97.8% were determined to have occurred in the spring, 9% and 2.2% in summer, for LP and UP, respectively.

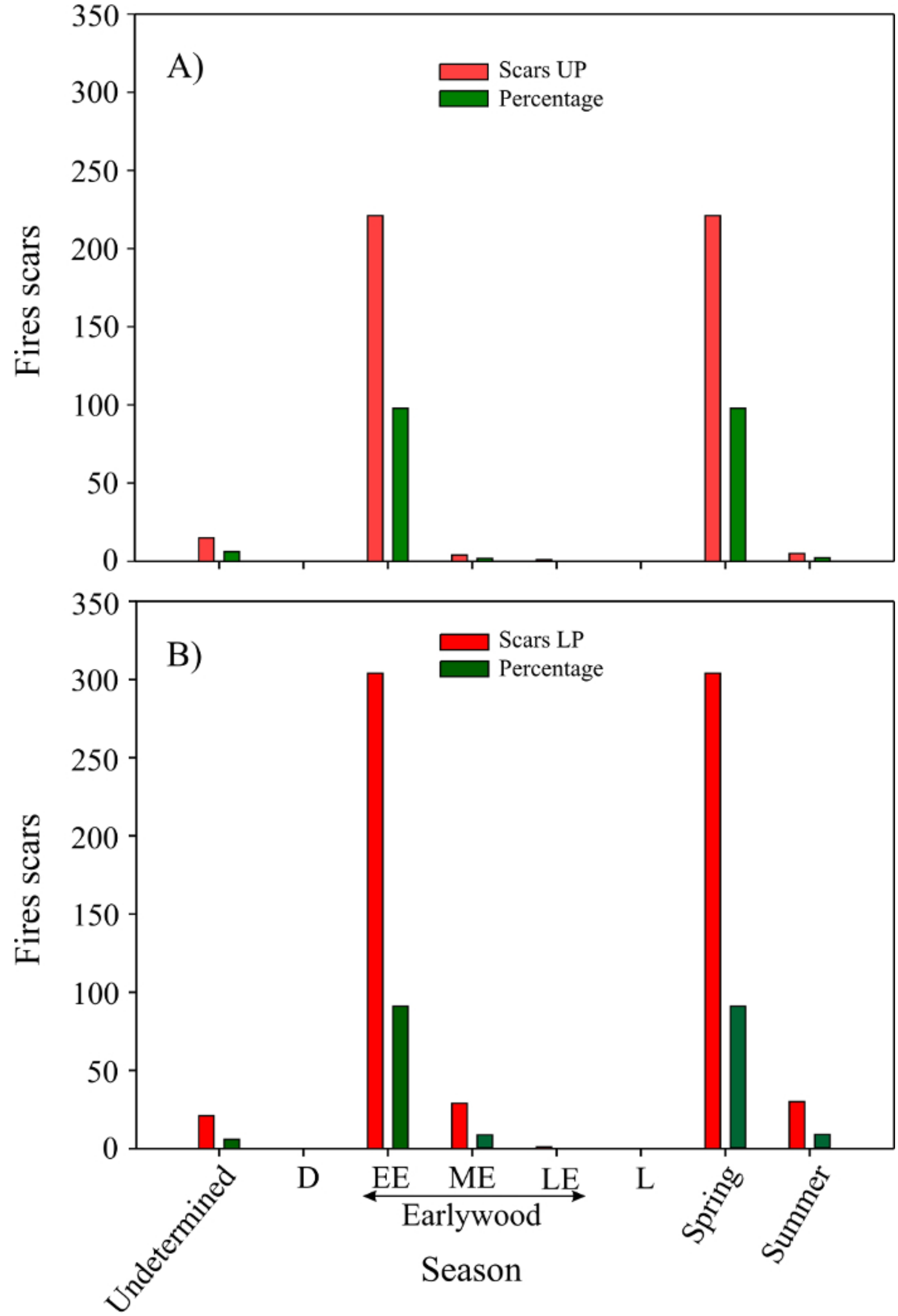

Figure 8: Fire seasonality (number and percent) based on the position of the fire scar within the tree-ring between 1575 and 2008. (**A**) Seasonality of fire occurence for the UP and (**B**) LP sites. Most fire-scars were identified early within the growing season. More than 90% of the scars occurred during the spring season. Please click here to view a larger version of this figure.

