Laboratory of Tree-Ring Research, University of Arizona

Final Report

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U.S. Department of Agriculture, Forest Service
Rocky Mountain Research Station

Research Work Unit No. RM-4156

Research Joint Venture Agreement 00-JV-11221615

TITLE: Temporal and spatial variation in the fire regime at Monument Canyon RNA, Santa Fe National Forest, NM: Baseline data for fuel treatments and fire restoration.

Overview. The first major phase of our research project at Monument Canyon Research Natural Area (MCN, the phase supported under this Research Joint Venture Agreement (RJVA), has concluded successfully. The project was completed within budget and on schedule, and all project objectives fulfilled or exceeded. In this report we summarize the main accomplishments, especially those since the last report date or not previously reported, as well as completion of specific tasks enumerated in the RJVA.

Enumerated tasks. In the RJVA, §III.A, the Cooperator (the University of Arizona, Laboratory of Tree-Ring Research) agreed to:

1. ***Establish an intensive permanent plot sampling grid, layout plots and fuels transects with an emphasis on collection of fire scar samples at grid points across the MCRNA. Conduct pilot tree demographic sampling. Prepare fire scar specimens and conduct cross dating.***

Research site. We conducted our investigations of the fire regime at Monument Canyon Research Natural Area (MCN), Santa Fe National Forest, New Mexico. Fire history data were collected at the 280-ha Monument Canyon Research Natural Area (MCN), Jemez Mountains, New Mexico (Figure 1). MCN is located at lat 47° 16′38″ N, long 106° 37′ 30″ W; elevations range from 2,438-2,560 m (8,000-8,400 ft) AMSL. Topographically, MCN sits on the prow of a rising mesa system on the south margin of the Valles Caldera. Redondo Peak (3,428 m, 11,254 ft), visible to the north, is the highest of a system of emergent domes within the remains of a massive volcano that exploded most recently 1.2 MYA (Allen 2001). Soils at MCN are generally derived from consolidated tuff and other well-drained soils of volcanic origin.

MCN is near the upper elevation limit for Ponderosa pine dominance on mixed topography in northern New Mexico (Regional forest type 122.3, Petran Montane Conifer Forest) (Brown and Lowe 1980). As elevation increases above this level, and on northerly aspects, forest communities transition to mixed-confer types (121.3, Petran Subalpine

Conifer Forest). In MCN, mixed-conifer stands are found mostly on north-facing slopes and drainage bottoms.

Monument Canyon was among the first Research Natural Areas created in the United States (Peterson and Rasmussen 1985), and contains some of the oldest remaining *Pinus ponderosa* stands in the southwestern United States, including stands of Ponderosa pine more than 400 years old. The oldest living trees sampled to date in Monument Canyon germinated in the 1500s, and current research has identified many trees older than 450 yr (Touchan, Allen et al. 1996; Morino, Baisan et al. 1998). Remnant dead wood has been dated to the early 1300's. The site has a long human cultural history; elders of the nearby Pueblo of Jemez know Monument Canyon as *wa ha dóc wha*, "Place Where the Clouds Live". Given its age, size, and cultural significance, MCN ranks among the most significant extant old-growth Ponderosa pine stands in the Southwest.

Historically, surface fires burned on the mesas of Monument Canyon at low intensity, relatively high frequency, and considerable spatial heterogeneity (Touchan, Allen et al. 1996; Morino, Baisan et al. 1998). The natural fire regime has been absent for nearly a century due to the combined effects of grazing and subsequent fire exclusion in surrounding areas. As a consequence, large portions of the RNA are now covered by unnaturally dense thickets of small stems (in some areas, > 9,000 stems ha^{-1}), most of which are morbid and have little prospect of reaching the canopy. The dominant overstory trees have been adversely affected by increased root-zone competition, reflected in deteriorating vigor and increasing vulnerability to disease.

We established a gridded system of sample points 200 m on center throughout the entire 256 ha study area (Figure 2). To establish the grid system, we calculated point locations (UTM coordinates) prior to fieldwork, and then navigated to the pre-determined coordinates using GPS with real-time accuracy ± 7 m. Each georeferenced grid point is permanently staked with #3 rebar and identified with a numbered metal tag to aid future relocation. The use of a systematic sampling grid has been found advantageous when the study objectives include explicit control of area and scaling effects (Fulé, Covington et al. 1997; Heyerdahl, Brubaker et al. 2001). The total grid for the study area is 8 × 9 = 72 4-ha cells.

Fire scar sampling. We sampled in two phases, first collecting samples from 36 alternate grid cells (lag = 400 m); in the second phase, we collected specimens from an additional randomly-selected 14 cells to create areas of higher spatial resolution (lag = 200 m). The final sample covered 50 of the 72 grid cells (69% of study area) (Table 1). At collecting sites, we established a 0.5 ha (radius = 39.9 m) circular plot around the grid marker (Figure 3 a,b). We used these plots to define a fire-scar search area; the 0.5-ha plot also constitutes out minimum spatial resolution for reconstruction of fire occurrence patterns. Within the plot, we flagged all fire-scarred trees, and then selected up to 10 with the most complete visible record for sampling. Where fire-scarred trees were sparse at the grid location, we allowed the search area to expand slightly, but in no case were trees more than 50 m from the grid point. Where scarred trees of different age classes were present, we attempted to include samples of all age classes (Figure 4 a-g).

We collected fire scar samples from both live and dead trees. Dead trees included both snags (standing dead) and fallen logs. The inclusion of dead material tends to extend the temporal extent of a dendrochronological sample, in addition to minimizing the impact of sampling on old living trees in the study forest. Samples were extracted from standing trees by making parallel cuts into the trunk with a chain saw, perpendicular to the vertical axis, and then separating the specimen from the trunk with a "plunge" cut. This procedure allows removal of a portion of the scarred surface, while removing a minimum of cross-sectional area of structural significance to the tree. Samples from fallen trees were generally taken as full cross-sections. In some cases, two or more samples were taken from a single tree if the visible pattern of fire scars appears to change along the trunk axis. Samples were numbered, marked and wrapped in the field. All trees are permanently marked with metal tags at ≈ 2 m height facing the grid point. Fallen trees are tagged near the base where wood is most sound. The location of each sampled tree was measured as distance (m ± 0.1 m) and bearing (° mag ± 1 °) from the grid point. Each tree was identified (if possible) to species, and its diameter measured: dbh preferentially; otherwise, diameter at stump height, 50 cm above the tree base (dsh); otherwise, diameter at the root crown (drc). We developed site- and species-specific regression equations to convert dsh and drc to dbh.

All field methods are described in ***Field Sampling Protocols for Fire History and Tree Demography*** (Figure 5).

Laboratory methods. Specimens were cut laterally with a band saw to expose the surface with the most complete fire scar record. Fragile specimens were glued to plywood bases for permanent stabilization. Each specimen was examined, numbered, and recorded in a computerized database (Table 3). All specimens are organized and stored at the LTRR and are available to other researchers.

In the laboratory, each specimen was dried and sanded to a fine finish (400x) so that individual xylem cells were visible under a dissecting microscope. We crossdated specimens initially to master ring-width chronologies from nearby studies, (Douglass 1941; Madany, Swetnam et al. 1982; Swetnam, Thompson et al. 1985; Stokes and Smiley 1996), generating a chronology specifically for MCN. Specimens were completely crossdated from innermost to outermost rings to create maximum temporal extent of the site-specific ring-width chronology (Figure 4 h).

We dated fire lesions to year by identifying the annual ring in which the injury occurred (when possible, we determined the season of fire by position of the scar within the earlywood-latewood progression, although we do not include analysis of fire seasonality in this study). Fire scars are generally distinct from other forms of injury such as mechanical breaking or scraping, insect wounds, or frost damage (Ryan 1982; McBride 1983; Dieterich and Swetnam 1984; Gutsell and Johnson 1995). Lightning and fire damage can sometimes be difficult to distinguish; accordingly, injuries found only on a single tree were examined for other characteristic evidence specific to fire damage. Fire scars that could not unambiguously assigned to a single year (*e.g.*, where the lesion was not clearly within a single year's growth, or areas of wood deterioration) were held aside in the initial analysis, and were not used to establish a fire date unless at least one other tree in the immediate area recorded the same date.

Ponderosa pines often do not begin to record surface fires consistently until after an initial wound exposes the cambium and creates a region of thinner bark. In addition to localized fire injury, the initial wound can be caused by lightning or mechanical damage. For this reason, we did not count the initial scar on a tree as definitively of fire origin unless other trees in the area also recorded the same date (Grissino-Mayer 1995). Once damaged, trees tend to record fires at a higher rate because of exposure of the cambium, thinner bark on the healing curl, and higher concentrations of resin mobilized into the wound. Trees that have recorded an initial event that creates higher susceptibility are considered "recording" regardless of the cause of the initial wound.

We recorded the dates of inner and outer rings, and of fire and other injuries, in the analysis program FHX2 (Grissino-Mayer 1995; Grissino-Mayer 2001). FHX2 creates a discrete time series of fire events for each specimen in a set, tabulates events according to rules of selection, and computes many widely used statistical measures of fire regimes. These files were then compiled into a series of nested composite files for scaling analysis (Table 2).

Results. We sampled 198 fire-scarred trees in 50 grid cells distributed across the study area (Table 4), and 16 trees from locations outside the grid network, for a total collection of 214 trees. This makes MCN one of the most intensively sampled fire history study sites in the southwest.

The *Appendices* to this report include detailed research reports derived from analysis of these field collections.

2. ***Complete analysis and documentation of fire spatial and temporal relationships.***

Following crossdating and identification of fire years, we entered fire data into a widely used fire analysis program, FHX v2.0 (Grissino-Mayer 1995; Grissino-Mayer 2001). FHX2 files are provided to the RMRS as an attachment to this report. Samples were dated to year and season (dormant; early, middle, and late earlywood; latewood) whenever the condition and position of the fire scar permitted.

Because individual trees do not record (or retain the record of) every fire, we created a composite fire record (CFR) for each sampled grid cell, by combining the fire dates recorded by any tree within the search area into a superset. The grid cell was considered to be recording when at least one tree was in a recording condition, although we also analyzed fire dates using higher percent scarred thresholds. We determined sample size as a function of both the number of trees, and the number of grid locations, that were recording in any given year during the fire record.

See *Appendices* for results of fire history analysis for two research questions, scaling properties of the fire regime and the effects of sample size on fire history reconstruction.

2. Download global positioning system files, and develop a geographic information system that includes output of plot and sampling locations with background coverage of resource data layers from the Santa Fe National Forest.

We have established a project GIS database including layers for topography (Digital elevation model), roads and streams, land ownership, and vegetation. To these we added a data layer consisting of the grid point locations (Table 5). All points are permanently marked and the grid system is available for use by other researchers.

3. Collaborate with the Forest Service in developing a fuels treatment design and conduct intensive pre-fire baseline sampling.

MCN is now scheduled for fuel treatment and commencement of a regular program of prescribed burning beginning in 2004. The LTRR has the lead role for design and monitoring of these treatments and treatment effects. See the enclosed *Restoration Field Sampling Methods* (Falk 2003) (Figure 6) for a summary of field methods.

One of our ongoing interests lies in the effects of fine-scale heterogeneity in the fuel and fire environment. Using the same plot system established in the earlier phase of the project, we have recorded data at multiple scales from 1-m^2 resolution of fuels and understory data to the nested grid cell system covering the entire 260 ha study area. Data collection protocols include sampling for tree composition, density and basal area; litter and duff depth, bulk density, and biomass; tree seedling demography; understory composition and biomass; crown base heights and top of live crown; overstory tree condition and demography; canopy coverage; and other variables.

In collaboration with the SFNF-JRD (Jemez Ranger District), we established and sampled fuels transects and the full restoration baseline protocol at fifteen MCN grid locations, adapting standard USFS protocols for measurement of fine-scale heterogeneity (Brown, Oberheu et al. 1982; Keane and Lutes 2002) in 2003. These sites will be monitored again prior to mechanical treatments and following prescribed burning.

Additional deliverables. The following additional deliverables were included in the original proposal to the Joint Fire Science Program:

1. ***Detailed research study plan.*** We provide with this report a copy of our *Field Sampling Protocols for Fire History and Tree Demography* (Falk 2000) (Figure 5), which have evolved during implementation of this project. These protocols outline the methods used in a plot-based study, although they can be adapted to other applications as well (such as plotless or targeted sampling methods).

2. ***Ph.D. dissertation research, University of Arizona (D. Falk).*** Advanced to candidacy in Ecology & Evolutionary Biology March 2000. Dissertation chapters currently in Committee review, final defense anticipated January 2004 (Falk 2004). Dissertation Committee: T. Swetnam, L. Venable, and R. Robichaux, University of Arizona; W. Covington, Northern Arizona University; L. Graumlich, Montana state University.

3. ***At least one published paper in peer-reviewed journals, books, or Forest Service Technical Report.*** We have published five papers in peer-reviewed publications and one edited book with support from this grant. The PI's are co-authors on a framework paper on forest restoration principles and practices (Allen, Savage et al. 2002). The main purpose of this paper was to outline a series of principles that can be used to guide forest restoration, particularly in the Southwest, with the intention of encouraging experimentation with a wide range of treatment combinations and intensities. This paper has been cited twice in other refereed journal papers in the last year (Parrish, Braun et al. 2003; Rieman and Luce 2003).

   A second technical paper (Falk and Swetnam 2003) summarizes the results of our research into the scaling properties of fire regimes, and the use of probability models to generalize the variable behavior of fire regimes in space and time.

We have also published a series of papers on fire-climate relationships (Swetnam 2002; Swetnam and Baisan 2003; Veblen, Baker et al. 2003; Westerling and Swetnam 2003), which was the subject of the March 2002 workshop on fire and climate history in the Americas, supported in part under this RJVA.

4. ***MCRNA research database, archived as hard copy and on digital media, provided to RMRS. Database will ingrate relevant previous research efforts at MCRNA.*** With this Report we provide the following data sets:
   a. Locations (UTM) of all grid point sampling locations.
   b. Summary of collections by grid location.
   c. Specimen database (trees).

   FHX files of fire dates for individual grid locations, and nested composite files from the scaling analysis, are available for RMRS or JFSP researchers.

5. ***Presentation at one professional or scientific society meeting, and one workshop for Forest Service or other Federal land managers.*** Outreach and technical transfer of research findings are central to our mission at the LTRR. The PI's (Falk, Swetnam) have made numerous presentations at professional and scientific meetings, and workshops for Forest Service and other public agency personnel, including the following (partial listing):

2000

- National Conference on Fire Ecology & Management, Joint Fire Science Program and cooperators, San Diego, CA
- Monitoring Riparian Ecosystems, Rincon Institute and University of Arizona, School of Renewable Natural Resources
- Research Directions Workshop, Ecological Restoration Institute, College of Forestry, Northern Arizona University
- Joint Fire Science Program, Principal Investigator Workshops (2000-3)
- Presentation on fire history in SE Arizona to Malpais Borderlands ranchers group, annual science workshop, Douglas, Arizona
- Weaver Lecture at Auburn University, School of Forestry, Auburn, Alabama
- Presentation on fire history and fire ecology in western United States at Jones Research Center, Alabama, January 21
- Continuing Education in Ecosystem Management course at Northern Arizona University School of Forestry
- CLIMAS group at ISPE, on fire and climate in the SW
- "Fire and Climate 2000" for approximately 50 scientists and land managers from throughout western US and Florida, held at ISPE
- University of California, Davis on fire history and climate
- Ecological Society of America meeting in Snowbird, UT, co-author of symposium paper
- Forest fires and forest restoration lecture, Environmental Law class, Arizona State University Law School
- Fire and climate variability, Annual meeting of Southwestern Fire and Fuels Managers, Flagstaff, Arizona

2001

- EEB Noon seminar ("Spatial and temporal variation in Ponderosa pine fire regimes: Applications of dendrochronology")
- Society for Ecological Restoration Joint Annual Meeting, Niagara Falls, Ontario ("Determining temporal reference conditions and natural variability for ecological disturbance processes")
- Fire-Climate Workshop, Institute for the Study of Plant Earth, University of Arizona
- Biology Careers Day, University of Arizona
- Stanford University, on Forest Fires and Climate in Western US
- Organized and hosted a workshop (2nd year, with Barbara Morehouse, Gregg Garfin and Tim Brown) on "Fire and Climate 2001" for approximately 70 scientists and fire managers from throughout western US, held at ISPE
- Co-hosted and presented a talk at one-day "Fire-Climate in the Southwest" meeting, UA campus
- "Fire and Climate in the Southwest", Los Alamos National Laboratory
- University of California, Berkeley, Wildfire Seminar Series

2002-3 (partial listing)

- Organized and directed "Fire in the West" workshop in collaboration with CLIMAS, Tucson, AZ
- Organized, hosted, and presented at Paleofire History Workshop for about 70 participants from North and South America, March 23-28, Tucson, AZ
- Sky Island Islands conference on fire in the Southwest, Tucson, AZ
- Conference on Fire, Fuels, and Ecological Restoration, Colorado State University, Ft. Collins, CO ("Scaling properties in a frequent-fire regime)
- Ecological Society of America/Society for Ecological Restoration Joint Annual Meeting, Symposium, Adaptive Management Experimentation in Ponderosa Pine Restoration, and Concurrent session, Fire Ecology: Trees, Forests and Woodlands
- Fire Sciences Laboratory, Missoula, MT
- Two invited lecture/seminars at Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
- Department of Biology, University of North Carolina, Chapel Hill
- Southwest Fire Initiative Conference, Ecological Restoration Institute, Northern Arizona University ("Toward process-centered restoration: Temporal variability as the reference envelope")
- Ecological Society of America, Concurrent session on Fire Ecology: "Scaling rules for fire regimes." Savannah, GA

6. Active engagement of research community in MCRNA fire restoration and prescribed burn plans; stronger linkage between research effort and ecosystem restoration and management. Several Federal agencies have been close partners in our research at Monument Canyon RNA. The Santa Fe National Forest has been the principle partner throughout the project, assisting in the planning and design of the initial research. Staff of the Jemez District provided an initial orientation to the site, and facilitated our field research in every year. The fire management staff of the District was particularly helpful in sharing their extensive knowledge and understanding of the fire regimes of the Jemez Mountains.

As the research plan progressed from fire history to planning for fire restoration research, staff of the District and the Forest has continued to play an important role. The restoration phase of Monument Canyon research is funded separately by the

Collaborative Forest Restoration Program (CFRP). We have developed sampling methods for baseline data collection for ecological restoration, including thinning and prescribed fire treatments (Falk 2003) (Figure 6). Together these protocols offer a repeatable methodology for quantitative assessment of pre-treatment forest condition, treatment effects, stand conditions, and fire history.

Collaborations: Core collaborations on the project continue to include the SFNF, SFNF-JRD, USGS-BRD-Jemez Mountain Field Station, and USFS-RMRS. During 2000 the PI's established additional cooperation with the Jemez Pueblo, located near the research site. Forest Trust, in conjunction with the Jemez Pueblo, has provided Youth Conservation Corps (YCC) crews to assist with fieldwork.

Falk served (2001) on a review panel for proposals to the Federally-funded Southwest Fire Initiative coordinated by the Ecological Restoration Institute, College of Forestry, Northern Arizona University. The review panel evaluated proposals submitted for funding under the RFP for this innovative program designed to advance scientific knowledge of forest restoration. He also worked as a mentor for undergraduate students for the Columbia University Earth Semester. Earth Semester is a residential immersion program centered at BioSphere II in Oracle, AZ (2000-1). The Spring 2001 ES student assisted with data entry and analysis, and preparation and dating of MCN specimens from one grid point. The resulting project and poster was given a Research Award at the Earth Semester commencement in May 2001. In April 2001 the National Science Foundation awarded a Doctoral Dissertation Improvement Grant to DAF. The DDIG is given in recognition of outstanding potential for a dissertation to contribute to basic understanding in its field. In 2003 he was invited by Gov. Janet Napolitano to serve on the Arizona Forest Health Council. He is the 2003 recipient of the Edward S. Deevey Student Award in Paleoecology, given by the Paleoecology Section of the Ecological Society of America for the best oral or poster presentation in paleoecology by a graduate student at the annual meeting of the Society.

Swetnam presented invited testimony to US House of Representatives, Committee on Natural Resources, on Forest ecosystem health and restoration in Washington, DC and at a field hearing Albuquerque, NM (2000). He was appointed by President William J. Clinton to serve as a member of the Board of Trustees, Valles Caldera National Preserve. In 2001 he received the W. S. Cooper Award, Ecological Society of America, with J. L. Betancourt, for outstanding paper in geobotany and physiographic ecology (1998, *J. Climate*), and in 2002 received the Henry Cowles Award from the Association of American Geographers, Biogeography Specialty Group, with J. Speer, B. Wickman, and A. Youngblood for outstanding paper in biogeography (2001, *Ecology*). He serves currently as Program Chair for the Ecological Society of America for 2003-4. In 2003 he was invited by Gov. Janet Napolitano to serve on the Arizona Forest Health Council.

Ongoing support of this project by the University of Arizona Laboratory of Tree-Ring Research and the Department of Ecology and Evolutionary Biology, in the form of laboratory, computer, and administrative facilities, staff assistance, and faculty interactions, is gratefully acknowledged.

Appendices

In the Appendices we present the results of our research in two areas:

1. ***What are the scaling properties of fire regimes, and how does this affect management of fire as an ecosystem process?***

Fire regimes can be characterized by a variety of metrics that allow quantification of their properties in space and time, as well as characteristics of fire as a biophysical process. Common metrics of the temporal distribution of fire events include fire frequency and the time intervals between fires. Each of these can be characterized not only by mean values, but also by the distribution of vales about the mean, which provides a measure of the variability of fire regime in time. Common spatial measures include area within a perimeter, proportion of area burned within a fire perimeter, patch size, contiguity, and other measures. Again, both the mean and the distribution about the mean can be estimated for each of these spatial metrics, and the distribution expresses the spatial variability of fire as a process. When spatial and temporal variation are considered together, the scaling properties of the fire regime can be expressed.

Scaling in ecological research refers to a systemic change in a variable along a dimensional axis, such as mass, length, area, volume, or time. In the case of the fire regime, we can ask whether the measures used have the property of scale dependence, or alternatively whether they are scale-independent or scale invariant. If an ecological measure is scale-independent, then it is not necessary to correct for the scale of observation when reporting or interpreting a statistic. On the other hand, if a measure is scale-dependent, then either scale correction is necessary, or at least reporting of the scale of observation.

A more extensive treatment of this topic is found in Falk (2004).

2. ***What are the effects of sample size on fire history reconstruction?***

Fire history research requires the reconstruction of ecological events that occurred in the past, using evidence that survives to the present. We can calibrate this evidence of past events with contemporary observations, for example by observing the processes of ring growth or fire scar formation under known conditions. However, as in any paleoecological reconstruction, any individual remnant evidence represents an incomplete picture of the events and conditions at the time of their creation.