A fire history record was reconstructed following section 6 (steps 6.1 to 6.3), from 1700s to the early 1950s, when fires occurred frequently at both sites (**Figure 9**). The pattern of frequent fires was interruption in the mid-20th century. The UP site shows a change in fire frequency starting in the early 20th century. In general, fire frequencies have been altered at both sites in recent decades.

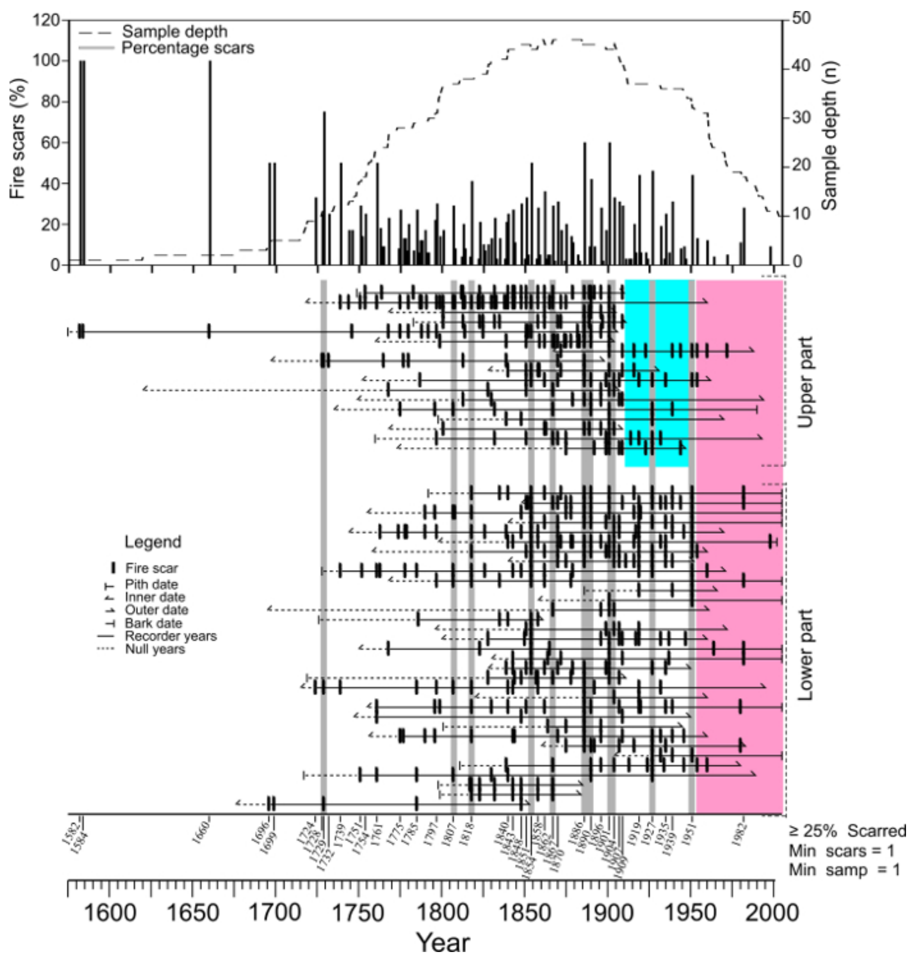

Figure 9: Fire history chart for low and high elevation sites (LP and UP) along the elevation gradient within the watershed for the period 1575–2008. Each horizontal line represents the lifespan of a sample, vertical black lines represent fire-scars, and the gray shaded lines highlight widespread fires affecting both sites (years when fires were recorded at both sites within the same year). The pink shaded area indicates a long period (50 years) with an absence of large fires (lack of synchrony among fire scars between trees), and the blue shaded area is a period when fire frequencies began to be altered, one hundred years ago at the higher elevation site. This figure has been modified from Cerano-Paredes et al., 2019[32].

Please click here to view a larger version of this figure.