Fire scar formation and retention thus reflect a variety of stochastic processes. First there is the variable behavior (rate and direction of spread, duration at any point) and intensity of a fire, which is influenced by a number of factors including fuel depth (biomass), bulk density (mass volume^{-1}), and moisture; temperature, speed, direction, and relative humidity of air masses; and local topography (Finney 1993; Agee 1996; Finney 1999; Saito 2001; Ward 2001). Second, a variety of tree variables, particularly bark thickness, height to live crown, rooting depth, and vigor influence tree-level response to local fire (Gill and Ashton 1968; Loehle 1988; Ryan and Reinhardt 1988; Reinhardt and Ryan 1989; Ryan 1990; Gutsell and Johnson 1995). Third, a set of contingencies affects the retention and preservation of lesions, including saturation of the scar by resin, subsequent burning, mechanical damage, and wood decomposition. Finally, the frequency of fires over a period of years is influenced by spatial distribution and production rates of fine fuels and interannual climate variation. The net result of these factors is that any given tree may retain a record of only a portion of the fires that occurred in its proximity. The evidence from a single tree provides an accurate, but incomplete, record of fire events.

The probabilistic nature of a sample of multiple trees in a stand is the basis for the common practice of forming a composite fire record (CFR) (Dieterich 1980). The CFR is the superset of events recorded on any tree in a collective sample; thus, it is correct to assert that the CFR represents events recorded by at least one tree *somewhere* within the area in which the sampled trees are located (but not that every event detected occurred *everywhere* in the area sampled). The CFR can be used to estimate statistics of the fire regime, such as mean, median, or modal fire interval (the mean fire interval calculated from a CFR is commonly referred to as a Composite Fire Interval, CFI) (Dieterich 1980). Inferences based on the CFR have the advantage of replication by independent experimental units (trees), particularly if the trees are drawn from relatively homogeneous conditions with respect to factors (such as topographic setting) that influence fire spread and intensity. In this research we tested the effects of sample size on estimation of metrics of the fire regime, including the effect of the number of trees as well and the number of sampling sites within a study area.

A more extensive treatment of this topic is found in Falk (2004).

Attachments, Figures, Tables, and Literature Cited.

(See additional figures and tables in *Appendices*.)

Figures.

1. **Map of Jemez Mountains study area land ownerships.** Monument Canyon RNA (MCN, in yellow) is located to the southwest of the Valles Caldera National Preserve in the southwestern Jemez Mountains, New Mexico.
2. **Sampling grid at MCN.** Red dots are grid locations (lag distance = 200 m). See Table 5 for UTM coordinates.
3. **Plot layout in MCN study area.** *a.* Circular 0.5-ha plot used for fire scar collection at each sampled grid point. *b.* Square 0.25-ha plot showing nested plot series of 0.1- and 0.01-ha subplots.
4. **Field sampling and laboratory forms.**
5. ***Field Sampling Protocols for Fire History and Tree Demography.*** Details of field methods and protocols used in fire history and forest demographic sampling. These methods are available to be adapted by other research projects.
6. ***Restoration Field Sampling Methods.*** These methods are developed specifically for joining a local fire history and ecological baseline data to a thinning and fire restoration program.

Tables.

1. **Summary of sampled grid locations at MCN study area.** 50 grid locations were sampled for fire history (*FS*), 30 for the nested plot series for forest structure and demography (*.25 - .01 ha plots*). Fifteen sites are being monitored weekly for understory phenology and fine fuel dynamics (*understory*), and to date 14 plots have pre-treatment baseline data for thinning fire and restoration (*2003 protocols*).
2. **Grid point fire history analysis summary and nested plot series analyzed at MCN.** Fire history analysis details showing creation of FHX files, output reports, and grid-cell scale composites (see *Appendices*). All files are available to RMRS and JFSP researchers.
3. **Fire history specimens at MCN.** Specimens were crossdated and fire dates analyzed at the LTRR, and are maintained as an archive for use by RMRS and JFSP researchers.
4. **Summary of collections and temporal extent of fire history at sampled grid points.** For each grid cell, the table lists the number of trees sampled, and a summary of temporal extent for the composite fire record (CFR) composed of all trees at the site, including inner and outer ring dates, total extent of the tree-ring record, and earliest and latest fire dates.
5. **UTM coordinates of permanent sample points at MCN.** Locations are shown as UTM coordinates. All points are permanently staked with #3 rebar and a numbered metal identifying tag.

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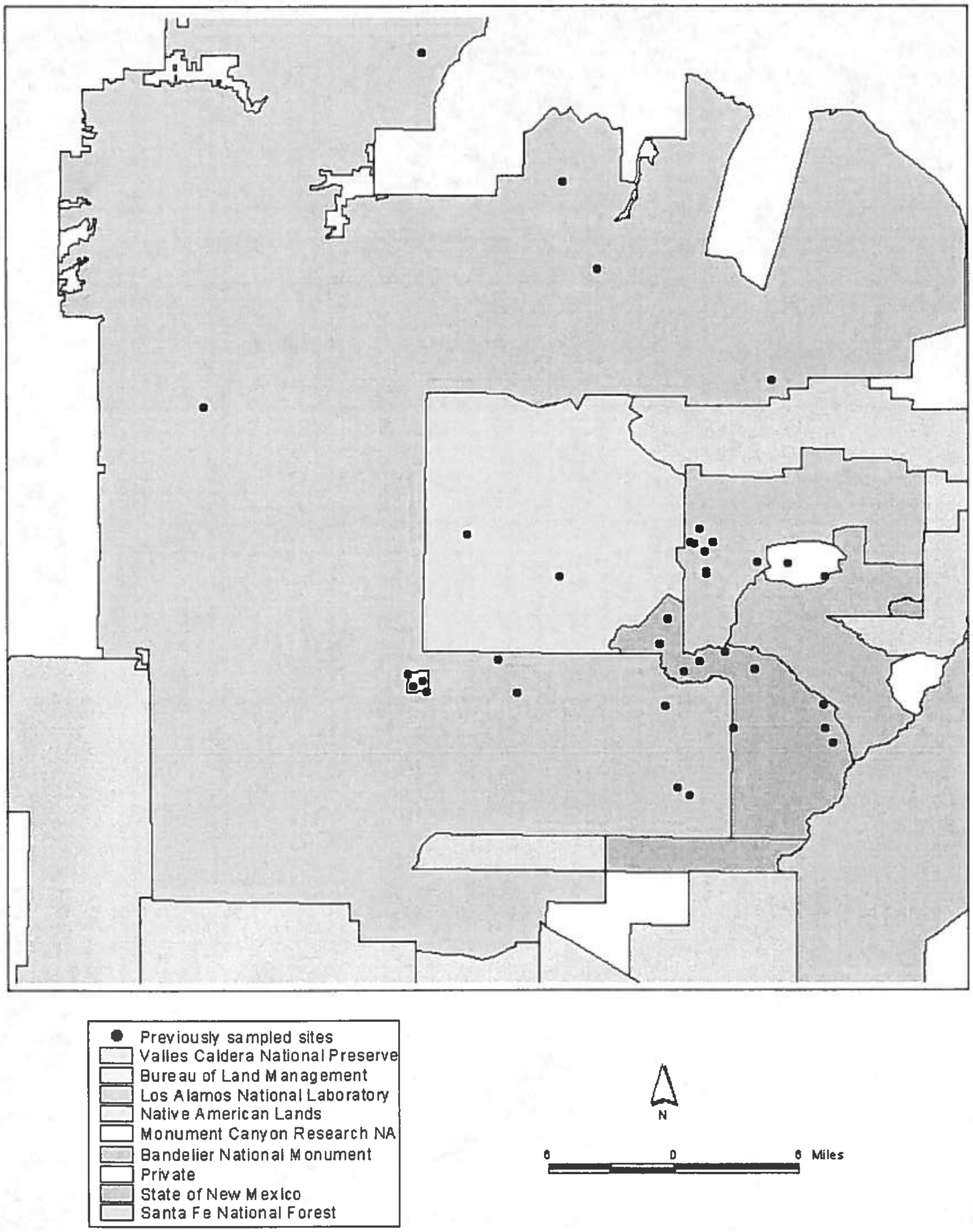


Falk & Swetnam. Figure 1.

Fig 2.

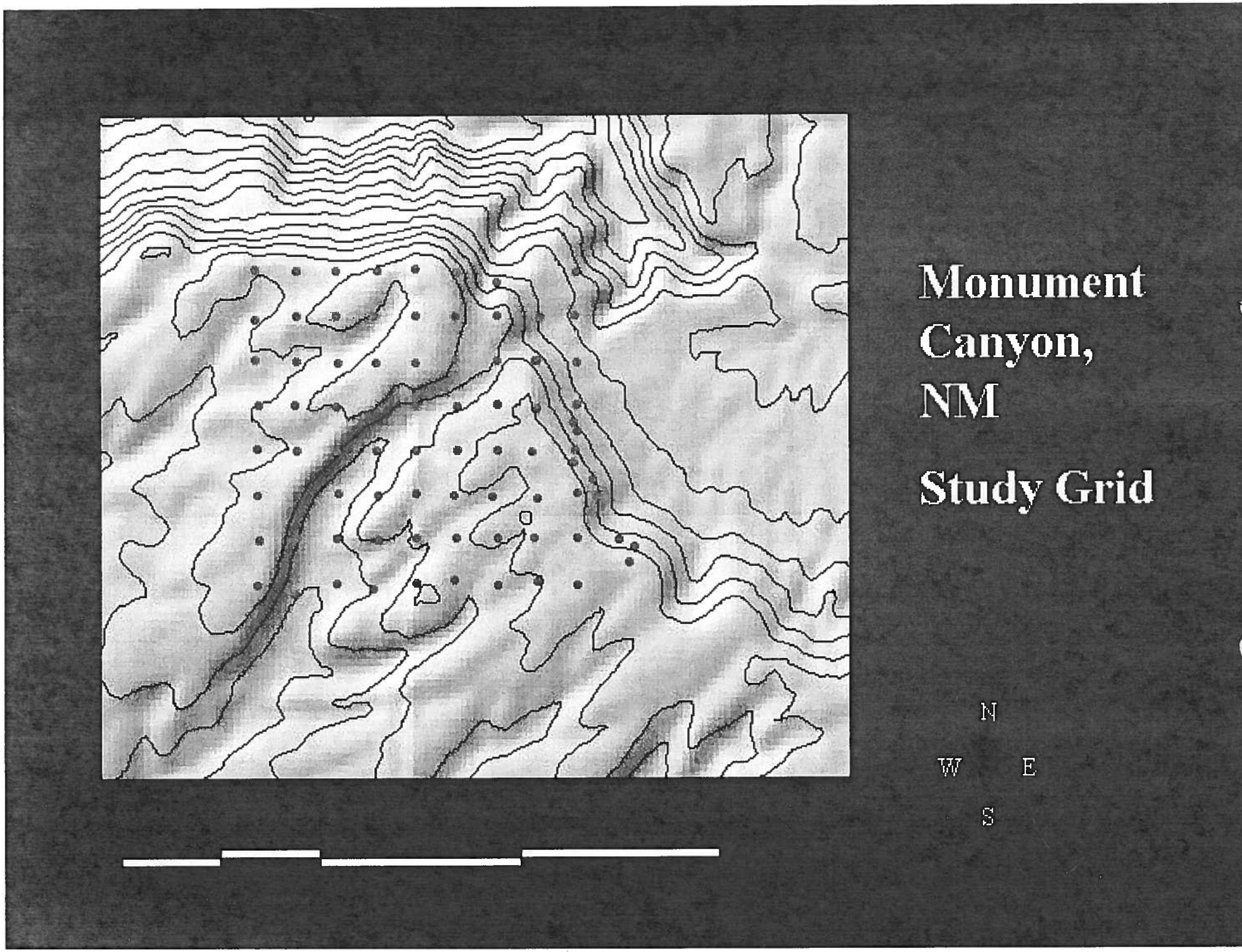
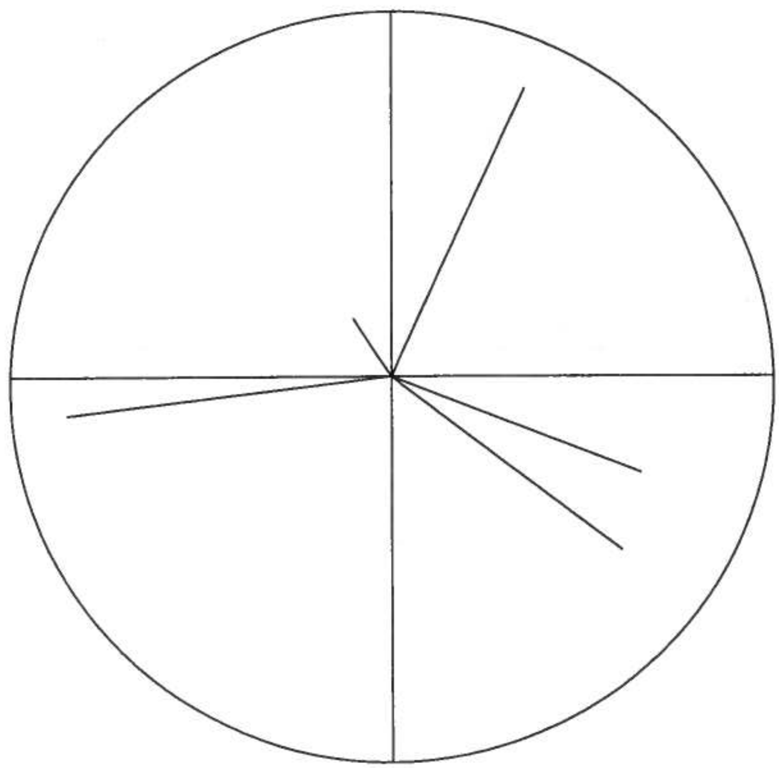


Figure 3.

a. Schematic of fire-scar collection area. Area is centered on grid point; radius = 40 m (area ≈ 0.5 ha).



b. Schematic of nested plot layout. Large square is 0.25-ha (50 m x 50 m) overstory size/density plot, centered on grid point. Nested 0.1-ha (20 m x 50 m) overstory age/spatial structure plot runs parallel to contours. Four possible locations of 0.01-ha (10 m x 10 m) subplots are centered within overstory plots. Dashed lines indicate tape layout.

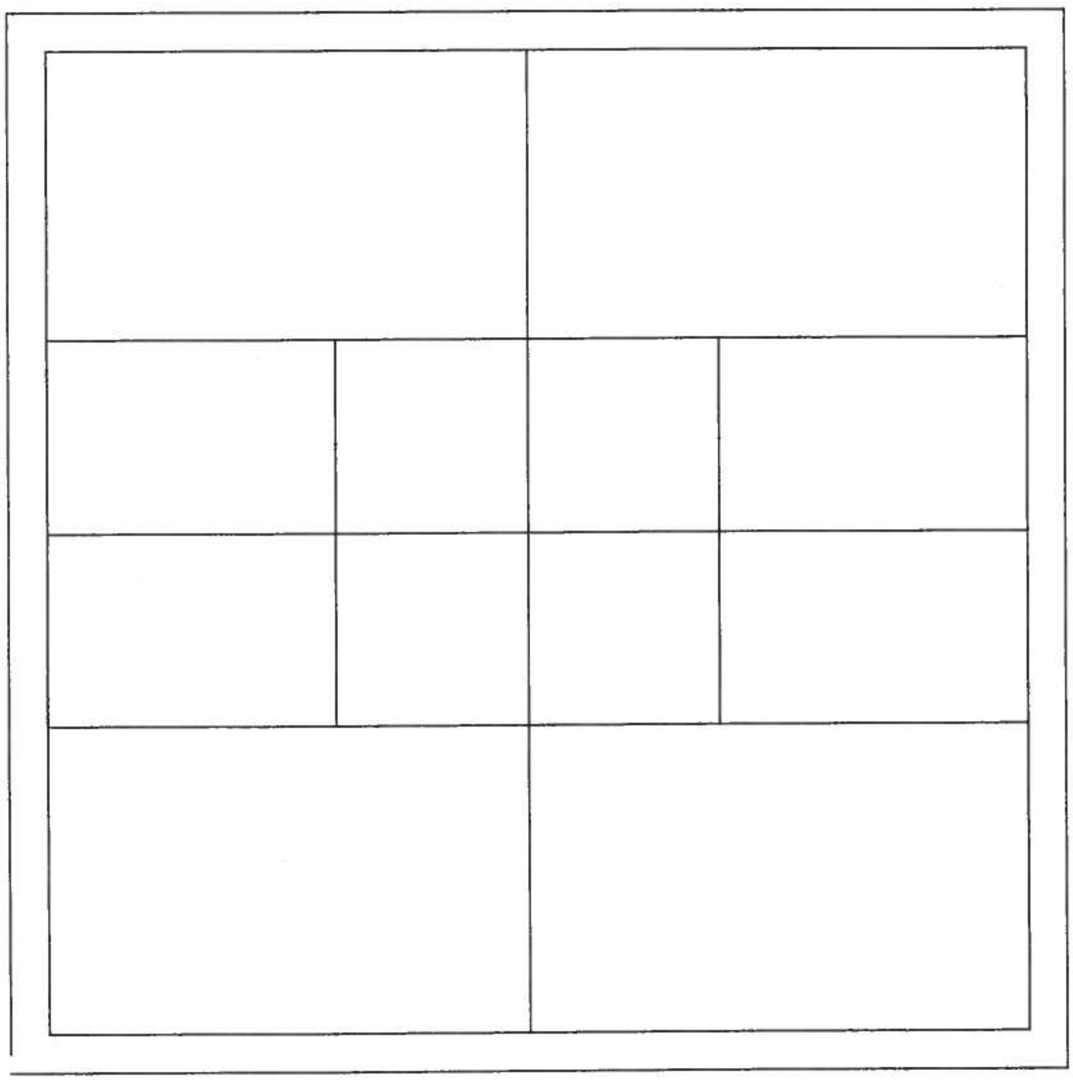


Fig 4

Monument Canyon Research Project
Field Data Form A
200-m Grid Point and .5-ha Fire Scar Search Area

GRID POINT

Date(s)	Page	of

Name(s)

UTM Easting	Northing	Actual? Y N

Start times	End times

GPS waypoint(s)	Search radius (m)

Slope (%)	Aspect (°M)	Stand conditions:

Marked tree # _________

Tag	Species	GPS waypoint(s)	Plot map

Bearing from grid point (°M)	Distance from grid point (m)

DBH/DSH/DRC (cm)	Condition: Live / E G F P Dead / S F P / F B L I R

# Fire scars	Scar CX

Core number, height (cm), side (°M):

# Sections collected	LTRR Section Data Form? Y N:

Marked tree # _________

Tag	Species	GPS waypoint(s)	Plot map

Bearing from grid point (°M)	Distance from grid point (m)

DBH/DSH/DRC (cm)	Condition: Live / E G F P Dead / S F P / F B L I R

# Fire scars	Scar CX

Core number, height (cm), side (°M):

# Sections collected	LTRR Section Data Form? Y N:

Monument Canyon Research Project
Field Data Form FST
Fire-Scarred Tree Microtopography

Date	Page	of

Name(s)

Grid Point	Tag	Species	Slope	Aspect	Side topog	Down topog	Position	Notes
No.	No.	Code	(%)	(° M)	Code	Code	Code	

Topography:
C Concave
F Flat
V Convex

Position:
V Valley bottom
L Lower side slope
M Mid side slope
U Upper side slope
R Ridge top

Monument Canyon Research Project
Field Data Form OS
.25-ha Overstory Size/Density Plot (50 m x 50 m)

Grid point Date Page of

Name(s)

UTM Easting Northing Aspect (°M)

Photo # Grid pt. N E S W Data check Gear check

Tag	SP	Coord (x, y)	Dtype	Diam	CX	Mto	Scar #	Scar CX	Notes
No.	Code	0.1 m	Code	0.1 cm	Code	1-6	No.	EGFP	

Monument Canyon Research Project
Field Data Form C
.1-ha Overstory Age/Spatial Plot (20 m x 50 m)

Grid point	Date	Page	of

Name(s)	Long axis ⊥ aspect? Y N:

Data check	Gear check

PIPO ≥ 25 cm dbh or other species ≥ 20 cm dbh:

Tag	SP	Coord (x, y)	D type	Diam	Core #	Core Ht	Core side	CX	Mto	Ht to DC/LC/TC/TL	Notes
No.	Code	0.1 m	Code	0.1 cm	A-Z	0.1 cm	U/S/D	Code	1-6	0.1 m	

Monument Canyon Research Project
Field Data Form CA -- Continued
.01-ha Contemporary Age/Size Sub-plot (10 m x 10 m)

Grid point	Date	Page	of

Trees ≥ 2.5 cm dbh *and* ≥ 1.4 m ht:

Tag	Species	Coord (x,y)	D type	Diam	Core/ sec #	Core Ht and side	Ht to DC/ LC/LT/TL	CX	Mto	Notes
No.	Code	0.1 m	Code	0.1 cm	A-Z	0.1 cm, U/S/D	0.1 m	Code	1-6	

Monument Canyon Research Project
Field Data Form TSM
Tree seedling measurement

Grid point **Date** **Page** **of**

Species	Height to crown	Height to tip	Diam.	Root depth	Bark thickness	Notes
Code	0.1 cm	0.1 cm	mm	0.1 cm	0.1 mm	

Monument Canyon Research Project
Understory biomass measurement
Form UB

Session: ____ **Page:** ____________

Nearest grid point	Date	Species	Cover	Collector	Notes
		Code	cm^2	Name	

Specimen ID: MCN ______________	**Inner Year:** __________ **Type:** ________
Grid point: ______________	
Collection Date: ______________	**Outer Year:** __________ **Type:** ________
Species: ______________	

Dated by:	**Date:**
Checked by:	**Date:**
FHX Entry by:	**Date:**

Comments, notable years:

☐ **NONRECORDING PERIODS:**

#	Year	Scar Type	Season	Accuracy /Alt Yrs	Comments
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Monument Canyon Research Project
Field Sampling Protocols for Fire History and Tree Demography
Rev. 5/28/00

200 m centered grid and .5-ha fire record sampling area

A. Establishing a grid point marker.

1. Select pre-computed UTM coordinates for grid point.
2. Navigate by GPS to coordinate point in field.
3. Average ≥ 100 GPS coordinate readings to maximize accuracy; record actual averaged coordinates (easting, northing) on data sheet, and correct waypoint in GPS unit.
4. Place, tag, and spray paint permanent plot stake.
5. Mark stake and two trees on either side of point with orange flagging, using enough flagging to allow good visibility and movement in wind. Write grid point number on tree flags.
6. Record slope (%) and aspect (°M).
7. Describe stand conditions briefly.
8. Collect and inventory gear. Perform data check.[1]

EQUIPMENT NEEDED:
Data forms (200-m Grid Point, first sheet) and holder
Rebar stakes, preferably ≥ 12 cm (30")
Tags, wire, and nails
Hand sledge
Pliers with wire-cutters
GPS, extra batteries
Orange flagging
Large marker
Sighting compass
Clinometer or laser rangefinder
Obnoxious orange spray paint
(Umbrella)

B. Fire scar search.

1. Establish a search radius of 40 m from the grid point, using 2 100-m tapes laid out in a cross, creating a circular plot of ≈ .5 ha, or by measuring distance to individual trees.
2. Search the sampling area for the best-recording fire-scar trees within the search radius. The search should include all dead (standing and down) material.[2] If many trees are scarred, mark up to a dozen samples.