The mean frequency intervals (MFI) were generated following section 6 (steps 6.1, 6.2, and 6.4). The results show that, during the last centuries, fires occurred at intervals of every 3-years for both sites (LP and UP) considering all scar filters and at intervals of 9 and 6 years for the most extensive fires (10% filter) in LP and UP, respectively. However, this frequency changed dramatically after 1951, with current extensive fire-free intervals for LP and UP, of 27 and 48 years, respectively (**Table 2**). Fire return intervals were described using three filters: 1) all scars, which included every fire year that was recorded in at least one sample, 2) ≥10% scars, which included only fire years recorded by at least 10% of the recording samples, and 3) ≥ 25% scars, which included only fire years recorded by ≥25% of the recording samples. The ≥25% filter is widely used in the literature as an estimate of fire frequency for large fires.

Site/analysis period	Categor of analysis	No. intervals	MFI	Min	Max	WMPI
Lower site 1739-1982	All scars	77	3.16	1	16	2.69
	10% scarred	56	4.34	1	20	3.73
	25% scarred	28	8.68	1	31	7.22
Upper site 1739-1954	All scars	76	2.63	1	7	2.45
	10% scarred	60	3.33	1	9	3.14
	25% acarred	32	6.25	1	19	5.44

Table 2: Fire interval statistics. This table has been modified from Cerano-Paredes et al., 2019[30].

The influence of climate on fire occurrence was obtained following section 7. The Superposed Epoch Analysis (SEA) shows that years in which fires occurred were dry and preceded by wet years (**Figure 10**). In the last 300 years, there has been a significant relationship ($P < 0.01$) between the fire occurrences and lower than normal rainfall (**Figure 10A**). The SEA also showed that fire years occurred when El Niño Southern Oscillation (ENSO) NĨNO 3 indices were negative. This suggests tropical climate patterns indicated by the NĨNO 3 indices has had a significant effect ($P < 0.05$) on the fire occurrences within this study area (**Figure 10B**). In addition, both indices (precipitation and NIÑO 3) were significantly ($P < 0.01$) greater than normal 1 year prior to the fire year, suggesting wetter than normal conditions on years prior to the fire events.