---

[1] Someone other than the recorder should check data sheets before leaving site.
[2] Dead trees may represent older age classes; they are also at greater risk of being destroyed in the next fire.

3. Mark and temporarily number each tree with yellow flagging (apply a metal tag so that it can be removed later, if the site is not to be collected immediately) on the side of each tree facing the grid pin, and record:
   a. Tag or tree number,
   b. Location (GPS waypoint, map location, or bearing (° M and distance from grid point to nearest 0.1 m),
   c. Species,
   d. DBH, DSH, or DRC (0.1 cm),
   e. Number and condition of visible fire scars,
   f. Tree condition code,
   g. Notes.
4. If mesotopography (*i.e.*, the scale of the .5-ha search area) is significantly non-uniform (*e.g.*, a cliff or road within the area), sketch the main topographic features to scale on a Plot Diagram sheet.
5. Collect and inventory gear, perform data check. Record end time.

EQUIPMENT NEEDED:

Data forms: 200m Grid Point (first and second sheets) and holder
Plot diagram sheet
Tree condition code key
Yellow flagging
Sighting compass
GPS, extra batteries
2 DBH tapes
2 claw hammer
2 100 m tapes
3 50 m tapes
6 tent stakes
Tags and nails
(Laser range finder)

C. Fire scar collection.

1. Collect a section or other appropriate sample from the 3-5 best-recording trees.[3]
2. Complete the MCN data form (number and condition of visible fire scars, number of sections collected) and LTRR Section Data Sheet for each specimen, including a detailed drawing of the sample.
3. Permanently tag each tree from which a section is collected.
4. Wrap each specimen with packing tape to protect the fire-scarred surface, and mark with the tag number. ("MCN ###").

---

[3] The purpose of collecting scars from two or more trees is to increase sample depth for the time period they cover. Additional trees may be sampled if they will increase temporal coverage of the fire record (*e.g.* very old trees); it's desirable to locate additional specimens of similar age at the location. If in doubt, collect dead material, which may be relatively old (extending the temporal range of the record) and valuable. Limit sampling from live trees to the minimum necessary to document the site, and do not fell live trees unless unavoidable.

5. If time allows, take photos of each tree from which a section is collected (before and after is even better), as well as the section itself. Identify specimens with numbered cards in photo.
6. Collect and inventory gear, perform data check. Record end time.
7. At the end of each day, inventory all sections collected against the completed data sheets.

EQUIPMENT NEEDED:

LTRR section forms
MCN data forms (200-m Grid Point, first and second sheets)
Chainsaw and accessories
Markers
Packing tape
(Camera and film)
Photo cards

1-hectare intensive fire-sampling cells (100 m x 100 m = 10,000 m^2)

1. Locate pre-selected grid corner and cell orientation using map, compass, and GPS.
2. Tape or flag sides, using physiographic and land-use (roads, RNA boundary) features for convenience. Flag and GPS corners.
3. Systematically cruise cell, in strips of no more than 20 m (see *Group Search Procedures*).
4. For all fire-scarred objects, apply a metal tag and record:
   a. Unique identifying number,
   b. Location (GPS waypoint, map location),
   c. Species,
   d. DBH, DSH, or DRC (.1 cm),
   e. Height (.1 m),
   f. Scar location (if any), and approximate compass bearing (° M).
   g. Number and condition of visible lesions,
   h. Tree condition (code),
   i. Notes.
5. If a section or other appropriate sample is extracted, complete LTRR Section Data Sheet.
6. If a core is extracted, record coring side and height on data sheet.
7. Collect and inventory gear. Have someone other than the recorded check data sheets. Record end time.

If sampling area is defined by topographic or other features rather than pre-established grid points, area sampled will be computed during GIS analysis.

NESTED PLOT SERIES

.25-hectare overstory size/density plots (50 m x 50 m = 2,500 m^2)

1. Record start time, and locate a pre-selected grid point.
2. Record slope and aspect if not already on 200-m Grid Point Data Form.
3. Tape off 50 m x 50 m plot. Start by creating a cross with two 50 m tapes centered on the grid point, one following the aspect line and one directly across. Temporarily anchor a 100 m tape at the end of each of the two tapes on downslope and left sides (when facing upslope), and pull them 25 m toward the lower-left corner. Align the two tapes so they meet at exactly 25 m and anchor the corner. Now pull the tapes along the sides, following the aspect or cross-aspect bearing. At 50 m place a pin and turn to outline the second side of the plot, taking care to align the plot sides parallel and perpendicular to the slope contours. The tapes should meet in the upper-right corner at their 100 m points. Flag and GPS (or map) corners.
4. For *all*:
   a. Standing trees, snags or fallen logs of any species ≥ 30 cm DBH,
   b. Scarred trees, or
   c. PIPO with old-growth morphology (see *Old-growth characters*),

   tag on the side facing the grid pin and record:
   a. Tag number,
   b. Species,
   c. Number and condition of fire scars (if plot is in previously-surveyed 1-ha cell, these will have already been recorded),
   e. Plot coordinates (x, y to nearest 0.1 m); easiest with two people,
   f. DBH, DSH, or DRC (0.1 cm).
   g. Condition (code).
   h. Notes.
5. Take a photograph from grid pin facing 4 cardinal directions, using 50m (normal focal length) lens held at eye height. Record photo sequence on data sheet.
6. Collect and inventory gear, perform data check. Record end time.

.1 hectare overstory age/spatial plots (20 m x 50 m = 1,000 m^2)

1. Record start time.
2. Orient a .1-ha (20 m x 50 m) plot end-to-end within the .25-ha plot, with the long axis parallel to contours (perpendicular to slope) using 2 50-m tapes. Temporarily flag ends for visibility within plot.
3. For *all*:
   a. Standing trees, snags or fallen logs of any species with DBH ≥ 25 cm,
   b. Scarred trees, or
   c. PIPO with old-growth morphology (see *Old-growth characters*), (already tagged and recorded if the .25-ha plot has been read), *and*
   d. Non-PIPO trees ≥ 20 cm DBH,

   collect at least 2 core(s) at right angles from as low on the tree stem as possible. If neither core hits the pith ring, collect up to 4 cores or until reaching pith.[4] Record:
   a. Tag number and species,
   b. Core letter and height (0.1 cm),
   c. Heights (0.1 m) to dead crown/live crown/live crown top/leader,
   d. DBH if not previously recorded (0.1 cm),
   e. Mistletoe Rating,
   f. Plot x, y coordinates (0.1 m) from lower-left corner,
   g. Notes.
4. Collect and inventory gear, perform data check. Record end time.

[4] Generally, a crew of 4-5 people will consist of a recorder, a measurer, and 2-3 corers. Corers use calibrated borers or dbh tapes to to evalaute whether a tree is within size range for coring. Once the corer is satisfied that enough cores have been collected, s/he moves on to the next tree, leaving the cores in straws protruding from the borer holes. The measuring/recording team takes all measurements, including diameter, coring height and side.

.01-ha contemporary size/age-structure/density subplots (10 m x 10 m = 100 m^2)

1. Select an orientation from the grid point by random method (4 possibilities).
2. Tape off 10m x 10m plot, laying out tapes from lower-left corner (if the .25-ha plot is in place, two sides will already be taped). Temporarily flag and map corners.
3. Record mean slope (%) and aspect (° M) for the subplot.
4. Core or collect stem from *all* live trees as follows:
   - *Core* if DBH ≥ 5 cm
   - *Collect stem* if DBH is 2.5-4.9 cm, severing at ground level and 1 m
   - *Collect every fifth stem* (by counting across subplot) if DBH < 2.5 cm *or* height < 1.4 m, including seedlings.

   For each cored or collected tree ≥ 2.5 cm, tag and record:

   a. Species,
   b. Tag number,
   c. Number and condition of fire scar (if plot is in previously-surveyed 0.1-ha cell, these will have already been recorded),
   c. DBH, DSH, DRC (0.1 cm),
   d. Height (0.1 m) to dead crown/live crown/live crown top/tip of leader,
   e. Condition code.
   f. Subplot coordinates (0.1 m) from lower-left corner.
   g. Mistletoe rating.

   For collected stems, tie flagging onto collected stems. Mark top and bottom of collected stems as well as remaining root in ground.
5. For all standing stems <2.5 cm DBH *or* < 1.4 m height (including seedlings):

   a. Tally number living and dead by species, placing a stake flag by each,
   b. Estimate average height (0.1) to tip of leader by species,
   c. Flag and collect stem from every fifth plant, marking both ends of sample and top or root.
   d. Record how many stems are collected of each species.
   e. Note average mistletoe rating.
6. Collect and inventory gear, perform data check. Record end time.

EQUIPMENT NEEDED FOR NESTED PLOT SERIES:

Data forms
Condition and old-growth keys
Mistletoe rating card
RNA grid map
Clipboard
GPS with extra batteries
2 sighting compasses
22 surveying stakes
2 claw hammers (or 1 + 1 sledge)
3 100-m tapes
4 50-m tapes
2 30-m tapes
4 15-m tapes
2 5-m tapes
Clinometer
1 28 in increment borer
4 20 in increment borer
2 14-16 in increment borer
2 12 in increment borer
Boomerang handle
Chopsticks, golf tees
WD40
Long drill bit
Straws and core tubes (small and medium)
4 DBH tapes
Hand trowel
Pruning saw
Folding/bow saw
Hand pruners
25-30 stake flags
Binoculars
Tag bag, tags, nails
Large and Ultrafine markers
Pencils with erasers
Yellow and orange flagging
Laser range finder
Spray paint
Camera
(Right angle prism)

2 m x 2 m ground layer and phenology microplots (4 m^2)

1. Locate the pre-selected anchor corner of a .01-ha (10m x 10m) subplot.
2. Use tape, frame, or flagging to create microplot. Stake (rebar or PVC), flag, and map GPS corners (anchor corner will already be recorded for .01-ha subplot). Microplot will be read repeatedly over the course of the field season, so clear marking is important.
3. For each species in the shrub and herb layers (including all vascular and non-vascular herbaceous species, seedlings of woody species, and non-colonizable substrates such as bare rock), record:
   a. Percent cover,
   b. Number of stems,
   c. Growth and reproductive stage (vegetative, flowering, fruiting, seed set).
   d. Include the seedling stage in the collection. If species identity is uncertain, collect and field-press a voucher, preferably from outside the microplot.
4. Collect and inventory gear. Have someone other than the recorded check data sheets. Record end time.

Codes and protocols:

a. *Field methods.*
b. *Tree condition codes.*
c. Mistletoe rating card.
d. *Old-growth tree characteristics.*
e. Field forms for grid point, 0.25-, 0.1-, and .01-ha, and microplot sampling areas
f. Plot diagrams on graph paper.
g. Map of study area showing grid points.

Magnetic North declination ≈ 11° east of True North; **TN = MN - D (°).**

Monument Canyon Research Project
Tree Condition Codes

1a. Live (L)? Go to 2.
1b. Dead (D)? Go to 3.

2. Rate live tree condition based on crown health, growth form, apparent vigor:
   Excellent (LE)
   Good (LG)
   Fair (LF)
   Poor (LP) .

3. Rate dead tree macrocondition:
   Standing/leaning snag (DS)
   Fallen (DF)
   Stump (DP)
   Then go to 4.

4. Choose the first of:
   Foliage/fine branches present (D*F)
   Bark remaining (D*B)
   Main limbs remaining (D*L)
   Bole intact (D*I)
   Bole rotting, un-coreable (D*R)

Flagging conventions

Orange: Grid points
Yellow: Marked trees for fire-scar sampling

Other abbreviations

DBH	Diameter Breast Height (1.4 m)
DRC	Diameter at Root Crown (original ground level)
DSH	Diameter Stump Height (50 cm)

Mistletoe Rating System

MCN Restoration: 2003 Field Sampling Methods.

General notes for all protocols:

1. Sampling should take place in the order shown, so as to minimize the effect of trampling and disturbance on collected data and samples.
2. When making measurements, the measurer should call out the data, and the Recorder should call it back in response. This helps ensure that the Recorder heard the data properly.
3. Try to minimize foot traffic and soil disturbance during the sampling process. In particular, do not walk in the 10 x 10 inner plot unless necessary for sampling.
4. ***Data preparation:*** For protocols (large tree and seedling/sapling demography, crown base heights) involving re-visiting trees that have been previously tagged and inventoried, field data recording with the handheld can be facilitated by sorting all sheets as follows:
   a. First, separating out dead and live trees;
   b. Then, sorting the live trees by tree tag number.

   This procedure will make it easier to identify trees that do not need to be re-examined, and also to keep track of which trees have been measured and which remain.

Plot relocation and establishment

1. Navigate to grid point and set up an existing 10 x 10 m (0.01 ha) plot (Figure 1). Tape off the plot using the existing plot data; the right and left plot sides should follow the azimuth for the aspect line (which as of this writing is recorded in a file called "plottopog". Lay out tapes so that the lower (downslope)-left corner is at the coordinates {0, 0}; one will be pulled first along the x-axis, and then up the right side of the plot (facing uphill); the other tape will run up the y-axis and then across the top of the plot. Stake-flag corners, one of which should be the rebar grid point marker.
2. If the 0.01-ha plot is not permanently marked, mark the corners with rebar and top with colored rebar caps. Before setting rebar, check the coordinates of a few trees near the boundaries of the 0.01-ha plot to ensure that orientation is correct.
3. If this is a new grid point, use a random selection procedure to pick one of four plot orientations to grid point (see 2002 field methods).
4. For measurements of crown base height and tree condition, the approximate location (but not the actual edges) of the 50 x 50 m (0.25 ha) plot also needs to be re-established. Do this by running a 50 m tape from the grid marker following the recorded aspect line (which should run more or less directly downhill) for 25 m. Then run the rest of the tape 25 m in the other direction (which should be aspect ± 180°). Do the same procedure at right angles to the aspect line (*i.e.*, aspect ± 90°). The end result should be a pair of crossed tapes meeting at the grid point (25, 25) and extending 25 m in 4 directions. Note that the orientation of the tapes should be such that the 0, 0 point (*i.e.*, the ends of the tapes) should be in the lower left

corner of the plot when looking uphill. Both x and y coordinates can be read from these tapes.[1]

5. When plot sampling is completed, flag at least two trees on either side of point with long streamers (5 ft or more) of orange flagging to allow good visibility and movement in wind. Write grid point number on tree flags. Re-spray grid point rebar marker with Day-Glo paint.
6. Collect and inventory gear, perform data check.

Crew:

3 people

Estimated time at plot:

Navigate to plot: 15 min
Plot setup: 15 min
Flagging plot: 5 min
Total: 35 min

Equipment:

GPS and accessories
2 sighting compasses
Clinometer
Open reel tapes:
- 2 20m or 4 10 m
- 2 50 m or 1 100 m
- 2 100 m

15 surveyor's stakes
Orange flagging to re-mark GP
Orange Day-Glo paint to re-mark GP
Heavy black markers
3 3 ft rebar sections (used to mark corners of 0.01-ha plot)
Hand sledge
Field Data Recorder (FDR), spare batteries

[1] If this plot location encountered a road or other non-natural condition, a different orientation of the .25-ha plot to the grid point may have been chosen. The location should be recorded on a plot diagram and explained.

Litter and duff depth and mass (0.01 ha)

The general fuel sampling protocol follows the FIREMON *Fuel Load Sampling Methods* and the *Integrated Sampling Strategy* v2.0 (see www.firemon.org). Refer to this document for more detail on sampling methods and rationale.

1. Inside the 0.01-ha plot, run a transect following the aspect line (*i.e.*, running up/downslope) from midway along the x-baseline {5, 0} to midway along the top line {5, 10}. Also set up a grid of sampling points (Figure 2) within the 10x10 m plot at 2.5 m spacing, starting with each baseline, using stake flags. There should be 5 rows of 5 flags (25 total). Finally, outside the plot place stake flags 10 m from each corner at the two right angles from each corners of the 10 x 10 m plot (Figure 2).
2. ***Woody fuels:*** Lay out three lines running from the x-baseline ($y = 0$ m) to the top of the plot ($y = 10$ m). Along each line, tally and record the number of pieces of wood in 1-, 10-, and 100-hr fuel classes (see FIREMON protocol). All fuel size classes are measured from the x-baseline up to the 5 m mark; from 5-10 m, tally and record 100-hr fuels only. Repeat this procedure for all three transects. If there is a rock, tree, or other obstacle in the way of any transect, relocate it 50 cm to either side and record new x coordinate.
3. ***Litter and duff:*** At each flagged point on the sampling grid, cut through the litter (dry, unconsolidated needles and debris) and duff (darker, partly decomposed material) with a trowel, and then pull the litter and duff back to expose the undisturbed vertical surface. Measure the total depth from mineral soil to the top of the litter layer, to the nearest 0.5 cm. Then gently sweep away the litter from the cut and measure the depth of the duff layer. Calculate litter depth by subtraction of duff depth from total depth, taking care to define the litter-duff boundary. Identify each sample by its coordinates (*e.g.* "0, 5" would be the sample at $x = 0$ m, $y = 5$ m). The full set of 25 coordinates should already be set up on each grid point spreadsheet in the FDR prior to beginning sampling.
4. Take litter and duff measurements at the 8 additional points outside the 10 x 10 m plot, giving a total of 33 points per location (Figure 1). These points are identified as "top left", top right", "right upper", "right lower", "left upper", "left lower", "bottom left", and "bottom right" (Figure 2).
5. To ***calibrate litter depth to mass***, go flag 4 points, each 1 m **outside the plot** tape midway along each side. At each of these points, measure and record litter depth as in Step 3 above. Locations are identified in the spreadsheet by their coordinates: Bottom = (5, -1); Right = (11, 5); Top = (5, 11); Left = (-1, 5).
6. Collect a sample of **litter only**, removing any woody material (*i.e.*, 1-, 10- and 100-hr fragments) before collecting the sample. Also, do not collect live herbaceous material (grasses), or dead material that is still connected to the plant; these are inventoried in a separate protocol. Place each litter sample in a separate collecting bag labeled with the grid point number and location (*e.g.*, "GP137 litter right"). In some cases it may be necessary to use more then one bag for each

location, in which case accurate identification of the bags ("1/3", *etc.*) is essential. The samples will be dried and weighed in the laboratory.

7. Now make a similar collection of **duff** at each sampling point in the 0.1 m^2 PVC frame. Be sure to label the location and contents of each bag.[2]
8. Record completion of the protocol in the file "gridsampled.xls".

Crew:
1 recorder
2 measurers in plot
2 coordinate markers

Estimated time at plot:
Flagging plot: 5 min
Measure and record depths, make collections: 35 min
Total: 40 min

***Equipment*:**
4 10 m open reel tapes
50 pink or yellow stake flags
2 metal hand trowels
0.1 m^2 (= 1,000 cm2) PVC or wooden frame for litter collections (31.62 cm x 31.62 cm inside dimension)
2-3 short metric rulers or short stiff metal tapes
2-3 fuel depth and size ("Go/No-Go") gauges
Many small paper or plastic (with label section) collecting bags
Black medium Sharpie markers
FDR and accessories

[2] Has also been recommended to take smaller volume, *e.g.* soil collecting cans.

Tree seedling demography (0.01 ha)

5. Working in quadrants or other sections of the 10 x 10 m plot (to avoid overlap), place a stake flag at the base of every tree or shrub that it not already tagged; most of these should be ≤ 2.5 cm stem diameter. If there are very large numbers of seedlings (> 100), see Step 2.
6. For plots with more than 100 seedlings or saplings, estimate the total number in the plot by dividing the plot into quadrants and counting or estimating in each quadrant. Then flag 100 stems in the total plot, selecting stems randomly by counting off stems as needed to avoid bias.
7. For each flagged stem, record its species, height (to 0.1 cm), max stem diameter (0.1 cm), condition class, and *x*, *y* coordinates (0.1 m) on the 10x10 plot coordinate system. Coordinates are easily determined by pulling a tape at right angles to the nearest perimeter tape of the plot; one axis will be the intercept of this tape on the baseline, while the other axis will be the length of the tape or 10 m minus this length.
8. Note that some plants will already have been recorded from previous years; in this case, add data to existing row on spreadsheet if possible; if unsure, make notes or ask crew chief.

Crew: 2-3 measurers (depending on expected seedling density from previous years)
2 coordinate markers
1 recorder

Estimated time at plot *(times are for typical plot in PIPO; triple sampling times for dense mixed conifer):*
Flag seedlings: 10 min
Identify, measure, and call coordinates: 30 min (for dense plots, 2 hr)
Total: 40 min (for dense plots, 2 hr)

Equipment:
2 20m reel tapes
4 surveyor's stakes
2 10m reel tapes
120 stake flags
Hand tapes or rulers for measuring heights and diameters
Hand lens
FDR and accessories

Understory biomass (0.01 ha)

1. For each species of grass found inside the 10x10 plot, find 2-3 specimens **outside** the plot boundary.
2. Measure cover in cm^2 (this can later be converted to the percent cover in a 1-m^2 plot by multiplying by 100)[3]. Record this area for each sample, numbering samples sequentially by species for each grid point (*e.g.* MUAZ117-1, MUAZ117-2, *etc.*).
3. Collect a sample by severing the plant at ground level. Place the material in a collecting bag and the sample ID and cover area (cm^2) on each bag. Samples will be dried and weighed in the laboratory.

Crew: 2 measurer/collectors 1-recorder (optional)

Estimated time at plot:

Microplot setup: 15 min
Identify (grass) species in plot and locate specimens outside plot: 20 min
Find and measure specimens outside, make collections: 15 min
Total: 50 min

Equipment:

20 pink or yellow stake flags
Hand tapes or rulers for measuring cover
Sharp knife or plant shears or clippers
Many small paper or plastic (with label section) collecting bags
Black medium Sharpie markers
FDR and accessories

[3] The plot is $(1\ m)^2 = (100\ cm)^2 = 10{,}000\ cm^2$. So each $1\ cm^2 = 1/10{,}000$ of the plot, or 0.01% cover. So (cm^2 covered) × 100 = percent cover.

Understory composition (0.01 ha)[4]

1. Navigate to grid point with established understory plots.
2. Once per season, record percent cover in broad classes (as used in FS Habitat Typing system) for species found in 10x10 plot but not in one of the 1-m^2 microplots.[5]

Crew: 2 measurer/collectors/recorders.

Estimated time at plot:

Plot setup: 15 min
Identify species, measure and record cover in 5 microplots: 30 min.
Find and measure specimens outside, make collections: 15 min
Total: 60 min

Equipment:

[4] Protocol is being adapted following field season 2003.
[5] This will allow us to characterize each plot according to US Forest Service. 1997. *Plant associations of Arizona and New Mexico. Vol. 1*: Forests. 3rd Ed., Southwest Region. Albuquerque, NM. This would involve estimating percent cover by general categories (see p.8): absent, < 1%, 1-5%, 5-25%, and 25-50%. The benefit if that the association is likely to change after thinning and burning (which can be assessed with multivariate analysis); see also Steuver (2003:24-25).