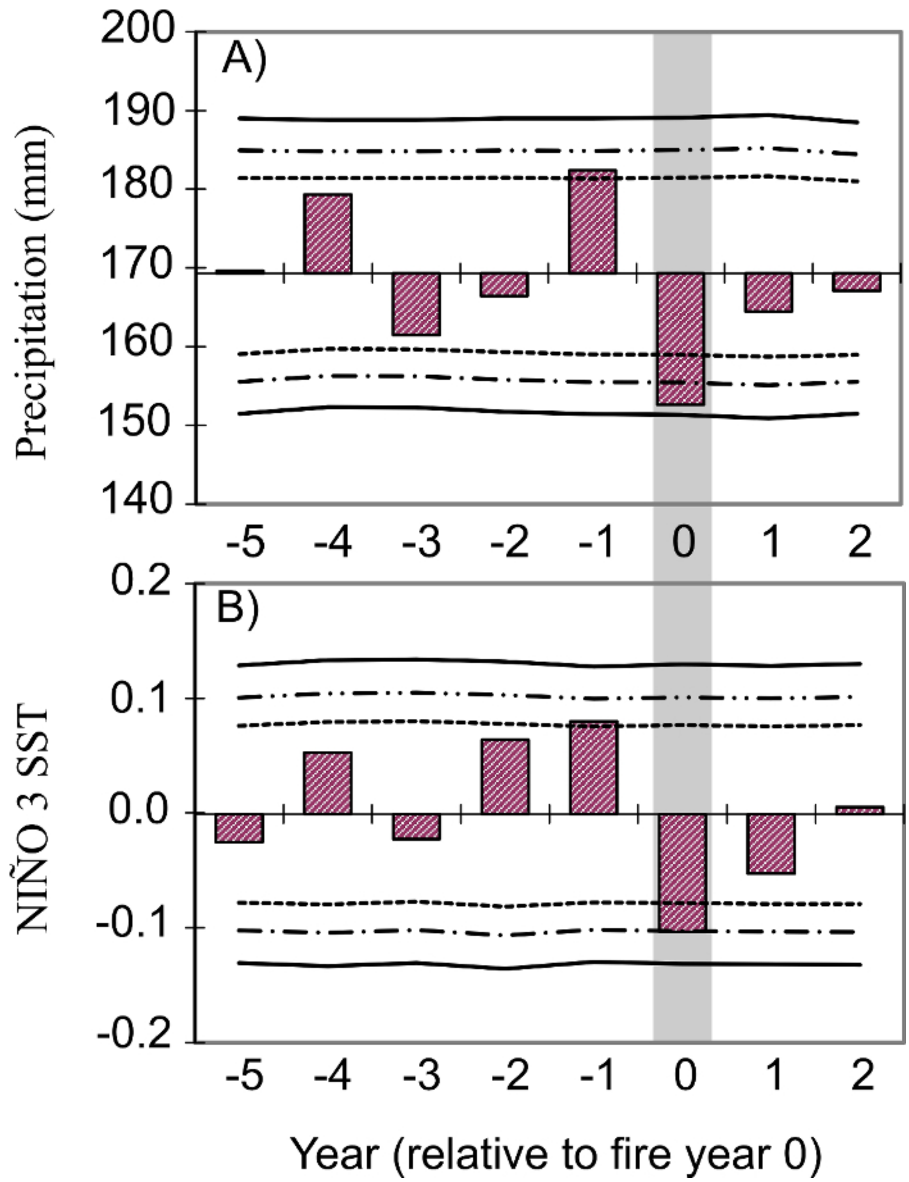

Figure 10: Superposed Epoch Analysis (SEA) showing the relationship between climatic variability [reconstructed precipitation[33], ENSO indices (NIÑO 3)][34] and reconstructed fire frequency, for both the LP and UP sites. The year when the fire occurred is indicated as year 0 (gray bar), while years prior to the fire year are indicated as negative and years following the fire as positive numbers along the X-axis. In this example, average weather conditions 5 years prior and 2 years after the fire are shown. Climate conditions are indicated along the Y-axis, where values below zero are below average and values above zero represent conditions above average. The upper and lower horizontal lines on each graph indicate the confidence intervals (dotted, $P < 0.05$; dashed, $P < 0.01$; and solid, $P < 0.001$). This figure has been modified from Cerano-Paredes et al., 2019[32]. Please click here to view a larger version of this figure.

The relationship between climate and fire frequency over time can be analyzed graphically by comparing the climate variability of the study region (employing a tree-rings chronology, reconstructed precipitation, ENSO index, PDSI index, among others) and the fire reconstruction (**Figure 11**). However, it will always be very important to know the statistical relationship between both variables.

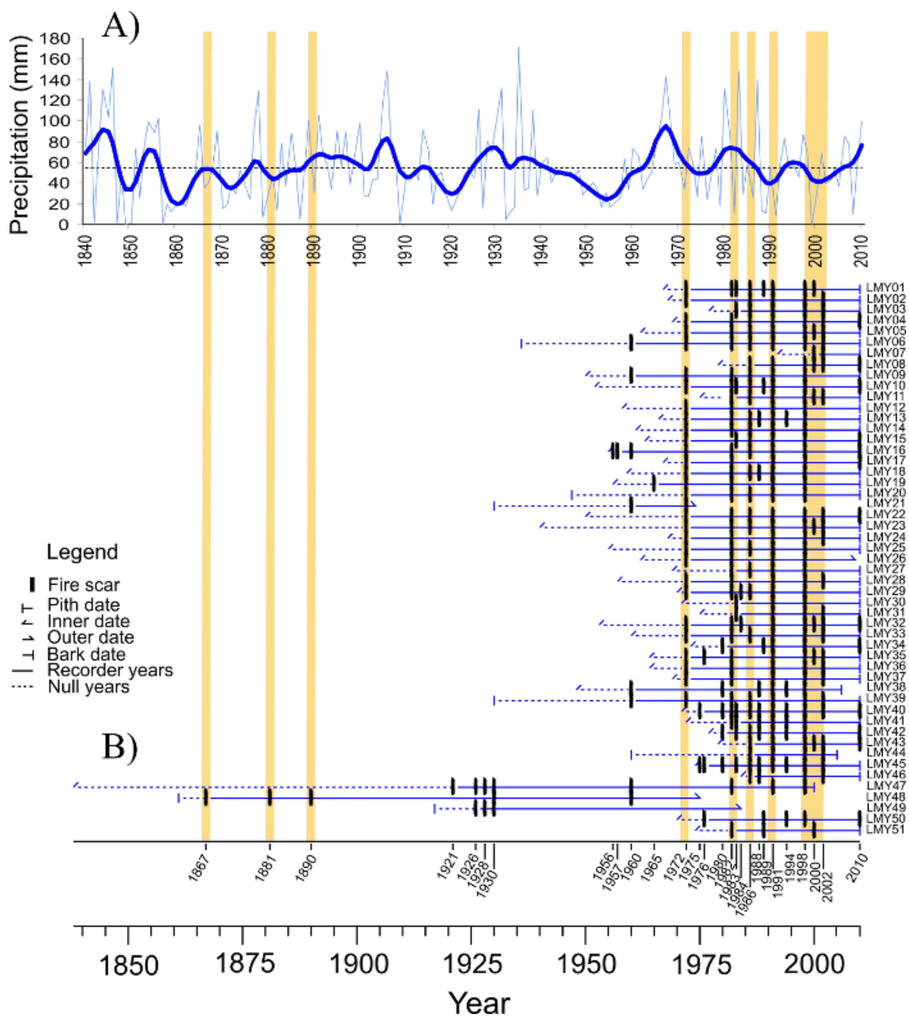

Figure 11: Relationship between the climate variability and the fire history. (**A**) Represents winter-spring precipitation reconstructed, the bottom blue line represents the annual variability; the flexible blue curve is a smoothing spline at 10-year intervals (spline) to detect dry and wet events; and the dotted horizontal line indicates average precipitation and (**B**) represents the fire history reconstruction. The yellow vertical line allows analyzing the relationship between fire frequencies and decreasing precipitation below average (droughts). This figure has been modified from Cerano-Paredes et al., 2015[39]. Please click here to view a larger version of this figure.

Discussion

In forested ecosystems, fire is a key ecological process; therefore, reconstructing historical fire regimes is important toward understanding the frequency, seasonality, and variability of fires overtime. Changes to the historical fire regime can potentially lead to unintended consequences in regards to forest structure and health; therefore, such information is critical in forest management. This methodological approach focuses on the importance of selecting the study area and sites, collecting the best fire-scarred trees, as well as the laboratory sample preparation and dating. Likewise, we describe step-by-step analytical procedures to successfully reconstruct the fire history in a forested study area. Such detail procedures are generally summarized and not as well-described in typical fire history study publications. This protocol can be implemented in different ecosystems where trees form annual rings and fires play an important role in forest dynamics.

Forest fire regimes, specifically fire return intervals, frequency, extent, and seasonality, vary over space and time; therefore, it is important to understand these patterns in regions and forests of interest. In some mixed-conifer forests, fire frequencies have been altered by fire suppression efforts since the beginning of the 19th century[25,35]. While in other regions, fire regime changes occurred later in the mid-20th century[36,37,24,38,32], whereas in some sites fire frequencies have remained unchanged[39,40,41,42]. Conversely, anthropogenic factors have increased fire frequency at other areas[43]. In most instances, changes to the natural fire regimes have brought about major alteration to the forest and fuel structure, culminating its un-natural fire behavior and stand replacing fires in forests that are not adapted to such events.