Fire behavior and percent live canopy (0.01 -- 0.25 ha nested plots)[6]

The purpose of this protocol is to populate variables that are needed to run various fire behavior and fire effects models.

1. Open the 0.01-ha worksheet in the grid point file, which should be sorted in tree tag order to facilitate recording. It is also useful to separate out dead trees in the previous record, since these do not have to be revisited.
2. Locate each live tree in the database. If the tag is loose, reset properly (nail points downward, space between tag and bark). If tag is missing, make note in database or make new tag with correct number using tag kit.
3. **Crown base height:** Using a telescoping graduated (stadia) rod or laser/tape and clinometer method (below), measure and record the height to nearest 0.1 m to the lowest live foliage (not the branch connection to the stem) that is part of a continuous canopy on each live tagged tree in the 0.01 plot. "Continuous" is defined here as less than 5 m away from the next highest branch; the intent is to exclude small isolated clusters of leaves that would be unlikely to spread fire up into the higher branches). Foliage may hang down from the main branch; measure the height of the foliage.
   a. ***Graduated (stadia) rod:*** Raise the rod until it touches the lowest live foliage.
   b. ***Laser/tape and clinometer method:*** Standing back away from the tree at least 10 m, sight the lowest foliage (as above) and record the angle in percent. Then sight the base of the tree and measure that angle, also in percent; if your eye is higher than the tree base, this reading will be a negative number (*e.g.*, -20 %). The total angle subtended by the tree is the sum of the absolute values of the two angles (*e.g.*, 39% to the crown base and –23% to the base of the tree = 62% total angle subtended). With the tape or laser, measure and record the baseline distance to the tree stem, also to the nearest 0.1 m. In the data sheet, enter the baseline distance times the percent cover as a proportion (0 to 1); for example, a baseline distance of 14 m, and a total angle from crown base to the tree base of 67% would be entered as (14 * .67). The product is the crown base height, in meters.
4. **Top of live crown.** Measure height to the highest leaf-bearing meristem (usually the leader) to the nearest 1 m, using one of the methods above. If the tree has a dead leader (a spike of dead wood extending above the live canopy), record the height to its top in the notes (used in calculating of percent live canopy). If you are using the clinometer-tape method, sight the top of the tree for one angle, the tree base for another, and use the sum of the absolute values of the two angles as in 2.b above.
5. Make the same measurements for all standing live, tagged overstory trees in the **0.25- and 0.1-ha plots** (these can be separate crews). It is easiest to record all the trees in the 0.1-ha plot first, which will all be on the same page of the spreadsheet, then survey trees in the top and bottom bands of the 0.25-ha plot (Figure 1). Use

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[6] This protocol can be combined with the assessment of overstory tree condition and demography (p. 9).

the 10 x 10 m "cells" on the stem map to find trees; find all the trees in one cell and then move to the next.

Crew: 2 measurer/collectors/recorders per crew.

Estimated time at plot:

0.01 ha plot: 15 minutes
0.25 and 0.1 ha plots: 45 minutes
Total: 60 min

Equipment:

Graduated stadia rod
Clinometer
Laser rangefinder or 2 50 m open reel tapes
FDR and accessories
Claw hammer and/or hand sledge
Tag kit (blank tags, number stamps, wire)

Tree condition and demography (0.01 to 0.25 ha nested plots)

This protocol can be combined with the previous (p. 8) for fire behavior variables.

1. For efficiency, divide into separate crews for each plot size; one crew can work the 0.01-ha inner plot, while the other records in the overstory (0.1- and 0.25-ha plots).
2. Relocate all tagged individual trees in the 0.01-ha plot, using stem map and tag numbers. If the stem map coordinates or any other data are incorrect, enter corrected coordinates into GP file and mark on map.
3. As each tree is visited, reset loose tag nails; if the tag is missing, write/score tree number and nail to tree.
4. For each tree located, record tree condition class by scoring five variables on scales of 0-2 (see **MCN Live Tree Condition Scoring,** this document). For dead trees use existing MCN classes. **Note:** If a tree was alive at the time of the last survey, **do not** overwrite the live condition score. Instead, enter the new dead condition class in the first column of the condition survey ("Foliage condition").
5. Note: Live canopy ratio is also used to assess tree condition; see previous protocol (*Fire behavior*).
6. Make the same measurements for all standing live, tagged overstory trees in the 0.25- and 0.1-ha plots (these can be separate crews). It is easiest to record all the trees in the 0.1-ha plot first, which will all be on the same page of the spreadsheet, then survey trees in the top and bottom bands of the 0.25-ha plot (Figure 1). Use the 10 x 10 m "cells" on the stem map to find trees; find all the trees in one cell and then move to the next. Remember, **do not overwrite** the condition class of trees from the previous survey.

Crew: 2-3 people per survey crew
1 recorder

Estimated time at plot *(times are for typical plot in PIPO; triple sampling times for dense mixed conifer):*

Tree examination: 90 min
Total: 90 min

Equipment:

Stem map for grid point
Graduated (stadia) rod
Laser rangefinder *or* clinometer
2 50-m reel tapes
Binoculars
Grid cell stem maps
Hammer
Blank or pre-numbered metal tags or tag punch kit
FDR and accessories

Canopy images (0.01 ha)

1. Set up camera on tripod at the center of the 0.01-ha plot, lens at 25 cm height. If actual height is different, record; height should be the same for all images. Camera should be level.
2. Set timer and move out of plot while camera takes image. Images should be recorded at medium resolution (1024 × 768 pixels).
3. Check image in viewfinder and record image number.
4. Repeat steps 1-3 at 4 points 7.05 m and 45 ° from each plot corner (these will be the midpoint of a line connecting the two duff/litter measurement points outside the plot in the fuel sampling protocol).
5. If time permits, canopy images should be recorded at every grid point in the study site, not just those with plots established.
6. When Flash Card is downloaded to PDA or PC, rename file "GP###".

Crew: 1-2 people

Estimated time at plot *(times are for typical plot in PIPO; triple sampling times for dense mixed conifer):*

Camera setup: 5 min
Take image and record information in FDR: 5 min
Total: 10 min

Equipment:
Camera
Tripod
Extra Li battery
Extra memory chip (Flash Memory card)
FDR and accessories

MCN Live Tree Condition Scoring.

Scores 0-2 for each of the following five categorical variables. In each case, score "2" for trees in the best (healthiest) condition for that variable, "0" for trees in the worst (unhealthiest) condition. The minimum and maximum possible scores are 0 and 10 respectively.

Leaf condition. What is the condition of the leaves (needles) that exist? Healthy trees have leaves or needles with rich dark saturated color. Unhealthy leaves are yellow (chlorotic) or even brown (dead or dying), which can reflect drought stress or nutrient starvation.

Leaf density. How much foliage is there in relation to the size and species of tree? Healthy trees have full canopies, needles well along the branch. Unhealthy trees have few or sparse leaves or needles, often clustered at the tips.

Stem structural condition. Is the trunk of the tree structurally sound? Healthy trees have strong, straight upright stems, robust for their height and free from apparent injury. Unhealthy trees have weak, leaning, bent or crooked stems, appearing too weak for their height, or evidence of mechanical injury, lightning strikes (a characteristic spiral split often running the entire length of the tree).

Insects, diseases, and parasites.[7] Healthy trees are free from apparent signs of insect attack, parasites, or diseases. Unhealthy trees may show evidence of the following:

- *Bark beetles* leave small (5-8 mm diameter or sometimes larger) circular or elliptical holes in the bark. A healthy tree can "pitch out" the boring insect, which may result in streams of dried pitch or sap running down the trunk.
- *Other boring insects* may leave small piles of sawdust around the base of the tree as a symptomatic character.
- *Leave herbivores* (many of which are larval stages) result in leaves with chewed holes, blackened or yellowed portions, or other signs.
- *Mistletoes* are hemiparasitic flowering vascular plants that attach to the host plant and derive its nutrition from the host. Pine mistletoes (*Artheucobium* sp.) are yellow-green in color and attach to branches or the main stem.

Score 2 if there is no evidence of insects, diseases, or parasites, 1 if there is evidence of an attack that the tree was able to resist, and 0 if the tree appears affected.

Growth rate. Healthy trees have a healthy apical meristem, relatively few dead major branches, and evidence of steady stem elongation between annual nodes. The apical meristem of unhealthy trees may have been killed or injured by insects or lightning, resulting in a dead leader or forked tip. Unhealthy trees may also show little or no growth between years (although in old trees, vertical growth slows down naturally and is not necessarily a sign or poor health), and substantial dieback of the lower crown (as

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[7] Review by forest entomologist for visual signs.

evidenced by many whorls of large dead branches, indicating the branch death is occurring faster than the natural shedding of lower branches).

Figure 1. Schematic of nested plot layout. Large square is 0.25-ha (50 m x 50 m) overstory size/density plot, centered on grid point. Nested 0.1-ha (20 m x 50 m) overstory age/spatial structure plot runs parallel to contours. Four possible locations of 0.01-ha (10 m x 10 m) subplots are centered within overstory plots. Dashed lines indicate tape layout.

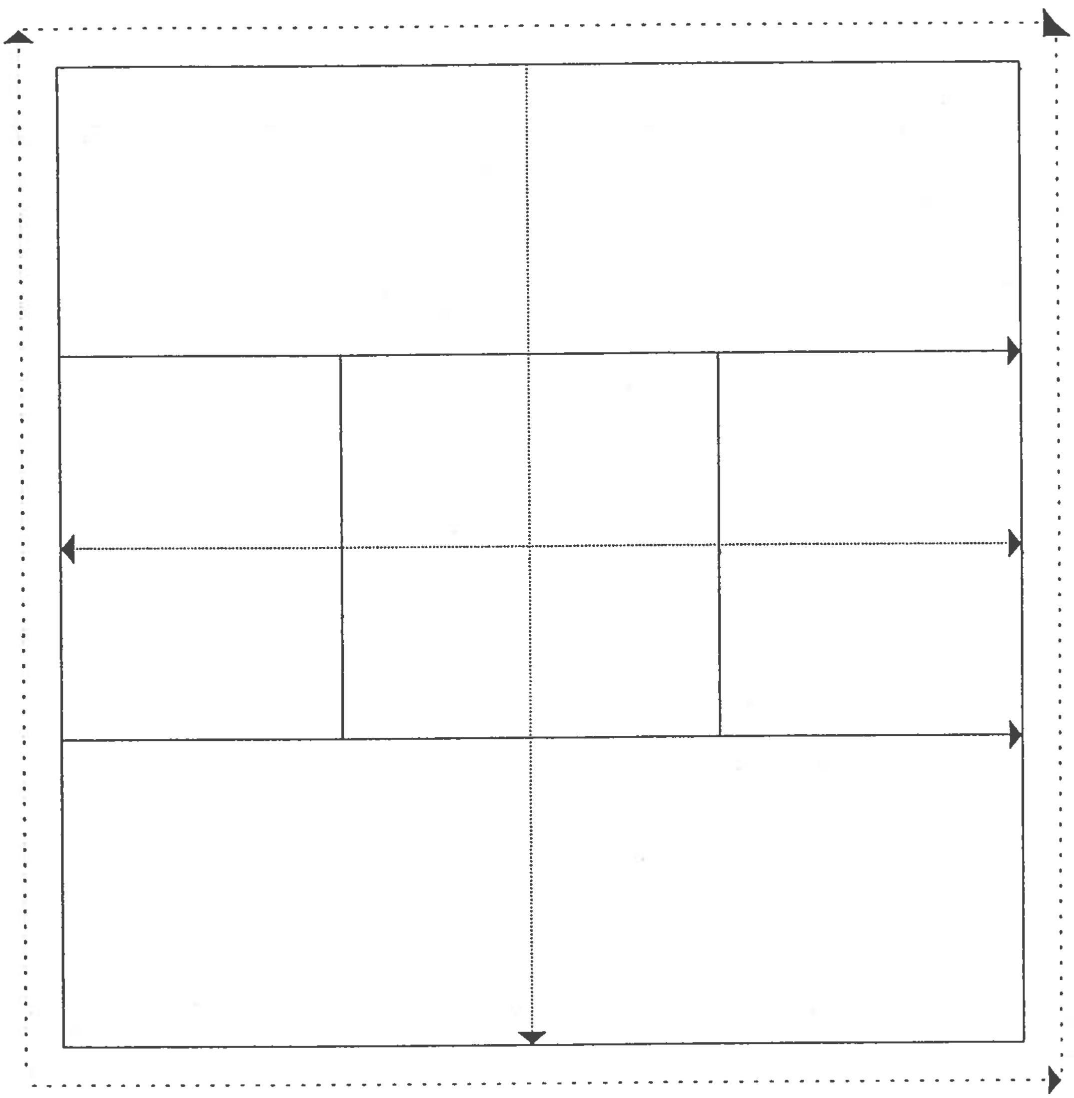

Table 1. Grid point sampling status								
As of	25-Jul-03							
	.5 ha	.25 ha	.1 ha	.01 ha				
Grid point	**FS**	**plot**	**plot**	**plot**	**dead**	**understory**	**2003 protocols**	**Canopy**
100								
101	18-Aug-99	18-Aug-99	18-Aug-99					
102	17-Jun-99							
103	13-Jul-01							
104								
105	19-Aug-99							
106	14-Jul-01							
107	19-Aug-99							
108								
109	9-Jul-99	03-Jun-00	03-Jun-00	03-Jun-00	01-Jul-01			
110								
111	10-Jul-99	04-Jul-00	04-Jul-00	04-Jul-00	17-Aug-00	03-Jul-03	22-23 Jul 03	Y
112	12-Jul-01							
113	10-Jul-00	05-Jul-00	05-Jul-00	05-Jul-00	01-Jul-01	03-Jul-03	21-23-Jul-03	Y
114								
115	11-Jul-99	06-Jul-00	06-Jul-00	06-Jul-00	01-Jul-01	03-Jul-03	21-22-Jul-03	Y
116	14-Jul-01							
117	11-Jul-99	06-Jul-00	06-Jul-00	NA	NA			
118								
119	14-Aug-99	14-Aug-00	14-Aug-00	14-Aug-00	15-Aug-00			
120								
121	14-Aug-99	03-Jul-00	03-Jul-00	03-Jul-00	01-Jul-01	03-Jul-03	22-Jul-03	?
122	12-Jul-01							
123	15-Aug-99	05-Jul-00	05-Jul-00	05-Jul-00	01-Jul-01	03-Jul-03	22-Jul-03	N
124								
125	19-Aug-99	01-Jul-00	01-Jul-00	30-Jun-00	01-Jul-01		16-Jul-03	Y
126								
127	9-Jul-99	11-Aug-00	11-Aug-00	11-Aug-00	12-Aug-00			
128								
129	13-Jul-99	15-Aug-00	15-Aug-00	15-Aug-00	16-Aug-00			
130	18-Aug-99	21-Jun-99	22-Jun-99	22-Jun-99	01-Jul-01			
131	10-Jul-99	02-Jul-00	02-Jul-00	02-Jul-00	16-Aug-00	03-Jul-03	22-24-Jul-03	Y
132	11-Jul-01							
133	8-Jul-99	30-Jun-00	30-Jun-00	29-Jun-00	01-Jul-01			
134								

	.5 ha	.25 ha	.1 ha	.01 ha				
Grid point	FS	plot	plot	plot	dead	understory	2003 protocols	Canopy
135	12-Jul-99							
136								
137	16-Aug-99	12-Aug-00	12-Aug-00	11-Aug-00	12-Aug-00	03-Jul-03	20-21-Jul-03	Y
138	8-Jul-01							
139	1-Jul-01	16-Aug-00	16-Aug-00	01-Jul-01	01-Jul-01			
140	19-Jun-99							
141	18-Aug-99	04-Jun-00	04-Jun-00	04-Jun-00	16-Aug-00	03-Jul-03	21-23-Jul-03	Y
142	19-Jun-99							
143	17-Aug-99	13-Aug-00	13-Aug-00	13-Aug-00	15-Aug-00			
144	12-Jul-99							
145	8-Jul-99	10-Aug-00	10-Aug-00	10-Aug-00	01-Jul-01			
146	8-Jul-01							
147	8-Jul-99	08-Aug-00	08-Aug-00	08-Aug-00	01-Jul-01	03-Jul-03	24-Jul-03	Y
148	8-Jul-01							
149	8-Jul-99	01-Aug-99	01-Aug-99	02-Aug-99	01-Jul-01	03-Jul-03		
150								
151	10-Jul-99	11-Aug-00	11-Aug-00	12-Aug-00	12-Aug-00			
152								
153	8-Jul-01							
154	16-Aug-99	09-Aug-00	09-Aug-00	09-Aug-00	13-Aug-00	03-Jul-03	18-24-Jul-03	Y
155								
156	16-Aug-99	16-Aug-99	18-Aug-99	18-Aug-99	01-Jul-01	03-Jul-03	19-24-Jul-03	Y
157	9-Jul-01							
158	17-Aug-99	01-Jun-00	01-Jun-00	31-May-00	01-Jul-01			
159								
160	17-Aug-99	17-Aug-00	17-Aug-00	17-Aug-00	01-Jul-01			
161								
162	9-Jul-99	09-Aug-00	09-Aug-00	09-Aug-00	14-Aug-00			
163								
164	19-Jul-99	19-Aug-99	19-Aug-99	18-Aug-99	13-Aug-00	03-Jul-03	17-24-Jul-03	?
165								
166	8-Jul-99	02-Jun-00	02-Jun-00	01-Jun-00	01-Jul-01		18-19-Jul-03	Y
167								
168	17-Aug-99							
169								
170	14-Jul-99							
179								
180	12-Jul-99							

	.5 ha	.25 ha	.1 ha	.01 ha				
Grid point	**FS**	**plot**	**plot**	**plot**	**dead**	**understory**	**2003 protocols**	**Canopy**
188	13-Jul-99							
	52							
Non-grid								
locations								
E352598/N3	14-Jul-98							
E353983/N3	12-Jul-99							
E353986/N3	12-Jul-99							
E354005/39(	12-Jul-99							
E354082/N3	12-Jul-99							
E354107/N3	12-Jul-99							
E354264/N3	13-Jul-99							
E354288/N3	13-Jul-99							
noloc 120	14-Jul-98							
noloc 142	15-Jul-98							
noloc 148	14-Jul-98							
noloc 149	14-Jul-98							
noloc 155	14-Jul-98							
noloc 165	15-Jul-98							
noloc 170	15-Jul-98							
noloc 180	15-Jul-98							
noloc 185	15-Jul-98							
					0			

Table 2. Grid point analysis status

Grid point	Date completed/updated FS	FHX entry	FHX.out	Composite created on	Composite output
100					
101	18-Aug-99	14-Oct-02	21-Oct-02	05-Aug-03	14-Mar-03
102	17-Jun-99	16-Sep-02	21-Oct-02	05-Aug-03	14-Mar-03
103	13-Jul-01	16-Sep-02	21-Oct-02	05-Aug-03	14-Mar-03
104					
105	19-Aug-99	6-Dec-02	21-Oct-02	05-Aug-03	14-Mar-03
106	14-Jul-01	16-Sep-02	21-Oct-05	05-Aug-03	14-Mar-03
107	19-Aug-99	12-Sep-02	21-Oct-02	05-Aug-03	07-Mar-03
108					
109	9-Jul-99	21-Jan-03		05-Aug-03	07-Mar-03
110					
111	10-Jul-99	6-Dec-02	21-Oct-02	05-Aug-03	07-Mar-03
112	12-Jul-01	24-Dec-02		05-Aug-03	07-Mar-03
113	10-Jul-00	6-Dec-02	21-Oct-02	05-Aug-03	07-Mar-03
114					
115	11-Jul-99	6-Dec-02	21-Oct-02	05-Aug-03	07-Mar-03
116	14-Jul-01	9-Dec-02	21-Oct-02	05-Aug-03	07-Mar-03
117	11-Jul-99	13-Dec-02	21-Oct-02	05-Aug-03	07-Mar-03
118					
119	14-Aug-99	4-Oct-02	23-Oct-02	05-Aug-03	07-Mar-03
120					
121	14-Aug-99	13-Dec-02	23-Oct-02	05-Aug-03	07-Mar-03
122	12-Jul-01	16-Sep-02	23-Oct-02	05-Aug-03	07-Mar-03
123	15-Aug-99	27-Sep-02	23-Oct-02	05-Aug-03	07-Mar-03
124					
125	19-Aug-99	13-Dec-02	23-Oct-02	05-Aug-03	07-Mar-03
126					
127	9-Jul-99	2-Nov-01	23-Oct-02	05-Aug-03	07-Mar-03
128					
129	13-Jul-99	24-Dec-02	23-Oct-02	05-Aug-03	07-Mar-03
130	18-Aug-99	13-Dec-02	23-Oct-02	05-Aug-03	07-Mar-03
131	10-Jul-99	22-Oct-02	23-Oct-02	05-Aug-03	07-Mar-03
132	11-Jul-01	16-Sep-02	23-Oct-02	05-Aug-03	07-Mar-03
133	8-Jul-99	18-Jan-02	23-Oct-02	05-Aug-03	07-Mar-03
134					
135	12-Jul-99	20-Dec-02	23-Oct-02	05-Aug-03	07-Mar-03
136					
137	16-Aug-99	23-Dec-02		05-Aug-03	07-Mar-03
138	8-Jul-01	19-Dec-02		05-Aug-03	07-Mar-03
139	1-Jul-01	No file	No file	No file	No file
140	19-Jun-99	24-Dec-02		05-Aug-03	07-Mar-03
141	18-Aug-99	27-Sep-02		05-Aug-03	07-Mar-03
142	19-Jun-99	9-Jan-03		05-Aug-03	07-Mar-03
143	17-Aug-99	23-Dec-02		05-Aug-03	07-Mar-03
144	12-Jul-99	5-Jan-03		05-Aug-03	07-Mar-03
145	8-Jul-99	14-Oct-02		05-Aug-03	07-Mar-03
146	8-Jul-01	16-Sep-02		05-Aug-03	07-Mar-03
147	8-Jul-99	7-Oct-02		05-Aug-03	07-Mar-03
148	8-Jul-01	23-Dec-02		05-Aug-03	07-Mar-03
149	8-Jul-99	23-Dec-02		05-Aug-03	07-Mar-03