In the case study presented here, fires were very frequent prior to 1951 (**Figure 9**). Moreover, the fact that these fires scarred trees but did not kill them suggests that these were low severity surface fires. That is, the high fire frequencies maintained low fuel loads and tree densities, preventing high-severity fires. However, the process of fuel reduction by frequent fires ceased with fire suppression after 1951. As a result, fuel loads have increased and become more homogeneous within the study area. In the future, this could potentially lead to stand-replacing fires, particularly during extreme climatic conditions (drought), increasing the risk of deforestation, loss of wildlife habitat and affecting the services these forest provide[44,45]. Fire suppression in forests with a frequent surface fire regime is not a recommended management strategy, given that it can lead to changes in forest stand density, fuel accumulation, forest health issues, and an increased risk of high severity stand-replacing fires[5,46,47,48]. Whenever possible, fire should be used to restore the regime of frequent surface fires and reduce the risk of severe stand-replacing fires[49,38].

Dendro-based fire history reconstructions do have a number of limitations that are worth mentioning. First, of course is that such studies can only be applied in ecosystems with annual tree-rings. Moreover, tree-rings also need to be cross-datable. In dry forests, for example, trees can often have annual tree-rings but may not be cross-datable due to missing or double tree-rings as mentioned previously. To ensure tree-rings within a site cross-date, we suggest collecting and cross-dating core samples prior to sampling fire-scarred trees in a study area. Another potential limitation could be the lack of fire scars within a study area. Although this can suggest that fire is not common in such systems, fire-scars can also be healed over or “buried” within a tree, particularly in fast growing trees and/or when fire intervals are long, thereby allowing the trees to heal or cover the wounded area. In such cases, trees with buried fire-scars may have non-uniform or depression along the trunk. Using these abnormalities as cues, it may be worth cutting into such trees in search of buried fire-scars.

Another limitation of dendro-based fire history studies is that they only provide a limited record of the fire histories because most trees live, die, and decompose within a few centuries, at best. Therefore, the fire history records are short compared to charcoal-based fire histories, for example. However, the main advantage of tree-ring based studies is the annual to sub-annual temporal resolution. One of the advantages of the annual resolution is that forest fire dynamics can then be related to annual climate variability[50,51,24,38,50]. In general, large fires occur during dry years caused by atmospheric circulation climatic phenomena such as El Niño Southern Oscillation (ENSO)[24,38,50,39,47,32]. Understanding historical climate-fire relationships allows us to use contemporary weather information from buoys and satellites in the tropical Pacific to monitor and predict the evolution of the ENSO and other climate patterns. These forecasts, paired with region-specific information on historical fire regimes, could allow us to improve management strategies in order to mitigate the impact of shifting trends on fire behavior at multiple scales[32].

The results generated by this protocol and associated fire history reports and studies offer the forest managers´ greater understanding of the role of fire within a specific study area and/or region. This information can then be used to design fire management and prevention plans that allow for maintaining or restoring historical fire regimes into the future with the goal of forest sustainability and increasing the quality of ecosystem services.

Disclosures

The authors have nothing to disclose.

Acknowledgments

The research project was carried out thanks to the financing through the project: Study of the climate-fires relation in north-central Mexico, financed by the SEP-CONACYT fund.

References

1. Pyne, S. J. World fire. *The culture of fire on Earth.* University of Washington Press. Seattle, WA USA. 384 p (1996).
2. Keeley, J. E., Bond, W. J., Bradstock, R. A., Pausas, J. G., Rundel, P. W. *Fire in Mediterranean ecosystems: ecology, evolution and management.* Cambridge: Cambridge University Press (2012).
3. Bowman, D., Balch, J. K., Artaxo, P. Fire in the Earth system. *Science.* **324**, 481-484 (2009).
4. Falk, D. A. et al. Multi-scale controls of historical forest-fire regimes: new insights from fire-scar networks. *Frontiers in Ecology and the Environment.* **9** (8), 446-454 (2011).
5. Rodríguez, T. D. A., Fulé, P. Z. Fire ecology of Mexican pines and a fire management proposal. *International Journal of Wildland Fire.* **12**, 23-37 (2003).
6. Iniguez, J. M. et al. Tree and opening spatial patterns vary by tree density in two old-growth remnant ponderosa pine forests in Northern Arizona, USA. *Forest Ecology and Management.* **450**, 117502 (2019).
7. Agee, J. K. Alternatives for implementing fire policy. In *Proceedings, Symposium on fire in wilderness and park management.* pp. 107-112 (1993).