Grid point	FS	FHX entry	FHX.out	created on	output
150					
151	10-Jul-99	6-Dec-02		05-Aug-03	07-Mar-03
152					
153	8-Jul-01	16-Dec-02		05-Aug-03	07-Mar-03
154	16-Aug-99	8-Feb-02		05-Aug-03	07-Mar-03
155					
156	16-Aug-99	27-Sep-02		05-Aug-03	07-Mar-03
157	9-Jul-01	16-Sep-02		05-Aug-03	07-Mar-03
158	17-Aug-99	6-Dec-02		05-Aug-03	07-Mar-03
159					
160	17-Aug-99	14-Feb-02		05-Aug-03	07-Mar-03
161					
162	9-Jul-99	24-Dec-02		05-Aug-03	07-Mar-03
163					
164	19-Jul-99	16-Dec-02		05-Aug-03	07-Mar-03
165					
166	8-Jul-99	16-Jan-03		05-Aug-03	07-Mar-03
167					
168	17-Aug-99	No file	No file	No file	No file
169					
170	14-Jul-99	24-Dec-02		05-Aug-03	07-Mar-03
180	12-Jul-99	21-Dec-02		05-Aug-03	07-Mar-03
188	13-Jul-99	24-Dec-02		05-Aug-03	07-Mar-03

table 3

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
1	330		101	6/17/1999	CHRIS					☐	☐
2	506		149	8/1/1999						☐	☐
6	331		101	8/18/1999	LAB	D	Falk	9/3/2002		☑	☑
7	332	12	101	8/18/1999	LAB	D	Falk	1/30/2001		☑	☐
8	333		101	8/18/1999	CHRIS					☐	☐
9	334		101	8/18/1999	LAB OS	D	Falk	1/19/2001		☑	☐
10	335	12	101	8/18/1999	LAB	D	Baisan/Falk	1/19/2001		☑	☑
11	341	12	105	8/19/1999	LAB	D	Falk	10/1/2001		☑	☑
12	340		105	8/19/1999	LAB	D	Falk	10/9/2001		☑	☑
13	337		107	8/19/1999	LAB OS	D	Falk	12/6/2001		☑	☐
14	338		107	8/19/1999	LAB	D	Falk/Hallman	8/27/2002		☑	☑
15	339		107	8/19/1999	LAB	D	Falk	12/3/2001		☑	☐
16	233		111	7/10/1999	LAB	D	Falk	0/30/2000		☑	☑
17	237	AB	111	7/10/1999	LAB	D	Falk	0/29/2001		☑	☑
18	236		111	7/10/1999	LAB	D	Falk	11/1/2001		☑	☑
19	235	A	111	7/10/1999	LAB OS	D	Falk	0/31/2001		☑	☐
21	227	12	113	7/10/1999	LAB	D	Falk	9/27/2001		☑	
22	228		113	7/10/1999	LAB	D	Falk	0/29/2001		☑	☐
23	229		113	7/10/1999	LAB OS	D	Falk	0/16/2000	Morino	☑	☑
24	230		113	7/10/1999	LAB	D	Falk	0/10/2000	Morino	☑	☑
27	224	AB	115	7/11/1999	LAB	D	Falk	0/10/2001		☑	☐
28	225	AB	115	7/11/1999	LAB	D	Falk	0/11/2001		☑	☑
29	461	AB	115	7/11/1999	LAB	D	Falk/Ababne	9/5/2001		☑	☐
30	459	AB	115	7/11/1999	PC	D	Falk/Ababne	9/4/2001		☑	☐
31	221	A,B,C	117	7/11/1999	STAD	D	Morino	6/20/2000		☑	☐
32	222		117	7/11/1999	LAB OS	D	Morino	6/20/2000		☑	☑
33	223		117	7/11/1999	STAD	D	Morino	6/20/2000		☑	☑
34	301	A12B	119	8/14/1999	LAB PC	D	Falk	12/7/2001		☑	☑
35	302		121	8/14/1999	LAB OS	D	Falk	0/14/2001		☑	☐
36	303		121	8/14/1999	LAB	D	Falk	1/12/2001		☑	☑

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
38	305		121	8/14/1999	LAB	D	Falk	12/19/2001		☑	☐
39	306	AB	123	8/15/1999	LAB	D	Falk	12/6/2001		☑	☑
40	307		123	8/15/1999	LAB	D	Falk	12/7/2001		☑	☐
41	308		123	8/15/1999	LAB	D	Falk	12/6/2001		☑	☐
42	336	12	125	8/19/1999	LAB	D	Falk	12/19/2001		☑	☑
44	269	AB	127	7/9/1999	LAB	D	Falk	8/30/2001		☑	☐
45	270		127	7/9/1999	LAB	D	Falk	8/31/2001		☑	☐
46	385	AB123	129	7/13/1999	LAB	D	Falk/Morino	9/14/2001		☑	☑
47	390		129	7/13/1999	LAB	D	Falk	1/2/2001	Baisan	☑	☑
48	391		129	7/13/1999	LAB	D	Falk	9/13/2001		☑	☑
49	464	AB	130	8/18/1999	LAB	D	Falk	11/13/2001		☑	☐
50	466		130	8/18/1999	LAB	D	Falk	12/19/2001		☑	☑
51	467		130	8/18/1999	LAB	D	Falk	12/3/2001		☑	☐
52	242	AB	131	7/10/1999	STAD	D	Falk	10/25/2000	Morino	☑	☑
53	241		131	7/10/1999	STAD	D	Falk/Ababne	11/30/2001		☑	☐
54	240		131	7/10/1999	STAD	D	Falk	12/21/2001		☑	☑
55	239		131	7/10/1999	LAB	D	Falk	1/14/2002		☑	☑
56	238		131	7/10/1999	LAB	D	Falk	1/14/2002		☑	☐
57	460	AB	133	7/8/1999	LAB	D	Falk	1/14/2002		☑	☑
58	462		133	7/8/1999	LAB	D	Falk	1/15/2002		☑	☐
59	216		135	7/11/1999	LAB	D	Morino	6/20/2000		☑	☑
60	215	12	135	7/12/1999	LAB	D	Morino	6/20/2000		☑	☑
61	217		135	7/11/1999	LAB	D	Morino	6/20/2000		☑	☑
62	218		135	7/12/1999	LAB	D	Morino	6/20/2000		☑	☑
63	219		135	7/12/1999	STAD	D	Morino	6/20/2000		☑	☑
64	220		135	7/12/1999	STAD	D	Morino	6/20/2000		☑	☑
66	311		137	8/16/1999	LAB	D	Falk	7/31/2001		☑	☑
67	312		137	8/16/1999	LAB	D	Falk	7/31/2001		☑	☑
68	313		137	8/16/1999	LAB	D	Falk	8/1/2001		☑	☑
70	323		143	8/17/1999	LAB	D	Falk	10/16/2001		☑	☐

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
71	324		143	8/17/1999	LAB	D	Falk	10/18/2001		✓	✓
72	325	A12B	143	8/17/1999	A1-LAB PC, others-S	D	Falk	10/19/2001		✓	✓
73	210	AB	144	7/12/1999	LAB	D	Morino	6/20/2000		✓	
75	212		144	7/12/1999	LAB	D	Morino	6/20/2000		✓	✓
76	213	12	144	7/12/1999	LAB	D	Morino	6/20/2000		✓	✓
78	262		145	7/8/1999	LAB	D	Falk	1/16/2002		✓	✓
79	261		145	7/8/1999	LAB	D	Falk	1/15/2002		✓	☐
80	258		145	7/8/1999	LAB	D	Falk	1/16/2002		✓	☐
81	251		147	7/8/1999	LAB	D	Falk	1/17/2002		✓	☐
82	252	12	147	7/8/1999	LAB	D	Falk	1/17/2002		✓	✓
83	259	12	149	7/8/1999	LAB	D	Falk	1/22/2002		✓	✓
84	275		149	7/8/1999	STAD	D	Falk	1/18/2002		✓	✓
85	246		151	7/10/1999	LAB	D	Falk	9/12/2001		✓	✓
86	247		151	7/10/1999	LAB	D	Falk	6/3/2002		✓	✓
87	243	AB	151	7/10/1999	LAB	D	Falk	1/23/2002		✓	✓
88	263		154	8/16/1999	LAB	D	Falk	1/24/2002		✓	✓
89	264		154	8/16/1999	LAB	D	Falk	1/30/2002		✓	✓
90	267		154	8/16/1999	LAB	D	Falk	1/31/2002		✓	✓
91	314		156	8/16/1999	LAB OS	D	Falk	2/4/2002		✓	☐
92	315		156	8/16/1999	LAB	D	Falk/Hallman	2/26/2002		✓	✓
93	123		156	7/14/1998	STAD	D	Falk/Hallman	3/21/2002		✓	✓
94	319	12	160	8/17/1999	LAB OS	D	Falk	1/26/2002		✓	
95	320		160	8/17/1999	LAB	D	Falk	2/1/2002		✓	✓
96	321		160	8/17/1999	LAB	D	Falk	2/1/2002		✓	✓
97	322		160	8/17/1999	LAB	D	Falk	2/5/2002		✓	✓
98	268		162	7/9/1999	LAB	D	Falk	11/6/2000	Morino	✓	✓
100	250		162	7/9/1999	LAB OS	D	Falk	12/12/2000	Morino	✓	✓
102	273		164	7/9/1999	LAB OS	D	Falk	1/29/2002		✓	✓
103	274	AB	164	7/9/1999	STAD	D	Falk	1/31/2002		✓	✓
104	272		164	7/9/1999	LAB	D	Falk	1/30/2002		✓	☐

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
105	201		170	7/14/1999	LAB	D	Falk	2/5/2002		☑	☑
107	203		170	7/14/1999	LAB OS	D	Morino	6/20/2000		☑	☑
108	204		170	7/14/1999	LAB OS	D	Morino	6/20/2000		☑	☐
109	205		170	7/14/1999	LAB	D	Morino	6/20/2000		☑	☑
110	206		170	7/14/1999	LAB	D	Morino	6/20/2000		☑	☐
111	207		180	7/12/1999	LAB	D	Morino	6/20/2000		☑	☑
112	208		180	7/12/1999	LAB	D	Morino	6/20/2000		☑	☑
113	209		180	7/12/1999	LAB	D	Morino	6/20/2000		☑	☐
114	379		188	7/13/1999	STAD	D	Morino	6/20/2000		☑	☐
115	380		188	7/13/1999	LAB	D	Morino	6/20/2000		☑	☑
116	381		188	7/13/1999	LAB	D	Falk	10/1/2002		☑	☑
117	382		188	7/13/1999	LAB	D	Falk	10/1/2002		☑	☑
118	383		188	7/13/1999	LAB	D	Morino	6/20/2000		☑	☑
120	387		353983e/3963199	7/12/1999	STAD	D	Morino	6/20/2000		☑	☐
121	386		353983e/3963199	7/12/1999	STAD	D	Morino	6/20/2000		☑	☐
122	395		353986e/3963377	7/12/1999	STAD	D	Morino	6/20/2000		☑	☐
123	394		354005e/3963339	7/12/1999	LAB	D	Morino	6/20/2000		☑	☐
124	389		354082e/3963118	7/12/1999	LAB	D	Morino	6/20/2000		☑	☐
125	388		354107e/3963041	7/12/1999	LAB OS	D	Morino	6/20/2000	Falk	☑	☐
126	378		354264e/3962744	7/13/1999	STAD OS	D	Morino	6/20/2000		☑	☐
127	384		354288e/3962819	7/13/1999	STAD	D	Morino	6/20/2000		☑	☐
128	120		Cell 7F	7/14/1998	STAD	D	Falk	2/26/2002		☑	☑
129	142	12	NOLOC	7/15/1998	LAB					☐	☐
130	148	AB	353157e/3963772	7/14/1998	STAD	D	Falk	1/10/2001		☑	☐
132	155		353162e/3963298	7/14/1998	STADOS	D	Falk	2/26/2002		☑	☑
133	165		352549e/3962643	7/15/1998	STAD	D	Falk/Hallman	8/29/2002		☑	☐
134	170		NOLOC	7/15/1998	STAD OS					☐	☐
135	180	12	352540e/3962644	7/15/1998	STAD	D	Falk	0/30/2000	Baisan	☑	☐
136	185	ABC	352466e/3962579	7/15/1998	STAD	D	Falk/Hallman	3/21/2002		☑	☑
137	248		109	7/9/1999	LAB	D	Falk	9/6/2001	Falk	☑	☑

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
138	253		166	7/8/1999	LAB OS	D	Falk	1/15/2003			✓
141	149	A12B	NOLOC	7/14/1998	LAB					☐	☐
143	214	AB	144	7/12/1999	LAB	D	Morino	6/20/2000		✓	☐
144	124	AB	140	7/14/1998	STAD	D	Falk	3/12/2000	Baisan	✓	✓
145	131	AB	146	7/14/1998	LAB	D	Falk	10/20/2000	Morino	✓	✓
150	255		109	7/9/1999	LAB	D	Falk	1/17/2003		☐	✓
153	8	12	NOLOC							☐	☐
154	234	A1234B	111	7/10/1999	LAB	D	Falk	10/29/2001		✓	☐
157	211	AB	144	7/12/1999	LAB	D	Falk/Baisan	1/10/2003		✓	✓
159	202	A12B12	170	7/14/1999	LAB	D	Morino	6/20/2000		✓	✓
160	326		141	8/19/1999	LAB	D	Falk	10/16/2001		✓	☐
161	327	12	141	8/18/1999	LAB	D	Falk	10/15/2001		✓	☐
162	328		141	8/18/1999	LAB OS	D	Falk	10/15/2001		✓	✓
163	329		141	8/18/1999	LAB OS	D	Falk	10/14/2001		✓	☐
166	226	AB	113	7/10/1999	LAB	D	Falk	9/27/2001		✓	☐
167	231	AB	113	7/10/1999	LAB OS	D	Falk	11/2/2001		✓	☐
169	235	B	111	7/10/1999	LAB OS	D	Falk	10/31/2001		✓	☐
171	260	AB	162	7/9/1999	LAB	D	Falk	1/26/2002		✓	✓
172	249		109	7/9/1999	LAB	D	Falk	1/17/2003			✓
181	271	AB	162	7/9/1999	LAB	D	Falk	1/26/2002		✓	✓
185	256	AB	166	7/8/1999	LAB	D	Falk	1/13/2003		✓	✓
186	257	AB	166	7/8/1999	LAB	D	Falk	1/15/2003		☐	✓
187	304	AB	121	8/14/1999	LAB	D	Falk	10/12/2001		✓	✓
189	309	AB	125	8/15/1999	LAB	D	Falk	12/6/2001		✓	☐
192	310	ABC	137	8/16/1999	LAB	D	Falk	7/17/2001		✓	✓
218	789		153	7/10/2001	LABOS	D	Falk/Hallman	6/7/2002		✓	✓
219	790		146	7/8/2001	STAD	D	Falk/Hallman	8/23/2002		✓	✓
220	793		153	7/11/2001	STAD/OS	D	Falk/Hallman	7/9/2002		✓	✓
221	794	AB	153	7/10/2001	STAD	D	Falk/Hallman	6/6/2002		✓	✓
222	795		153	7/10/2001	STAD	D	Falk	5/30/2002		✓	✓

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
223	796	AB	146	7/8/2001	STAD	D	Falk/Hallman	7/25/2002		☑	☑
224	797		146	7/10/2001	STAD/OS	D	Falk/Hallman	9/6/2002		☑	☑
225	800		153	7/11/2001	STAD/OS	D	Falk/Hallman	9/6/2002		☑	☑
226	943		142	7/11/2001	STAD/OS	D	Falk/Hallman	8/19/2002		☑	☑
227	944		142	7/11/2001	STAD	D	Falk/Hallman	8/14/2002		☑	☑
228	946		142	7/11/2001	STAD	D	Falk/Hallman	7/9/2001		☑	☑
229	947		142	7/11/2001	LAB OS	D	Falk/Hallman	8/23/2002		☑	☑
230	948		142	7/11/2001	STAD/OS	D	Falk/Hallman	8/14/2002		☑	☑
231	949		132	7/11/2001	STAD/OS	D	Falk/Hallman	9/3/2002		☑	☑
232	950		132	7/11/2001	STAD	D	Falk/Hallman	6/20/2002		☑	☑
233	951		132	7/11/2001	STAD	D	Falk/Hallman	8/28/2002		☑	☑
234	952		132	7/11/2001	STAD	D	Falk/Hallman	8/23/2002		☑	☑
235	953		132	7/11/2001	STAD	D	Falk/Hallman	8/14/2002		☑	☑
236	954		122	7/12/2001	STAD	D	Falk/Hallman	8/19/2002		☑	☑
237	955		122	7/12/2001	STAD	D	Falk/Hallman	7/9/2002		☑	☑
238	956		103	7/12/2001	STAD	D	Falk/Hallman	8/13/2002		☑	
239	957		103	7/13/2001	STAD	D	Falk/Hallman	8/27/2002		☑	☑
240	958		116	7/14/2001	STAD	D	Falk/Hallman	8/15/2002		☑	☑
241	959		116	7/14/2001	Lab OS	D	Falk/Hallman	6/20/2002		☑	☑
242	960		116	7/14/2001	STAD	D	Falk/Hallman	3/21/2002		☑	☑
243	961	A, B1-4	106	7/14/2001	STAD	D	Falk/Hallman	8/26/2002		☑	☑
244	998		106	7/14/2001	STAD	D	Falk	8/27/2002		☑	☑
245	1000	AB	153	7/10/2001	A-STAD B-STAD/OS	D	Falk/Hallman	7/26/2002		☑	☑
247	1610		106	7/14/2001	LAB	D	Falk/Hallman	3/21/2002		☑	☑
248	1611		106	7/14/2001	STAD/OS	D	Falk/Hallman	9/5/2002		☑	☑
249	1612		116	7/14/2001	STAD/OS	D	Falk/Hallman	8/23/2002		☑	☑
250	1613	12	116	7/14/2001	LAB	D	Falk/Hallman	9/8/2002		☐	☐
251	1614		102	7/13/2001	CHRIS					☐	☐
252	1615		102	7/13/2001	LABPC					☐	☐
253	1616		102	7/13/2001	LAB	D	Falk	8/27/2002		☑	☑

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
254	1617		102	7/13/2001	STAD/OS	D	Falk	9/3/2002		☑	☑
256	1619		102	7/13/2001	LAB	D	Falk/Hallman	7/19/2002		☑	☐
257	1620		112	7/13/2001	STAD/OS	D	Falk/Hallman	8/26/2002		☑	☑
258	1621		112	7/13/2001	STAD/OS	D	Falk/Hallman	7/23/2002		☑	☑
259	1622		112	7/13/2001	LAB	D	Falk/Baisan	12/24/2002		☑	☑
261	1624		112	7/13/2001	LAB	D	Falk/Hallman	9/6/2002		☑	☑
262	1625	AB	112	7/13/2001	LAB	D	Falk/Hallman	9/6/2002		☑	☑
264	1627		112	7/13/2001	STAD	D	Falk/Hallman	9/4/2002		☑	☑
265	1628		112	7/12/2001	STAD	D	Falk	5/30/2002		☑	☑
266	1629		122	7/12/2001	STAD	D	Falk/Hallman	8/15/2002		☑	☑
267	1630	AB	122	7/12/2001	A-STAD, B-LABPC	D	Falk/Hallman	8/15/2002		☐	☑
268	1631	ABC	138	7/12/2001	LAB	D	Baison/Falk	11/25/2002		☑	☑
270	1633		138	7/12/2001	STAD	D	Falk/Hallman	8/13/2002		☑	☑
271	1634		157	7/11/2001	STAD	D	Falk/Hallman	6/20/2002		☑	☑
272	1635		157	7/11/2001	STAD	D	Falk/Hallman	8/23/2002		☑	☐
273	1638		148	7/11/2001	STAD	D	Falk/Hallman	7/18/2001		☑	☑
274	1639	B12	148	7/8/2001	A-STAD,B2-STAD O	D	Falk/Hallman	7/26/2002		☑	☑
275	1640		148	7/11/2001	STAD	D	Falk/Hallman	8/27/2002		☑	☑
276	1641	A12,B	148	7/8/2001	LAB	D	Falk/Hallman	9/4/2002		☑	☑
277	1642	A12,B1	148	7/11/2001	LAB	D	Falk/Hallman	6/5/2002		☑	☑
278	1643		148	7/8/2001	MISSING	D	Falk/Hallman	6/20/2002		☑	☑
279	1644		148	7/11/2001	STAD	D	Falk/Hallman	9/6/2002		☑	☑
280	1645	X	138	7/11/2001	STAD	D	Falk/Hallman	7/25/2002		☑	☑
281	1646		138	7/11/2001	STAD	D	Falk/Hallman	9/8/2002		☑	☑
282	1647		138	7/11/2001	STAD	D	Falk/Hallman	7/23/2002		☑	☑
283	1648	AB	148	7/11/2001	STAD	D	Falk/Hallman	9/3/2002		☑	☑
284	1649		138	7/11/2001	STAD	D	Falk/Hallman	9/8/2002		☑	☑
285	1650		138	7/11/2001	STAD	D	Falk/Hallman	7/10/2002		☑	☑
286	1652		153	7/9/2001	LAB/OS	D	Falk/Hallman	9/4/2002		☐	☐
287	2060		146	7/8/2001	STAD	D	Falk/Hallman	9/6/2002			

ID	Tree	Sec	Grid point	Coll date	Location	Status	Dated by	Dated on	Date ck	FHX2	Nonrec
288	2100		153	7/9/2001	SHOP/OS	D	Falk/Hallman	7/25/2002		☑	☑
289	2128	AB	146	7/9/2001	STAD	D	Falk/Hallman	7/26/2002		☑	☑
292	1623	AB	112	7/13/2001	LAB B-SHOP/OS	D	Falk/Hallman	6/3/2002		☑	☑
293	1626	AB12	112	7/13/2001	LAB	D	Falk/Hallman	8/29/2002		☑	☑
294	1632	AB	138	7/12/2001	A-STAD/OS. B-STA	D	Falk/Hallman	7/19/2001		☑	☑
297	2062		146	7/8/2001	STAD	D	Falk/Hallman	8/29/2002		☑	☐
298	1609		106	7/14/2001	LAB	D	Falk/Hallman	8/14/2002		☑	☑
300	1618	A,B	102	7/13/2001	A-STAD/OS, B-SHO	D	Falk	9/3/2002		☑	☐
304	999		132	7/11/2001	STAD	D	Falk/Hallman	8/23/2002		☑	☑
307	317		158	8/17/1999	Chris					☐	☐
308	318		158	8/17/1999	LAB	D	Falk	11/26/2002		☐	☑
309	316		158	8/17/1999	LAB	D	Falk	11/25/2002		☐	☑
310	254		166	7/8/1999						✓	✓
311	254		166	7/8/1999	LAB	D	Falk	1/14/2003		☐	✓

Table 4. Summary of collections and temporal extent of fire history at sampled grid cells at MCN.

Grid cell	Number of trees sampled	Inner and outer ring years	Temporal extent of record (yr)	Earliest fire year	Last fire year
101	4	1642-1999	358	1665	1933
102	3	1612-1999	388	1684	1933
103	2	1574-1999	426	1648	1880
105	2	1624-2000	377	1648	1887
106	5	1622-2001	380	1680	1942
107	3	1602-1999	398	1691	1880
109	2	1705-1999	295	1801	1929
111	5	1354-2000	647	1450	1880
112	9	1581-2001	421	1648	1961
113	6	1564-2001	438	1639	1905
115	4	1621-2000	380	1648	1912
116	5	1628-2001	374	1664	1876
117	3	1484-2000	517	1729	1887
119	2	1636-1999	364	1664	1893
121	4	1525-1999	475	1600	1929
122	4	1610-2001	392	1654	1893
123	3	1620-1999	380	1648	1936
125	2	1647-1999	353	1716	1880
127	2	1625-2000	376	1658	1893
129	3	1600-2000	401	1664	1955
130	3	1629-1999	371	1704	1929
131	5	1383-1999	617	1505	1937
132	6	1610-2001	392	1639	1887
133	2	1797-1999	203	1836	1899
135	6	1484-2000	517	1648	1911
137	4	1510-2000	491	1542	1951
138	9	1450-2001	552	1509	1893
140	1	1540-2000	461	1745	1801
141	4	1616-2000	385	1654	1893
142	5	1547-2001	455	1610	1942
143	3	1548-1999	452	1576	1915
144	5	1484-2000	517	1618	1929
145	3	1703-1999	297	1729	1896
146	7	1508-1999	492	1659	1899
147	2	1598-1999	402	1705	1896
148	7	1436-2001	566	1467	1937
149	2	1645-2000	356	1724	1876
151	3	1597-1999	403	1684	1893
153	8	1380-2001	622	1597	1904
154	3	1617-1999	383	1729	1921
156	3	1570-1999	430	1622	1893
157	2	1658-2001	344	1714	1893

158	2	1649-2000	352	1724	1955
160	4	1553-1999	447	1665	1893
162	4	1673-2000	328	1684	1938
164	3	1623-1999	377	1654	1981
166	5	1578-2000	423	1598	1893
170	6	1484-2000	517	1684	1929
180	3	1484-2000	517	1601	1909
188	5	1484-2000	517	1696	1892
Mean ± 1 s.d.	4.0 ± 1.9	1574 ± 87 to 2000 ± 1	427 ± 88	1654 ± 74	1909 ± 30
Study area	198	1354-2001	648	1450	1981

Table 5. MCN Grid Point UTM's
As of 21-Jul-2003

Grid point	*Easting*	*Northing*	*Verified*
100	352400	3962650	N
101	352588	3962602	Y
102	352799	3962653	Y
103	352983	3962633	Y
104	353199	3962653	N
105	353392	3962664	N
106	353598	3962645	Y
107	353800	3962657	Y
108	353998	3962648	N
109	352405	3962848	Y
110	352597	3962859	Y
111	352800	3962859	Y
112	353007	3962849	Y
113	353194	3962859	Y
114	353396	3962856	Y
115	353601	3962853	Y
116	353789	3962850	N
117	353999	3962853	Y
118	352401	3963054	Y
119	352599	3963054	Y
120	352807	3963056	Y
121	353011	3963054	Y
122	353197	3963056	Y
123	353392	3963054	Y
124	353579	3963039	Y
125	353797	3963034	Y
126	354004	3963059	N
127	352398	3963263	N
128	352599	3963253	Y
129	352801	3963253	Y
130	353000	3963257	Y
131	353195	3963250	Y
132	353399	3963254	Y
133	353600	3963255	Y
134	353778	3963243	Y
135	353995	3963253	N
136	352404	3963454	Y
137	352595	3963459	Y
138	352797	3963452	Y
139	353014	3963443	N
140	353199	3963454	Y
141	353399	3963449	Y
142	353599	3963453	N
143	353799	3963446	Y
144	353996	3963453	Y
145	352393	3963658	N
146	352598	3963652	Y
147	352807	3963647	Y

148	353000	3963647	N
149	353194	3963647	Y
150	353397	3963659	Y
151	353606	3963653	Y
152	353794	3963656	Y
153	352395	3963841	Y
154	352599	3963852	Y
155	352796	3963854	Y
156	352989	3963851	Y
157	353199	3963853	Y
158	353396	3963853	Y
159	353599	3963853	Y
160	353814	3963849	Y
161	353995	3963855	N
162	352392	3964065	N
163	352601	3964060	Y
164	352800	3964055	Y
165	353005	3964058	Y
166	353198	3964061	Y
167	353399	3964053	Y
168	353608	3964006	N
169			
170	354000	3964050	N
171			
179			
180	353998	3963649	Y
181			
182			
183			
184			
185			
186			
187			
188	354215	3962848	N

Non-grid locations:

200			
300	353983	3963199	Y
301	354264	3962744	Y
302	354288	3962819	N
303	354107	3963041	N
304	354082	3963118	N
305	354005	3963339	N
306	353986	3963377	N
307			
400	353799	3963653	Y
401	353199	3963453	N
402	352598	3963652	Y

Scaling rules and probability models for surface fire regimes in Ponderosa pine forests

Donald A. Falk and Thomas W. Swetnam[1]

Introduction

Many ecological processes scale in time and space in ways that are determined by underlying mechanistic or stochastic processes. For example, at the level of the individual organism, body size, growth and metabolic rates, and a variety of life history traits are related systematically and can be expressed as allometric or bioenergetic scaling rules (Wiens 1989; West, Brown et al. 1997; Enquist, West et al. 1999). Recent work (Enquist and Niklas 2001; Niklas and Enquist 2001) has shown that these scaling proprieties can be extended to the structure, composition, mass, and productivity of complex ecological communities. The unifying force across these levels of biological organization is the efficiency of energy flow, which is a strong selective force in organismal evolution. Ostensibly emergent properties of communities and ecosystems can thus be related to fundamental biophysical constraints.

Because they involve distribution and flows of energy and materials, disturbance processes can be expected similarly to following scaling rules in space and time (Holling 1992; West, Brown et al. 1997; Enquist, Brown et al. 1998; Ritchie and Olff 1999; Wu 2001). In general, we may predict that ecosystem process will scale both spatially and temporally with the factors that regulate events, and not simply as a function of geometry. Before we can assess scaling patterns in disturbances, however, we must be able to characterize disturbance events quantitatively and measurably.

Disturbances of a particular type are often grouped together under a "regime" (Pickett and White 1985; Agee 1993). While "regimes" are often discriminated qualitatively (*e.g.* "stand-replacing" *vs.* "surface fire" regimes), they can be more usefully defined by a series of quantitative descriptors (*see table of metrics, this report*). Because a disturbance regime involves multiple dimensions, we define a disturbance regime here

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as a multivariate space, not a single dimension. By defining disturbance regimes in multivariate terms, we open the way for quantitative analyses rather than verbal descriptors to characterize the regime at any given place and time. Moreover, by describing the regime with a set of quantitative variables, each with associated measures and statistical characterization, evaluation of the natural range of variability is possible at any period across locations and spatial scales, and across time for any given spatial extent.

To illustrate these principles, we examine a 450-yr record of fire events in an old-growth New Mexico (USA) Ponderosa pine forest, using tools of dendrochronology. Because fires in this ecosystem generally have low to moderate intensity of the flaming front with variable duration at the tree scale (Weaver 1951; Kilgore and Taylor 1979; Agee 1993; Allen 2001), mortality is size-dependent: most mature trees survive most fires, while most smaller and younger trees do not (*i.e.*, mortality decreases with size). For fires above a threshold of temperature and exposure time, the cambium of mature trees will be killed locally at the locus of highest exposure. This dead cambium, and the tree growth response around it, creates a lesion that persists in the wood long after the event has passed. In tree species with growth rings that can be dated with annual or sub-annual precision, the year (and, in many cases, season) of individual fire events can be dated to year (Arno and Sneck 1977; Kilgore and Taylor 1979; Dieterich 1980a; Romme 1980; McBride 1983; Swetnam and Dieterich 1985; Veblen, Kitzberger et al. 1999). The spatial distribution of fire events in any given year can be assessed if samples are suitably distributed across the landscape (Niklasson and Granström 2000; Heyerdahl, Brubaker et al. 2002). With these tools a record of disturbance events is created, and their distribution in space and time becomes available for analysis.

Disturbance regimes are ultimately composed of events. Where these events are discrete, they can be mapped in space and time, and their distribution and scaling properties analyzed (Falk and Swetnam 2003). In this paper we apply an analytical framework adapted from species biogeography and macroecology to study scaling effects in the disturbance regime. In effect, we substitute "fire date" for species", and then evaluate spatial and temporal scaling properties of the disturbance regime. We ask: Do quantitative descriptors of the fire regime scale in space and time? Is there an underlying probability distribution that can describe intervals between fire events? And finally, do these scaling relationships reflect governing biophysical processes, such as entrainment of the fire regime by climate?

Methods

Study site and field methods. Monument Canyon Research Natural Area (MCN) is located in the western Jemez Mountains of north-central New Mexico, USA (*see site map and description, field methods description, this report*). Further details of field sampling protocols are provided elsewhere in this report (Falk 2000).

Specimen preparation and data reduction.

Fire-scar specimens (partial or full cross-sections) collected in the field were prepared and analyzed at the University of Arizona Laboratory of Tree-Ring Research (LTRR), using standard techniques in dendrochronology **(Dieterich and Swetnam 1984; Fritts and Swetnam 1989).** Each section was crossdated to a local master chronology, to ensure accuracy of dating trees with possible locally absent or missing rings. Once the entire ring sequence for each specimen was dated, we recorded the year of each visible fire lesion.

Data analysis.

Fire dates for each tree were entered into FHX2, a software program designed specifically for fire history analysis (Grissino-Mayer 1995). The resulting data set is a years × trees matrix, in which each cell is valued as 1 (fire recorded for that year) or 0 (no fire recorded). Because individual trees do not always record every fire event in their vicinity, we made a composite record for each grid point consisting of all fire dates recorded by any tree at that location (Dieterich 1980b). Thus, the grid-based 0.5 ha search area constituted our minimum resolution or Minimum Map Area (MMA) for reliable reconstruction of the fire record. For the same reason, fire occurrence is recorded only as presence (1) or absence (0), not relative abundance (*e.g.*, proportion of trees recording a fire).

Fire history metrics. For each grid-point composite, we calculated statistical measures of the fire regime (*this report*), including total number of events detected, measures of central tendency (arithmetic mean, median, and mode) for fire intervals (yr $event^{-1}$), as well as higher moments (skewness and kurtosis).

Analytical tests. We applied a series of procedures commonly used in species biogeography to test for the occurrence of spatial and temporal scaling relationships in the statistical descriptors of the fire regime. We did so by substituting "fire years" for "species" in the 450-yr record of events. In a surface fire regime such as the one studied here, subsequent fires often do not eliminate the evidence of prior events. Thus, a given site can retain a record of individual fire events hundreds of years long, and individual trees with > 20 scars are not uncommon. This contrasts with high-intensity, stand-replacing regimes where large, catastrophic fires destroy the tree record of prior fires on a given location (Heinselman 1981; Romme 1982). The retention of a series of fire records at a single point in space allows us to map the spatial extent of individual fires as well as their progression in time. Tests used included:

Event-area relationships. Because they are entities distributed spatially across the landscape, fire spatial patterns can be studied by applying tools similar to those used in species biogeography. The relationship between species richness and area of a sample or ecosystem is among the most widely studied patterns in species biogeography (Arrhenius 1921; MacArthur and Wilson 1967; Connor and McCoy 1979; Palmer and White 1994; Rosenzweig 1995). At small scales the accumulation ("collector's") curve dominates (Pielou 1977; Magurran 1988), but once sample size is sufficiently large, the number of species encountered increases as a power function of area, $s = cA^z$, with s species richness, c a scaling constant that varies among organism groups, A area, and z a rate constant that varies with ecosystem type and biogeographic scale (MacArthur and Wilson 1967; Rosenzweig 1995). With logarithmic transformation, the relationship is a liner function, $\log s = \log c + z \log A$. The value of s at the y-intercept (c) represents the "point" (alpha) diversity. Steeper values of the slope term z indicate faster accumulation of new species with increasing area. Because $z < 1$ (nearly always the case; most values are in the range 0.15 - .35, except for comparisons among very large areas), the rule says in effect that small areas are more species-rich *per unit area* than large areas.

In the current context, we can assess event-area relationships in two ways. First, we can count the number of fires (F) detected in a sample; this will stand as equivalent to species richness (S). Because fires are events in both space and time, we must define the sample temporally as well as spatially; this is conventionally done by calculating fire frequency, which is the number of fires per unit time (typically per century), giving F units of fires $century^{-1}$. A related measure, fire interval, is the number of years between fire events, or 1/F, with units of yr $fire^{-1}$. Both frequency and interval can be expressed statistically as mean, median, or modal values, and their higher moments calculated.

We tested for the effect of area by making spatially explicit subsets of the data set. Because the data are from known locations, we can create composite fire chronologies for any defined area within the study site. This can be accomplished by creating either nested series of samples beginning at any point, or non-nested samples of varying area centered on random points in the study site up to the full extent of the study (Palmer and White 1994). Sample size and sample area can be varied independently in our study design (Falk 2004).

The interval-area relationship. The fire interval is of direct ecological interest because it represents the time between fire events. This interval is potentially important in forest demography because of size-dependent mortality: seedlings and saplings are unlikely to survive fires (Ryan and Reinhardt 1988; Peterson, Sackett et al. 1994), so if the time interval between events is short, the probability increases that they will be exposed to a lethal event. By contrast, longer fire-free intervals allow young trees to attain size and morphology that makes their survival more likely (although fires also become more intense with time since previous event, due primarily to fuel accumulation).

Both F (fire frequency) and MFI (mean fire interval = 1/F) can be tested for area dependence in a fashion similar to species richness. The predicted event-area function for frequency is a power law,

$$F = eA^y, \text{ hence } \log F = \log e + y \log A,$$

where e and y are scaling constants analogous to c and z in the species-area relationship. Similarly, the predicted interval-area relationship for mean fire interval over any defined period *t* is

$MFI_t = emA^x$, and $\log MFI_t = \log e + y \log A$.

We expect F(A) to have a positive slope, since sampling larger areas across the landscape should encounter more fires in a patchy fire regime (Arno and Peterson 1983). Likewise, MFI_t (A) should be negatively sloped, because if larger area samples detect more fires, the denominator of the interval statistic increases. The decreasing fire interval statistic can also be interpreted as follows: as larger areas are sampled, the likelihood increases of a fire occurring somewhere in any given year.

Probability models for interval distributions. Fire interval probabilities have most commonly been modeled using 2- and 3-parameter versions of the Weibull distribution (Johnson and VanWagner 1985; Johnson 1992; Johnson and Gutsell 1994), a continuous probability model that describes the effects of stress accumulation and hence is often used to model time to failure (*e.g.* metal fatigue, breaking points of materials, etc.) (Bain and Engelhart 1987; Johnson, Kotz et al. 1994). Although few alternative models have been explored adequately, use of the Weibull to model fire interval probabilities has become widespread (Clark 1989; Johnson 1992; Agee 1993; Swetnam and Baisan 1996; Gardner, Romme et al. 1999; Grissino-Mayer 1999). Here we introduce an alternative lognormal model based on first principles in surface fire ecology.

Continuous probability distributions such as the Weibull have generally been used to model fire intervals. However, it is not clear that continuity is an appropriate assumption for fire regimes in the Southwest. Fire data in the dendroecological record are inherently annual in their resolution, as reflected in the record of annual fire dates derived from analysis of fire scars or establishment dates. One way of making this evident is by attempting to increase the resolution of the record, which should be possible in a truly continuous distribution. When we ask about sub-annual patterns of fire occurrence, we are asking a different question (*i.e.*, seasonality), not simply improving the precision (*i.e.*, smaller units) of a fire interval estimate. Thus, fire dates are not infinitely divisible as is typically assumed for continuous data.

A related implication of a continuous distribution is that observations are unitary. For example, we do not interpret a temperature of 32° as the sum of two temperatures of 16°, nor a blood pressure of 120 mg as the sum of 80 mg and 40 mg. In fire history studies, the parallel assumption is that fire intervals of *t* years are a single event, which permits the use of a continuous frequency distribution.

Forest fires in Ponderosa pine ecosystems do not conform to this unitary assumption. Both the fire record and fire events are composed inherently of a series of discrete, binary events. In southwestern forests, fire occurrence has a finite probability each year, with an outcome of fire or no fire. Thus, each year can be defined as a Bernoulli trial, where the outcome is one of two possible states (0,1) (Bain and Engelhart 1987). A fire interval of 10 yr is thus the accumulation of 10 separate no-fire years. In this respect, discrete probability models such as the negative binomial (years before the first success) may be more appropriate. An assumption of Bernoulli probability is that each trial is independent, whereas fire (or its absence) in year *t*-1 may have some effect on the probability of fire in year *t*.

The capture of a fire scar in a sample is the result of a series of contingent events, each with its respective probability distribution (sufficient fuel, proper fuel moisture and wind, ignition source, trees of species, age and size likely to be scarred, survival of the fire, capture in a sample). Thus, the eventual probability P_{tot} that a fire event will occur, be recorded by the tree, and sampled by a researcher is the contingent product of the probabilities of N constituent factors:

$$P_{tot} = p_1 \times p_2 \times p_3 \times p_4 \times \ldots p_N = \Pi_{i=1 \ldots N}\, p_i .$$

Taking the log of both sides gives:

$$\log P_{tot} = p_1 + p_2 + p_3 + p_4 + \ldots p_N = \Sigma_{i=1 \ldots N}\, p_i .$$

Sums of random variables approach normality under the central limit theorem, provided there are a sufficient number (often ≥ 10 is enough) (Montroll and Shlesinger 1982). The resulting distribution of log-transformed variates is thus expected to approach normality. We therefore propose that fire intervals are lognormally distributed.

Results

We restricted our analyses to the period 1600-2000, for which there is sufficient sample size at all grid points.

Analytical tests.

Event-area and interval-area relationships. Fire dates accumulated in simulated samples of increasing area (Figure 1). The lack of downward concavity suggests high patchiness in the fire regime: with increasing area, new events continue to be encountered at a high rate, although many of these events were small.

Mean fire interval was strongly scale-dependent (Figure 2). Following the predicted power rule, the function is linear in log-log space (log MFI = 2.99 - 0.32 log A, r^2 = 0.98. Individual plots recorded fires at mean intervals ranging from 7-23 yr (mean = 12). Extrapolation to the tree scale (0.01-0.05 ha) suggests common intervals of 9-35 yr, although we consider this scale below the minimum reliable spatial resolution for field verification. As data from adjacent grid points were added together to form larger spatial composites, more fires were encountered and MFI decreased to 7 yr for 10-ha composite samples and 4 yr for sample areas of 100 ha.

Probability model. Lognormal functions provided a good fit to the observed distribution of fire intervals for spatial composites of 1-16 grid points (Figure 3). This suggests that the more parsimonious and theoretically grounded lognormal distribution has potential application in fire history research. Interestingly, a comparison of the computed Weibull median probability interval (WMPI) with the simple arithmetic mean was highly correlated (*i.e.*, little added information in the more complex model) for Monument Canyon; a similar result was obtained for a broader dataset from the southwestern United States (Figure 4 a, b).

Conclusions, discussion, and future research directions

Scale dependence is demonstrated in the fire regime of an old-growth Ponderosa pine forest. All measures of the fire regime tested appear sensitive to sample area; number of fires and mean interval were also found to be sensitive to sample size (number of trees). Thus, the notion of a unitary fire regime independent of scale is untenable; instead, we see that the fire regime is a scale-dependent characterization of an ecosystem.

Inclusion of additional samples from previous research efforts in adjacent areas of the Jemez Mountains (Morino, Baisan et al. 1998; Allen 2001) will allow the tests used here to be applied across 6 orders of magnitude in spatial scale (5×10^{-1} - 10^4 ha). Several other recent fire history studies have used a spatial array of sampling points (Brown, Kaufmann, and Shepperd 1999; Niklasson and Granström 2000; Skinner 2000; Veblen, Kitzberger, and Donnegan 2000; Heyerdahl, Brubaker, and Agee 2001). A meta-analysis of these studies may reveal even more general scaling rules.

Distinguishing sample size and sample area is important, for the same reasons as in species biogeography: the collector's curve can dominate the species- (event-) area function at small spatial scales. In the MCN case, the grid-based design allows sample size and sample area to be decomposed using a factorial procedure, assembling a composite data set for increasing sample size (number of trees) selected at random from a series of increasing sample areas (*this report*).

The event-area relationship has many potential applications in fire and forest management. In ecology, scaling relationships have important implications for forest demography and stand dynamics. In southwestern pine forests, both mortality and scarring of survivors from fire events is strongly age-and size-dependent. Individual trees are, however, affected only by fires that are near enough to generate the threshold values of exposure time and cambial temperature; fires that are too far away would have little effect. Thus, to understand the regulatory influence of fires of forest demography, we must evaluate fire occurrence (as well as fire-free intervals) at the "tree-scale". While much further research is required to define the radius of effect for fires on seedlings and saplings, the spatial domain of demographically effective surface fires is undoubtedly closer to 0.05 ha than to 500 ha. A fire occurring 1,500 m away probably has no demonstrable effect on the survival, growth, or reproduction of a target tree, whereas a fire within 50 m is likely to affect all three demographic parameters. Scale dependence in the fire regime is the key to understanding the spatial aspects of forest demography.

The event-area relationship can also be used as the basis for a measure of spatio-temporal synchrony of events. Independent fire events can be synchronized regionally by climate, particularly the period events such as El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). (Swetnam and Betancourt 1990; Swetnam and Betancourt 1992; Grissino-Mayer 1995; Grissino-Mayer and Swetnam 2000; Heyerdahl, Brubaker et al. 2001). When events (such as fires) are synchronous across the landscape, fires that occur anywhere occur everywhere; this would lead to a collector's curve that immediately reaches the asymptote and an MFI-area function with a flat (approaching 0) slopes, because as sample area increases, few events are encountered that have not already been detected. By contrast, during periods when fires are not synchronized regionally, the collector's curve rises more gradually, and the MFI-area function declines at a faster rate because the landscape is dotted with small, un-correlated events. We propose that the slope of the interval-area relationship provides a statistical measure of regional entrainment of the fire regime by climate, and an indicator of when "regime shifts" have occurred.

In terms of forest management, understanding the scaling relationships of the natural fire regime can be a powerful tool for restoring natural or prescribed fire intervals in fire management programs (Allen, Savage et al. 2002). In a simplistic example, fire intervals from data collected at the 100 ha scale (a common extent for fire history samples) might applied uniformly across the landscape down to the level of individual tree clusters. The negative slope of the MFI-area relationship shows, however, that smaller areas experience fires less frequently than do larger areas. Scaling rules could help to make prescribed natural fire programs more realistic in their application.

The non-zero slope of the MFI-area function also suggests the importance of reporting search area as an integral element of fire interval statistics. Because the mean fire interval is non-stationary over area, sample area should be reported explicitly for a particular sample area (*e.g.*, "7.5 yr per 100 ha). The use of area-corrected units should become standard practice to avoid confusion in interpretation of interval data in research and management alike.

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Figures:

1. Figure 1. Accumulation functions ("collector's curves") for the number of fire events recorded as a function of sample area.

2. Figure 2. Dependence of mean fire interval on sample area. Log MFI (ordinate) decreases with increasing area sampled (abscissa, log scale). Data points are means of MFI for simulated sample areas of differing sizes.
3. Figure 3. Scale dependence of the frequency distribution of fire intervals for nested spatial samples of 1-16 grid points, with fitted lognormal (red) and Weibull (green) distributions.
4. Figure 4. Correlation of mean and Weibull median probability interval (WMPI) for Monument Canyon and a network of sites in the American Southwest.