8. Wright, C. S. *Fire history of the Teanaway River drainage, Washington.* (1996).
9. Arno, S. F., Sneck, K. M. *A method for determining fire history in coniferous forests of the mountain west* (p. 28). Forest I. (Ed.). Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture. (1977).
10. Fritts, H. C. Dendroclimatology and dendroecology. *Quaternary Research.* **1** (4), 419-449 (1971).
11. Grissino-Mayer, H. D. FHX2—software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research.* **57**, 115-124 (2001).
12. Speer, J. H. *Fundamentals of tree-ring research.* University of Arizona Press. 509 p (2010).
13. Bull, W. B. *Tectonic geomorphology of mountains: a new approach to paleoseismology.* Blackwell Publishing. Reino Unido. 316 p (2008).
14. Black, B. A., Boehlert, G. W., Yoklavich, M. M. Using tree-ring crossdating techniques to validate annual growth increments in long-lived fishes. *Canadian Journal of Fisheries and Aquatic Sciences.* **62** (10), 2277-2284 (2005).
15. Van Horne, M. L., Fulé, P. Z. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. *Canadian Journal of Forest Research.* **36** (4), 855-867 (2006).
16. Falk, D. A., Swetnam, T. W. Scaling rules and probability models for surface fire regimes in ponderosa pine forests. *USDA Forest Service Proceedings RMRSP-29.* 301-318 (2003).
17. Cerano-Paredes, J. et al. Interpretación del historial de incendios en bosques mixtos de coníferas. CENID-RASPA INIFAP. Gómez Palacio, Durango. *Folleto Técnico.* **15** (2009).
18. Baisan, C. H., Swetnam, T. W. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. *Canadian Journal of Forest Research.* **20**, 1559-1569 (1990).
19. Cochrane, J., Daniels, L. D. Striking a balance: Safe sampling of partial stem crosssections in British Columbia. *BC Journal of Ecosystems and Management.* **9** (1), 38-46 (2008).
20. Stokes, M. A., Smiley, T. L. *An introduction to tree-ring dating.* University of Chicago Press, Chicago. 73 p (1996).
21. Robinson, W. J., Evans, R. A microcomputer-based tree-ring measuring system. *Tree-Ring Bulletin.* **40**, 59-64 (1980).
22. Holmes, R. L. Computer-assisted quality control in tree ring dating and measurement. *Tree-Ring Bulletin.* **43**, 69-75 (1983).
23. Dieterich, J. H., Swetnam, T. W. Dendrochronology of a fire-scarred ponderosa pine. *Forest Science.* **30**, 238-247 (1984).
24. Heyerdahl, E. K., Alvarado, E. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. *In* Veblen T. T., Baker W. L., Montenegro G., Swetnam T. W. eds. Fire and climatic change in temperate ecosystems of the Western Americas. New York, USA. *Springer-Verlag.* p. 196-217 (2003).
25. Swetnam, T. W., Baisan, C. H. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and

southwestern United States. *In* Veblen, T. T., Baker, W. L., Montenegro G., Swetnam T. W. eds. Fire and climatic change in temperate ecosystems of the western Americas. New York, USA. *Springer-Verlag.* p. 158-195 (2003).