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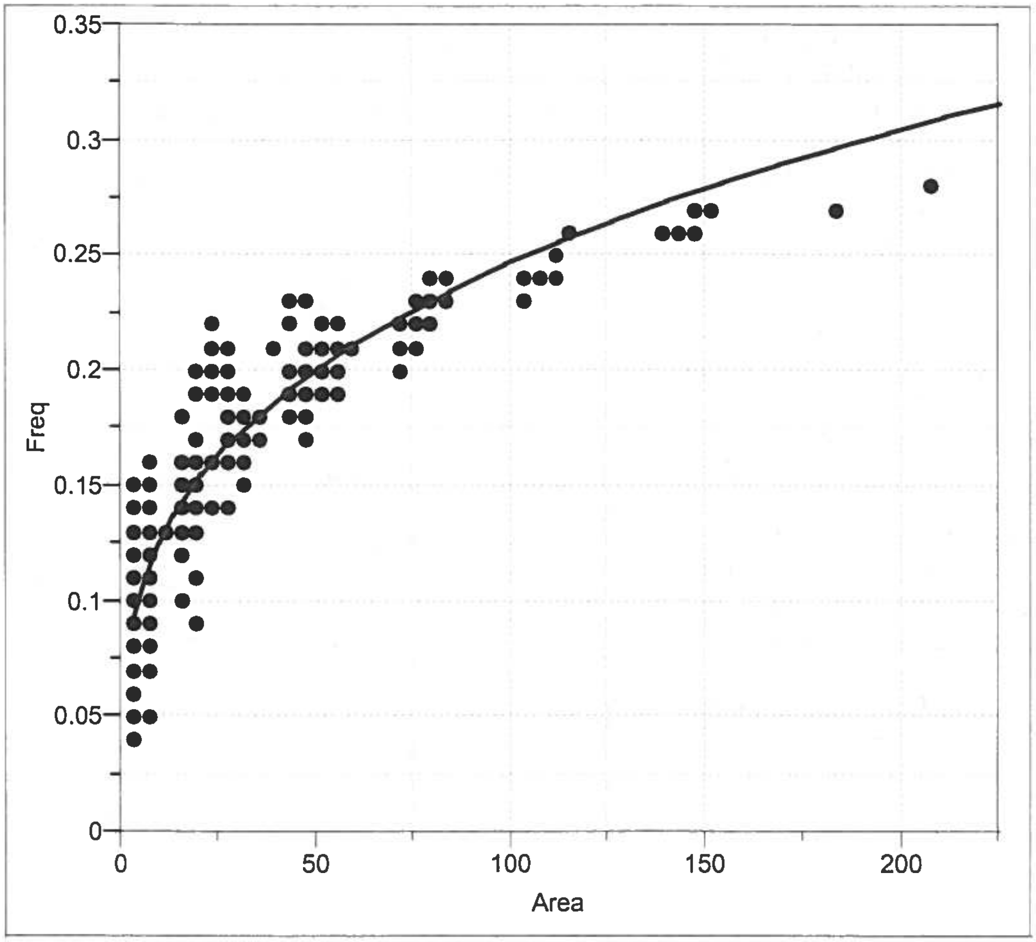
Figure 1.



Transformed Fit Log to Log

Log(Freq) = -2.797398 + 0.303681 Log(Area)

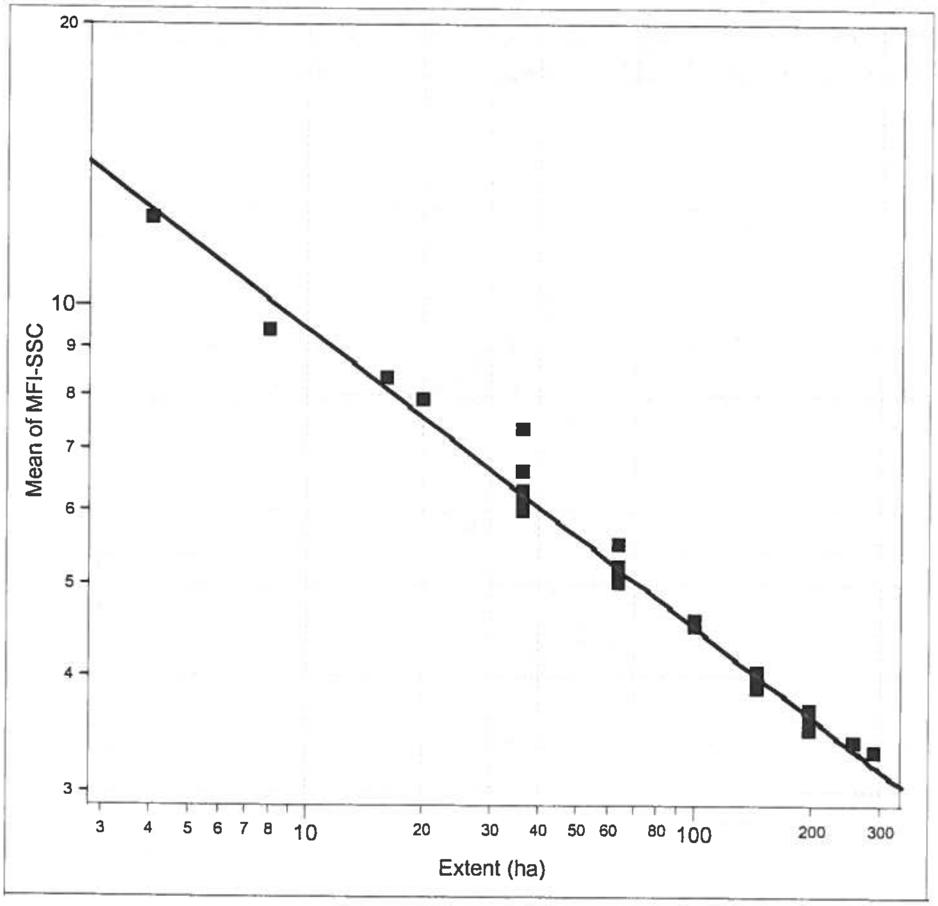
Summary of Fit

RSquare	0.74
RSquare Adj	0.74
Root Mean Square Error	0.21
Mean of Response	-1.92
Observations (or Sum Wgts)	241

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	28.48	28.48	676.91
Error	239	10.06	0.04	Prob > F
C. Total	240	38.53		<.0001

Figure 2. Summary of area effect on MFI (SS corrected). Log-log plot of mean fire interval (MFI) as a function of area (ha).



——Transformed Fit Log to Log

Log(Mean of MFI-SSC) = 2.9901034 - 0.3218465 Log(Extent (ha))

Summary of Fit

RSquare	0.98
RSquare Adj	0.98
Root Mean Square Error	0.04
Mean of Response	1.62
Observations (or Sum Wgts)	29

Analysis of Variance

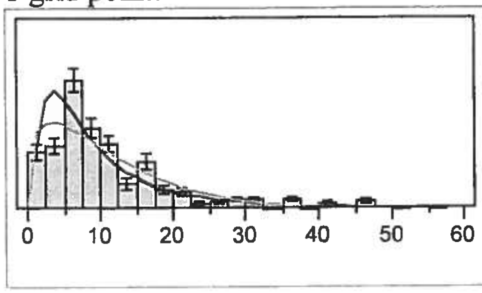
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3.05	3.05	1602.47
Error	27	0.05	0.00	Prob > F
C. Total	28	3.10		<.0001

FIG. 3

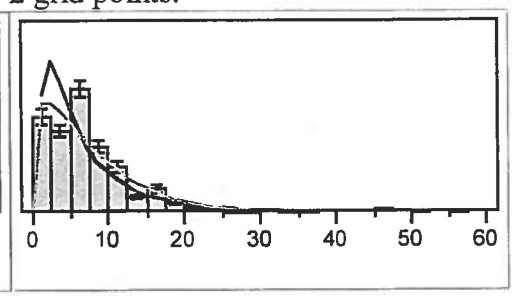
Scale dependence of modal fire interval for nested spatial samples.

Data composited for all sampled grid points at MCN. *x*-axis in yrs (interval since previous fire); *y*-axis in frequency. Fitted lognormal (red) and Weibull (green) functions show dependence of modal interval on sample area.

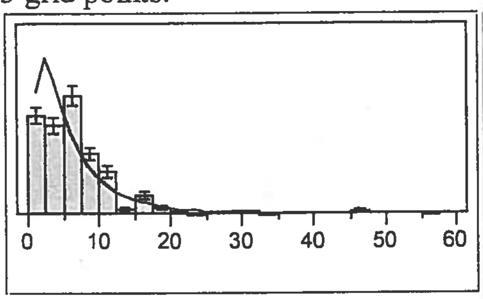
1 grid point:



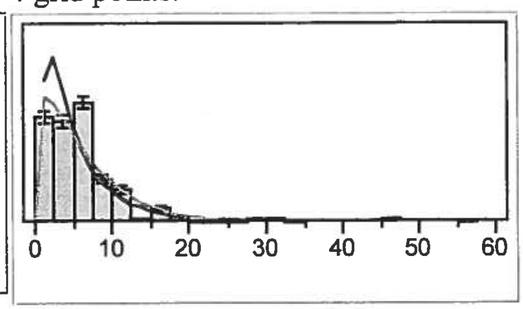
2 grid points:



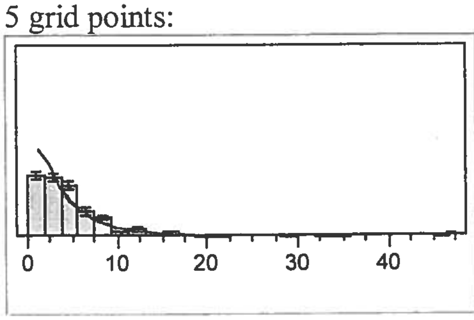
3 grid points:



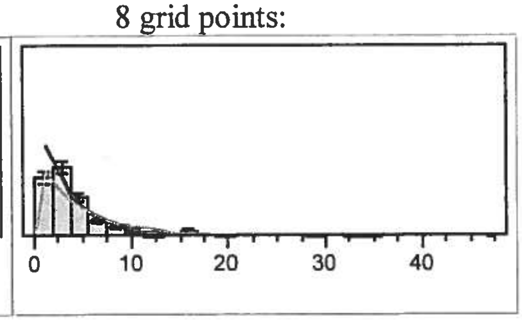
4 grid points:



5 grid points:



8 grid points:



16 grid points:

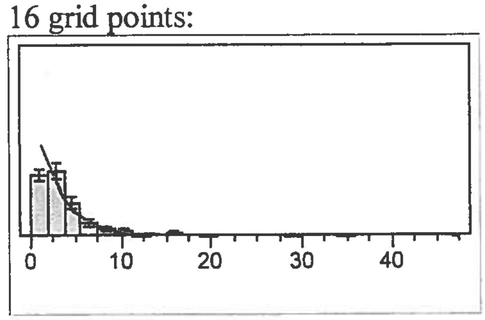
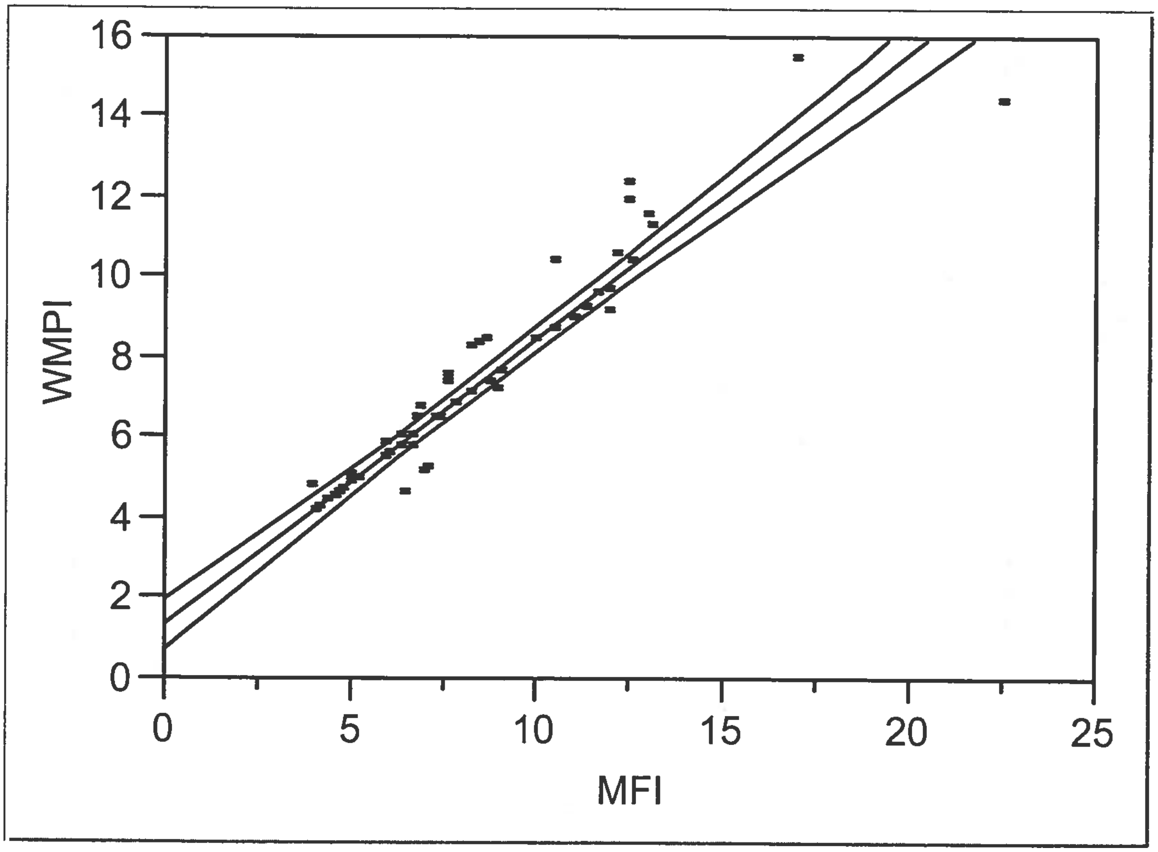


Figure 4.

a. Correlation of Mean and Weibull Median Fire Interval at Monument Canyon RNA, New Mexico

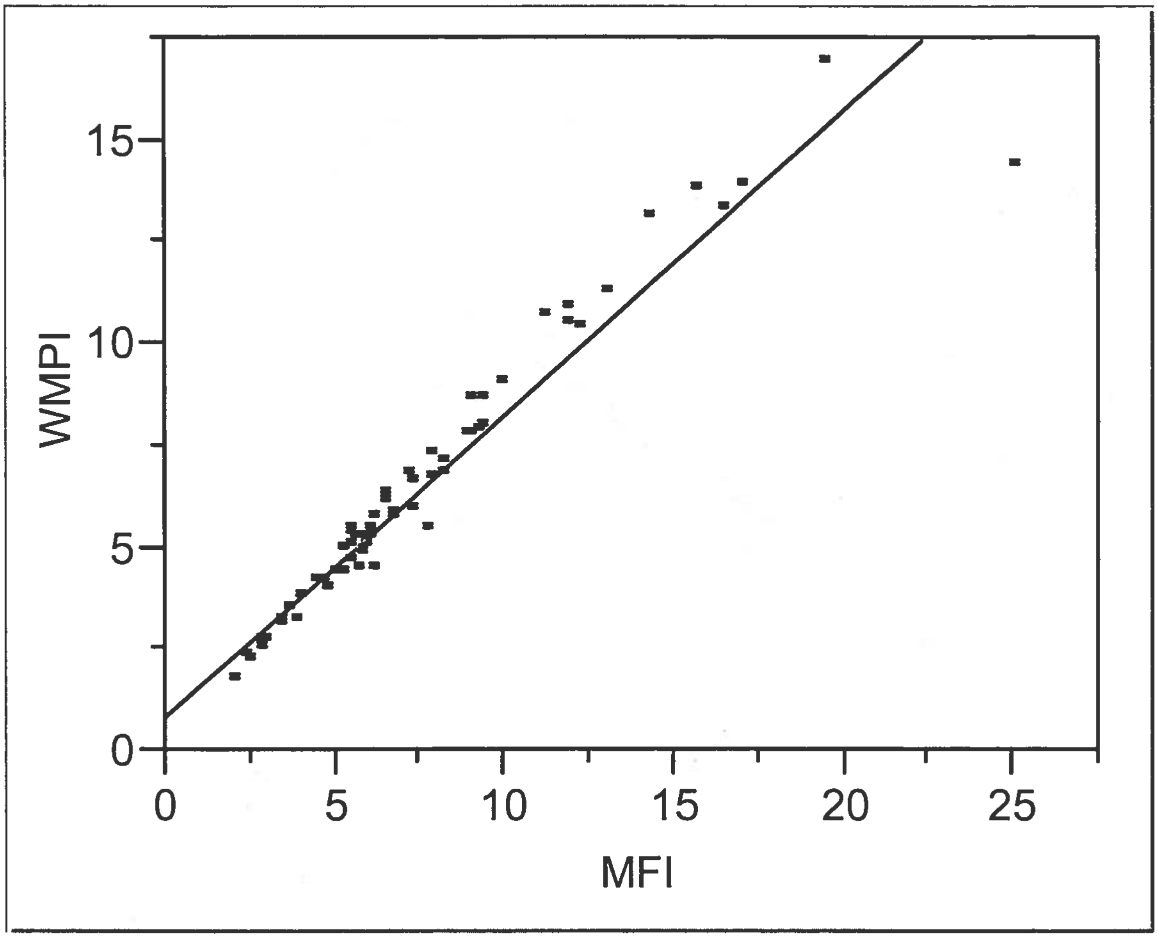


WMPI = 1.37 + 0.71 MFI

Summary of Fit

r^2	0.91
r^2 Adj.	0.90
Observations	53

b. Correlation of Mean and Weibull Median Fire Interval for 63 fire history sites in southwestern North America. Data from Table 2 of Swetnam & Baisan 1996.



WMPI = 0.80 + 0.74 MFI

r^2	0.93
r^2 Adj.	0.93
Sites	63

Theory and effects of sample size in fire history.[1]

Fire history research requires the reconstruction of ecological events that occurred in the past, using evidence that survives to the present. We can calibrate this evidence of past events with contemporary observations, for example by observing the processes of ring growth or fire scar formation under known conditions. However, as in any paleoecological reconstruction, any individual remnant evidence represents an incomplete picture of the events and conditions at the time of their creation. This limitation is well recognized by paleoecologists, who are careful to limit their domain of generalization. For example, variation in ring widths from an individual tree may represent an unknown combination of tree age and vigor, competition, water and nutritional status, genotype, mechanical injury, insect damage and fungal diseases, and interannual climate variation (Fritts 1976). For this reason, samples must be sufficiently replicated to eliminate sources of variation that apply only to a single tree or group of trees.

A similar *caveat* applies in fire history research. In the historic fire regime of forests of southwestern North America dominated by Ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelmann), low-intensity fires burned primarily through the surface (litter) and sub-surface (duff) fuels, less commonly through the crowns of mature trees. Such fires commonly caused basal damage to the lateral meristem (cambium) and roots of trees, heating cambial cells beyond a critical threshold near 60 °C, at which cell death

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occurs in most tree species (Hare 1961; Fahnestock and Hare 1964; Levitt 1972). Provided that the region of cell injury is not too large, the tree can survive using remaining uninjured portions of phloem for transport (Harrington 1993). However, lateral growth is no longer possible where the cambium has been killed, and the dead cells form a lesion ("scar"), which is overgrown by successive years' xylem growth. The lesion remains embedded in the tree, or on an exposed growth curl ("catface"), unless it is removed by rot, mechanical damage, or is burned off in a subsequent fire.

Fire scar formation and retention thus reflect a variety of stochastic processes. First there is the variable behavior (rate and direction of spread, duration at any point) and intensity of a fire, which is influenced by a number of factors including fuel depth (biomass), bulk density (mass volume^{-1}), and moisture; temperature, speed, direction, and relative humidity of air masses; and local topography (Finney 1993; Agee 1996; Finney 1999; Saito 2001; Ward 2001). Second, a variety of tree variables, particularly bark thickness, height to live crown, rooting depth, and vigor influence tree-level response to local fire (Gill and Ashton 1968; Loehle 1988; Ryan and Reinhardt 1988; Reinhardt and Ryan 1989; Ryan 1990; Gutsell and Johnson 1995). Third, a set of contingencies affects the retention and preservation of lesions, including saturation of the scar by resin, subsequent burning, mechanical damage, and wood decomposition. Finally, the frequency of fires over a period of years is influenced by spatial distribution and production rates of fine fuels and interannual climate variation. The net result of these factors is that any given tree may retain a record of only a portion of the fires that occurred in its proximity. The evidence from a single tree provides an accurate, but incomplete, record of fire events.

Composite fire records.

These uncertainties have long been recognized in fire history research, and form the basis for current investigations into mechanisms of heterogeneous fire spread at small scales, and processes of fire scar formation (Baker 1989; Collins 1992; Lertzman, Fall et al. 1998; Miller and Urban 2000; Baker and Ehle 2001).

The probabilistic nature of a sample of multiple trees in a stand is the basis for the common practice of forming a composite fire record (CFR) (Dieterich 1980). The CFR is the superset of events recorded on any tree in a collective sample; thus, it is correct to assert that the CFR represents events recorded by at least one tree *somewhere* within the area in which the sampled trees are located (but not that every event detected occurred *everywhere* in the area sampled). The CFR can be used to estimate statistics of the fire regime, such as mean, median, or modal fire interval (the mean fire interval calculated from a CFR is commonly referred to as a Composite Fire Interval, CFI) (Dieterich 1980). Inferences based on the CFR have the advantage of replication by independent experimental units (trees), particularly if the trees are drawn from relatively homogeneous conditions with respect to factors (such as topographic setting) that influence fire spread and intensity. Note that the CFR cannot absolutely distinguish Type II error (failure to detect an event) from correct inference that an event did not occur; the composite only reduces the probability of such error. Even in a sample of trees, a scar may not be present either because all trees failed to record an event, or because the event was patchily distributed within the sample area.

Effects of sample size: collector's curves for fire events.

While the CFR helps overcome the variable fidelity of individual trees to actual historical events, the introduction of multiple samples introduces a new problem. As sample size increases, the detection of events (fires) also increases at an unknown rate. Since we are interested ultimately in characterizing the fire regime of a given area, we need to account for the effect that sample size may have on the estimate of the number of fires that occurred within a given sample area. This correction is necessary if we are to distinguish the separate effects of sampling intensity (*e.g.*, number of trees) and area (Falk 2003).

The accumulation function reflects directly the effect of sample size on the number of events (fires) detected in a sample, and consequently the estimate of fire frequency (fires time^{-1}). By extension, sample size will also affect the inverse of frequency, the composite mean fire interval (CFI) of a sample, and other statistics of the fire regime that depend on the number of events in a given time and space, including median and modal fire intervals. Sample size may also affect higher moments of the distribution of fire intervals (*e.g.* skewness), and because the overall frequency distribution of intervals changes, may also affect parameters of modeled probability distributions. Therefore, without correction, sample size would confound the effects of scale (extent and area) on measures of the fire regime.

Methods.

We tested for the effect of sample size on several metrics of the fire regime as response variables, using data from a field fire history study in which sample size and area could be controlled separately. Fire history data were collected at the 280-ha Monument Canyon Research Natural Area (MCN), Jemez Mountains, New Mexico (*this report*).