26. Yocom, L. L., Fulé, P. Z. Human and climate influences on frequent fire in a high-elevation tropical forest. *Journal of Applied Ecology.* **49** (6), 1356-1364 (2012).
27. Sutherland, E. K., Brewer, P., Velasquez, M. E., Falk, D. A. FHAES: The Fire History Analysis and Exploration System. (2015).
28. Malevich, S. B., Guiterman, C. H., Margolis, E. Q. "burnr: Fire history analysis and graphics in R." *Dendrochronologia.* **49**, 9-15 (2018).
29. Grissino-Mayer, H. D., Baisan, C. H., Swetnam, T. W. Fire history and age structure analyses in the mixed conifer and spruce-fir forests of Mount Graham. Final report. Mount Graham Red Squirrel Study Committee. Phoenix, AZ, USA. U.S. *Fish and Wildlife Service.* 73 p (1994).
30. Swetnam, T. W., Baisan, C. H. Fire histories of montane forests in the Madrean Borderlands. *United States Department of Agriculture Forest Service, General Technical Report RM.* 15-36 (1996).
31. Sutherland, E. K., Brewer, P. W., Falk, D. A., Velasquez, M. E. Fire History Analysis and Exploration System (FHAES) user manual. (2015).
32. Cerano-Paredes, J. et al. Climatic influence on fire regime (1700 to 2008) in the Nazas watershed, Durango, Mexico. *Fire Ecology.* **15** (1), 9 (2019).
33. Cerano-Paredes, J. et al. Precipitación reconstruida para la parte alta de la cuenca del río Nazas, Durango. *Revista Mexicana de Ciencias Forestales.* **3** (10), 7-23 (2012).
34. Cook, E. R. NIÑO 3 index reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series Number 2000-052. NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, USA. (2000).
35. Brown, P. M. Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. *Ecology.* **87** (10), 2500-2510 (2006).
36. Fule, P. Z., Covington, W.W. Fire regimes and forest structure in the Sierra Madre Occidental, Durango, Mexico. *Acta Botanica Mexicana.* **41**, 43-79 (1997).
37. Fulé, P. Z., Covington, W. W. Fire regime changes in La Michilía Biosphere Reserve, Durango, Mexico. *Conservation Biology.* **13** (3), 640-652 (1999).
38. Fulé, P. Z., Villanueva-Díaz, J., Ramos, G. M. Fire regime in a conservation reserve, Chihuahua, Mexico. *Canadian Journal of Forest Research.* **35**, 320-330 (2005).
39. Cerano-Paredes, J., Villanueva-Díaz, J., Fulé, P.Z. Reconstrucción de incendios y su relación con el clima para la reserva Cerró el Mohinora, Chihuahua. *Revista Mexicana de Ciencias Forestales.* **1** (1), 63-74 (2010).
40. Fulé, P. Z., Ramos, G. M., Cortes, M. C., Miller, A. M. Fire regime in a Mexican forest under indigenous resource management. *Ecological Applications.* **21**, 764-775 (2011).
41. Cerano-Paredes, J. et al. Historia de incendios en un bosque de pino de la sierra de Manantlán, Jalisco, México. *Bosque.* **36** (1), 39-50 (2015).
42. Cerano-Paredes, J. et al. Régimen histórico de incendios y su relación con el clima en un bosque de *Pinus hartwegii* al norte del estado de Puebla, México. *Bosque.* **37** (2), 389-399 (2016).

43. Brose, P. H., Guyette, R. P., Marschall, J. M., Stambaugh, M. C. Fire history reflects human history in the Pine Creek Gorge of north-central Pennsylvania. *Natural Areas Journal.* **35** (2), 214-223 (2015).

44. Westerling, A. L., Hidalgo, H. G., Cayan, D. R., Swetnam, T. W. Warming and earlier spring increase western US forest wildfire activity. *Science.* **313**, 940-943 (2006).

45. Singleton, M., Thode, A., Sanchez-Meador, A., Iniguez, P. Increasing trends in high-severity fire in the southwestern USA from 1984-2015. *Forest Ecology Management.* **433**, 709-719 (2019).

46. Brown, P. M., Wu, R. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. *Ecology.* **86** (11), 3030-3038 (2005).

47. Yocom, L. L. et al. El Niño Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. *Ecology.* **91** (6), 1660-1671 (2010).

48. Iniguez, J. M., Swetnam, T. W., Baisan, C. H. Fire history and moisture influences on historical forest age structure in the sky islands of southern Arizona, USA. *Journal of Biogeography.* **43** (1), 85-95 (2016).

49. Pollet, J., Omi, P. N. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire.* **11** (1), 1-10 (2002).

50. Skinner, C. N., Burk, J. H., Barbour, M. G., Franco, V. E., Stephens, S. L. Influences of climate on fire regimes in montane forests of north-western México. *Journal of Biogeography.* **35**, 1436-1451 (2008).

51. Swetnam, T. W., Betancourt, J. L. Fire-southern oscillation relations in the southwestern United States. *Science.* **249** (4972), 1017-1020 (1990).