We created a composite fire record (CFR) for each sampled grid cell, by combining the fire dates recorded by any tree within the search area into a superset. The grid cell was considered to be recording when at least one tree was in a recording condition, although we also analyzed fire dates using higher percent scarred thresholds.

Statistical measures of the fire regime. Response variables in macroecological studies are often statistical measures (Brown 1995). In this study, response variables are a set of widely used metrics of fire regime analysis. A "fire regime" is a multivariate statistical characterization of multiple events in an ecosystem, including measures of central tendency and variability, in both space and time, in a variety of properties (Johnson 1992; Agee 1993; Whelan 1995; Lertzman, Fall et al. 1998; Chang 1999; Falk and Swetnam 2003). Here we focus on properties of the fire regime that pertain directly to the distribution of events in space and time, although similar analysis could be focused on other dimensions of the fire regime, such as fire intensity, severity, or effects. All measures used in this analysis were calculated based on the CFR.

We tested the sensitivity of several commonly-used fire regime metrics, including:

a. arithmetic fire frequency (f_{mean} or $\overline{f}$), the number of events (a count of fire dates) for a specified time interval (*e.g.*, fires century^{-1}). Like all uses of the mean to represent central tendency, this estimate is an unbiased estimator only for symmetric distributions; as the temporal distribution of events becomes increasingly skewed, the mean is sensitive to outlying values and may not accurately reflect the central value.
b. median (f_M) or modal (f_{mode}) intervals between events, and have the same

units as the arithmetic fire frequency (*e.g.*, fires century^{-1}). Because the median and mode are more robust measures of central tendency in skewed distributions, they may be better suited to the typically asymmetric and variable temporal distributions typical of many fire regimes. Unfortunately, these statistics are not widely used in the fire history, ecology or management literature.

c. Weibull Fire Frequency (f_{WM}), the inverse of the modeled Weibull Median Probability Interval (WMPI, *q.v.*), and is used in some widely used fire history analysis programs (Grissino-Mayer 1999; Grissino-Mayer 2001). In addition to the stability properties of the median, the use of a modeled distribution should add resistance to the effect of outlying values.

d. Composite Mean Fire Interval. Intervals between fire events are interesting ecologically because they reflect the recovery time for fire-sensitive processes. Since fires are potentially lethal events to many (but not all) individuals in a forest community, time between fire events plays a key role in the regulating effects of fire on tree demography and community physiognomy. For a time series of tree rings, there is a distribution of time intervals between events. The Composite Mean Fire Interval is the arithmetic mean of this distribution, and is a widely cited statistics in fire history and ecology. Like mean fire frequency ($\overline{f}$), CFI can be sensitive to outlying values (*i.e.*, unusually short or long intervals) or asymmetric distribution.

e. Median and Modal Fire Interval. Although less widely used, the median (FI_M) and modal (FI_{mode}) fire intervals are potentially useful fire regime metrics because of their resistance to outlier effects and the asymmetric distributions of intervals that are characteristic of many fire regimes (Johnson and VanWagner 1985; Clark 1989; Agee 1993; Grissino-Mayer 1999). The modal interval also has an ecological interpretation as the most commonly experienced time between fires, and may thus reflect prevailing conditions in which fire-sensitive organisms live and grow.

f. Weibull Median and Modal Probability Intervals. The Weibull Median Probability Interval (WMPI) is the median of the probability density function (pdf), and is used in fire history and ecology as an expression of central tendency, often as a complement to CFI. In addition to sample size effects, we tested the correlation of the arithmetic (CFI and FI_M) and Weibull median intervals. Like the arithmetic mode, the mode of the fitted Weibull density function is also a potentially useful metric but is not commonly used in fire history, although it may deserve more attention as an expression of prevailing conditions of the evolutionary environment.

Effects of sample size.

We tested for the effect of two components of sampling intensity, the number of trees in a constant area, and the number of study plots within the study site as a whole.

Effect of number of trees for a constant area. Because of the gridded, spatially explicit sampling design, we could create composites of varying area, from a single 4-ha grid cell to a composite of the entire 280-ha study area. Using a moving window approach (Bebi, Kulakowski et al. 2003), we assembled composite data sets for all fully populated combinations of contiguous 2, 4, and 5 grid cells (8, 16, and 20-ha windows), and all sets of 9, 16, 25, 36, 49, and 64 grid cells (36, 64, 100, 144, and 196 ha windows). For combinations of 9 or more grid cells, we allowed blank (unsampled) cells and tested for the effect of the number of cells sampled within the window extent.

For each composite data set in a given window size (*e.g.* a moving 20-ha window), we generated a CFR using all sample plots within the frame. We then calculated arithmetic and Weibull fire frequency (as fires 100 yr^{-1}), mean and median fire interval (CFI and FI_M respectively), and the Weibull Median Probability Interval (WMPI) individually for each CFR. We then plotted the estimates of each statistic for all CFR's from a given window size as a function of the number of trees in each composite. This gave us a distribution of estimates of each statistic, with sample size varying but sample area held constant.

For the set of combinations in a given sample area (box size), we regressed observed values of each statistic against a power function, the reciprocal of sample size (number of $trees^{-1}$) in each combination. This regression generated predicted values for the response statistic as a function of sample size. This regression captures the proportion of the variance in estimates of each statistic that is attributable to the number of trees. Residuals from this regression reflect the remaining variation among composite samples, from which the effect of sample size has in effect been removed; by definition, the mean of residuals for each sampling scale was 0. For each composite, the residual value is added back to the global mean of the variable for all composites at that window size, to create sample size-corrected parameter estimates. These resulting values retain variation among composite data sets, but with the main effect of sample size removed.

Effect of the number of CFR's (sample points).

We tested for the effect of the number of sample locations, using the dataset for the 280-study area as a whole, with a bootstrap resampling program, SSIZ (Holmes and Swetnam 1995). SSIZ creates sets of 1…N samples by drawing *n* CFR's randomly from the total sample pool, where N is the total number of sites. For each draw of *n* sites, the number of fire dates captured is recorded, from which fire frequency and intervals are calculated. This whole procedure is repeated iteratively with different random seeds for each run, and the pool of results for each sample size is used to generate confidence limits reflecting variation among samples. We performed 1,000 iterations of the procedure at each sampling scale (window size). We used the slope of the mean of the iterations at $n = 50$ (*i.e.*, the full complement of sampling locations) as a measure of how rapidly a resampling procedure was approaching its asymptotic value.

Sample depth (in this instance, the number of recording grid cells for a specified year) tends to decline in most dendrochronological samples with increasing time from present. We evaluated sample depth by year and limited resampling analysis of the effect of sample depth to the period for which at least half of the grid cells in the study area were recording.

Results.

We sampled 198 fire-scarred trees in 50 grid cells distributed across the study area (Table 1). For the study area as a whole, dated annual rings were found for the 648-yr period 1354-2001. The earliest dated fire scar was from 1450 A.D., and the latest from 1981, giving the site as a whole a 532-yr fire record.

Collections from the search plots in individual grid cells ranged 1-9 trees per site, with a mean of 4 trees per site. Grid cell composites record had an average start date of 1574, and a mean temporal extent of 427 yr. The mean first fire date among grid cell CFR's was 1654, and the mean last fire date was 1909, for a mean fire recording period among grid CFR's of 344 yr.

Using the moving windows, we generated CFR's from a total of 238 combinations of contiguous grid cell CFR's, ranging from the 50 individual grid cells to a single composite record for the study area as a whole. We excluded grid cells with only 1 tree (GP140) or fewer than 6 intervals (GP103, GP109) from analysis, as these did not have sufficient fire record to create a reliable local CFR, leaving 47 cells in the analysis. We analyzed 51 possible combinations of 2 adjacent grid cells (vertical or horizontal in grid), of which we excluded two (GP140+149 and GP102+103) with too few intervals for analysis. We used only fully populated combinations (all cells sampled) for combinations of 2, 4, and 5 grid cells. For combinations of 9 or more grid cells, we allowed blank cells and tested for the effect of the number of cells sampled within the window extent.

Sensitivity of metrics of the fire regime to sample size.

Fire frequency. Both arithmetic ($\overline{f}$ = CFI^{-1}) and Weibull (f_{WM} = WMPI^{-1}) fire frequency varied with sample size at most scales (Table 2, Figure 1). Estimates of $\overline{f}$ ranged from 8.9 fires century^{-1} for individual grid cells to 30.3 fires century^{-1} for the study area as a whole. Sample size accounted for less than 15% of the variance in estimates of fire frequency at some scales, but 42-70% of the variance for composites of 16, 100, and 144 ha. Regression slopes were significant except for individual grid cells and composites of 36, and 196 ha.

We found a similar pattern for the effect of sample size on estimates of Weibull fire frequency (Table 1.b, Figure 1). Estimates of f_{WM} ranged from 9.4 fires century^{-1} for individual grid cells to 28.0 fires century^{-1} for the study area as a whole. Sample size accounted for a higher proportion of the variance than for arithmetic fire frequency (≥15% at all scales except for individual grid cells and 36 and 64 ha composites). Regression slopes were significant for composites of 8, 16, 100, and 144 ha.

Arithmetic and Weibull fire frequency were highly correlated at all scales (Figure 2). For individual grid cells, Weibull frequency can be expressed as a linear transform of arithmetic frequency, $f_{WM} = 0.01 + 0.94\overline{f}$, $r = 0.92$. However, for cross-scale comparison, Weibull frequency is expressed more precisely as a square root transform of arithmetic frequency, $f_{WM} = -0.11 + 0.72\,(\overline{f}^{\,1/2})$, $r = 0.99$.

Composite mean fire interval. Mean estimates of the composite mean fire interval (CFI) varied from 12.4 yr fire^{-1} (mean of individual grid cells) to 3.3 yr fire^{-1} for the composite of the full study area (Table 3, Figure 3). Sample size generally accounted for 9-16% of variance in estimates of CFI, although this effect was stronger for composites of 20, 100, and 144 ha. Most regression slopes were shallow and only marginally significant, except for composites of 16, 25, and 36 grid cells (64, 100, and 144 ha), which had highly significant slopes.

Composite median fire interval. Mean values of the composite median fire interval (FI_M) decreased from 9.6 yr fire^{-1} for individual grid cells to 2.0 yr fire^{-1} for the study area as a whole. Sample size accounted for 7-34% of variance in estimates of FI_M, including more than 15% of variance for 8, 16, 20, 64, and 100-ha composites (Table 4, Figure 4). Regression slopes were significant ($p \leq 0.05$) at all scales except composites of

5 and 9 grid cells (20 and 36 ha).

Weibull Median Probability Interval. Mean values of the modeled Weibull Median Probability Interval (WMPI) ranged from 11.7 yr $fire^{-1}$ for individual grid cells to 3.6 yr $fire^{-1}$ for the study area as a whole (Table 5, Figure 5). Sample size accounted for more than 15% of variance in estimates of the WMPI at all scales except 36 and 64 ha, and was especially strong ($0.43 \leq r^2 \leq 0.70$) for composites of 8, 16, 100, and 144 ha. Regression slopes were significant at all scales except for composites of 8, 16 and 196 ha.

Sensitivity of fire frequency to number of sample locations.

The number of recording locations within the study area varied over the 532-yr temporal extent of the MCN fire record. 50% of sites were recording by 1598, and 90% by 1649 (Figure 6). Using the fire record for the 403-yr period 1598-2000, we tested the effect of the number of sample locations on estimates of fire frequency by randomly resampling from the total pool of recording grid cells (N = 50). Resampling parameters were varied to include (i) resampling with and without replacement, and (ii) including all fires, and restricting the sample to only those fires recorded in at least two grid cells.

Randomly resampled pools of fire dates (the event-accumulation function) followed the predicted form of a collector's curve for all combinations of resampling variables, (Figure 7). For all fires (*i.e.*, events recorded in any grid cell), accumulation curves for resampling without replacement had steeper slopes at the maximum sample size, $n = N$ ($\delta f / \delta n = 0.57$ fires $century^{-1}$) than for resampling with replacement ($\delta f / \delta n =$ 0.34 fires $century^{-1}$), suggesting that even the full complement of 50 plots was not enough grid points to saturate the fire record. Accumulation of fire events recorded in at least two grid cells reached an asymptote essentially within the pool ($0.00 \leq \delta f / \delta n \leq 0.05$, $n = N$), regardless of resampling method. Confidence intervals generated by the 1,000 iterations narrowed to 0 for resampling without replacement, while those generated by resampling with replacement were closer to parallel to the mean of the iterations (Figure 7).

Minimum sample size for various sampling scales.

We evaluated minimum sample sizes needed to generate a reliable estimates of fire regime parameters at each composite scale, using confidence limits from the replicated regression and individual pairwise tests of sample sizes within scales. Minimum sample sizes to generate a reliable estimate of all five metrics ranged from 4 trees for individual grid cells to 37 trees for 64-ha composites, depending on the statistic being estimated (Table 6).

For all statistics combined, a log-log regression provided the best model of sample size (number of trees) as a function of area in hectares (log SS = 0.36 + 0.78 log ha; $r^2_{adj} = 0.99$), although a linear function could also be used (SS = 3.50 + 0.51 ha; $r^2_{adj} = 0.97$).

Discussion.

Sample size enters into ecological sampling in different ways, depending on the objectives of research. Where the purpose is to estimate the distribution of a continuous state variable (stream pH, soil ion concentrations, population density, tree heights, canopy cover, body mass, sex ratios, fertility and mortality rates, annual productivity, standing biomass), sample size is a primary factor in stabilizing variance of estimates and determining statistical power (Southwood and Henderson 2000; Steidl and Thomas

2001). For these variables sample size exerts its effect primarily on the accuracy of an estimate.

By contrast, where the sampling objective is to compile as complete a census of discrete entities (most commonly, species) within a defined spatiotemporal domain, sample size has a different effect, *viz.* on the completeness of the sample. Of course, censuses of entities can also be analyzed as state variables (for example, indices of similarity and diversity), in which case sample size will influence the variance and stability of estimates (Pielou 1974; Alatalo 1981; Magurran 1988; Dixon 2001).

In fire history, sample size enters as a problem of the second kind, completeness of the sample: the initial objective of sampling is to compile as complete a census of fire dates in the tree-ring record as possible within logistical constraints. More precisely, the entities that accumulate are datable fire lesion in tree boles, which are discrete entities distributed across the landscape. Once the census is complete, a variety of continuous statistical measures (such as the descriptors of the fire regime, as well as indices of similarity and diversity) can be calculated. If the census is incomplete, the derived quantitative measures will be inaccurate.

The results of this study suggest that sample size can significantly affect estimates of various widely used metrics of the fire regime, even when sample area is controlled. Sample size (number of trees) influenced estimates of fire frequency and fire interval at every spatial scale of analysis. For the study area as a whole, the number of sample locations had a similar effect, suggesting that both sampling intensity and spatial distribution may be equally important. Sparse samples (few trees and/or few locations within the study area) are particularly prone to unreliable estimate of fire regime parameters.

In an ecological reconstruction using remnant evidence such as the present study, sample depth will vary with time, often declining with time before present. We restricted our analysis to the 403-yr period 1598-2000 when at least half of the sampling locations were active. The proportion of recording locations could be set lower or higher; for example, we could have used the 352-yr period 1649-2000 when ≥ 90% of sites were recording. Because of the dramatic reduction in fire frequency in the early 1900's in southwestern North America, we chose to maximize the temporal extent of the record to be analyzed. We note that even at the 50% threshold, the resulting sample density of 198 trees in 25 plots for a study area of ≈ 280 ha is higher than most published fire history studies to date.

All metrics of the fire regime were sensitive to sample size when area is controlled. Sample size effects for several metrics appeared strongest at smaller (≤ 16 ha) and larger (≥ 100 ha) sampling scales, and less important at mesoscale composites, using significant r^2_{adj} values as a measure. Small area samples reached equilibrium relatively quickly, with ≥ 4 trees generally sufficient for a 4 ha area. This probably reflects the smaller total number of fire events within a small sample area, which is thus more readily censused completely. Large areas may be sensitive to sample size because of the higher probability of undetected small or spatially dispersed events; as such, the accumulation function may continue to increase as samples are added. Our estimates of the minimum sample size for reliable estimation of fire frequency and intervals are based on the MCN data set, and it is not our intention to assert that these numerical values are universal; on the contrary, we assume that minimum samples will differ for other sites depending on fire history and the retention of tree-ring evidence. Our main intention is to suggest that investigators should take these sampling issues into account explicitly when designing their studies and reporting results.

Sample size and area are frequently confounded in the paleoecological literature, including studies of fire history. Sample area, number of locations, and number of trees all vary in the fire history literature, and their potential effect of fire regime quantification is rarely considered. We designed this controlled study to allow tests of the separate effects of sample size and area, because sample locations were spatially explicit, and sample extent was known and controlled though the moving window approach. Other fire history studies where sampling locations are spatially explicit could be reanalyzed in similar fashion. We predict that correction for sample size and area would account for some fraction of the observed variation in fire frequency and return intervals in similar forest types; after correcting for these factors, the residual variation would more accurately reflect differences of site and history. The overall result should be to sharpen our understanding of the ecological factors that contribute to variation in fire regimes in space and time.

Figures.

1. **Figure 1.** Sample size effects on arithmetic and Weibull fire frequency for individual grid cells and composites of 4-16 ha. For each window size (single grid cells to the full study area), arithmetic (1) and Weibull (2) fire frequency are plotted as a function of sample size. *a.* Uncorrected estimates with the group mean and 95% confidence limits of the fitted function. *b.* Sample-size corrected estimates.
2. **Figure 2.** Correlation of arithmetic (CFI^{-1}) and Weibull ($WMPI^{-1}$) fire frequency for Monument Canyon Research Natural Area study area. (a) Correlation plot for 47 individual grid cells (linear fit, $r = 0.92$). (b) Correlation plot for all window sizes (square root fit, $r = 0.99$).
3. **Figure 3.** Effect of sample size (number of trees) on the mean fire interval (CFI) for single grid cells through a 9-ha composite. *a.* For each window size, CFI is plotted as a function of sample size, and the predicted values from a reciprocal regression ($trees^{-1}$) shown. *b.* Residuals from the regression; the global mean is added to these residuals to generate sample-size corrected estimates of CFI.
4. **Figure 4.** Same as Figure 3 but for median fire interval for single grid cells through 20-ha composite.
5. **Figure 5.** Same as Figure 3 but for Weibull Median Probability Interval for single grid cells through 16-cell (64-ha) composites.
6. **Figure 6.** Proportion of grid cells recording by year.
7. **Figure 7.** Event-accumulation functions for 1a) all fires (recorded in any location), resampling without replacement, 1b) all fires, resampling with

replacement, 2a) fires recorded in at least two locations, resampling without replacement, and 2b) fires recorded in at least two location, resampled with replacement.

Tables.

1. **Table 1.** Field collections at Monument Canyon Research Natural Area, New Mexico, by grid cell, mean ± 1 s.d. of grid cells, and composite for the full study area.
2. **Table 2.** Mean estimates of fire frequency for each sampling scale, and results of sample-size regression. Unless otherwise noted, all residuals were within $Q_{.95}$ of the normal quantile plot at all scales.
3. **Table 3.** Mean estimates of composite mean fire interval for each sampling scale, and results of sample-size regression. All residuals were normally distributed ($p(W) \geq 0.10$, within $Q_{.95}$ of the normal quantile plot) at all scales.
4. **Table 4.** Mean estimates of median fire interval for each sampling scale, and results of sample-size regression. Residuals significantly non-normal ($p(W) \leqq 0.05$) at several scales, although all were within $Q_{.95}$ of the normal quantile plot).
5. **Table 5.** Mean estimates of composite Weibull Median Fire Interval (WMPI) for each sampling scale, and results of sample-size regression. All residuals were normally distributed (within $Q_{.95}$ of the normal quantile plot) at all scales.
6. **Table 6.** Minimum sample sizes by sample area for accurate estimation of various fire regime metrics. The number in parenthesis is a marginal sample depending on the statistic. Minimum sample sizes could not be determined for composites of 100 ha or greater.

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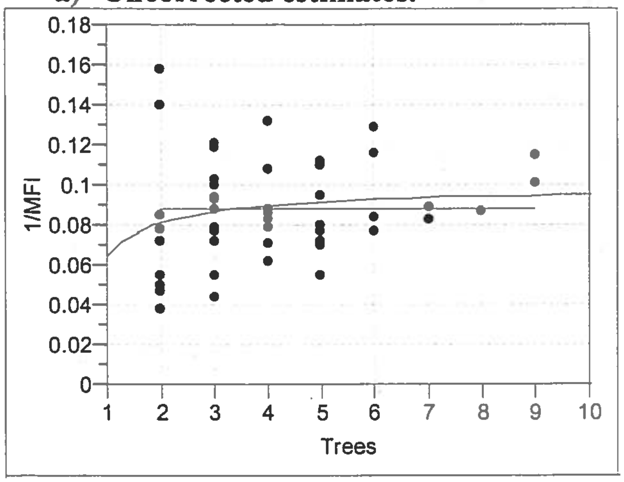
Figure 1.

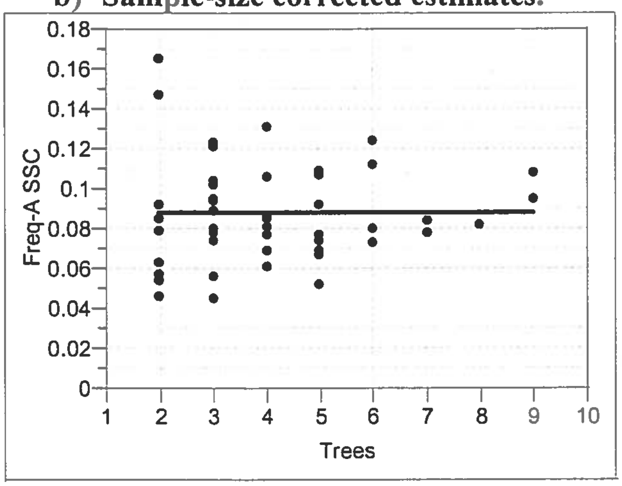
4-ha grid cell.

1) Arithmetic frequency ($\overline{f}$).

a) Uncorrected estimates.

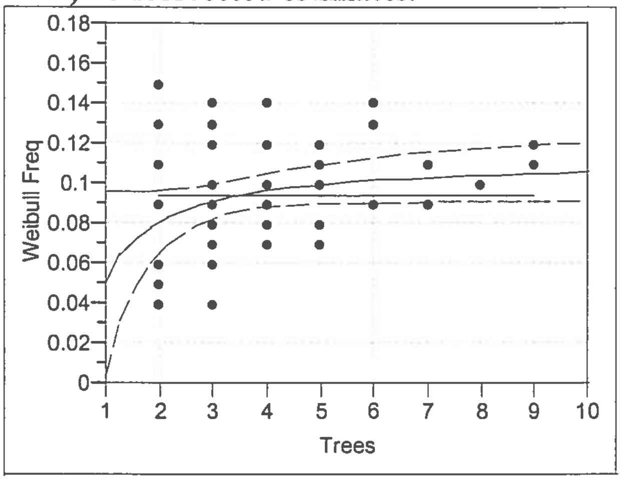


b) Sample-size corrected estimates.

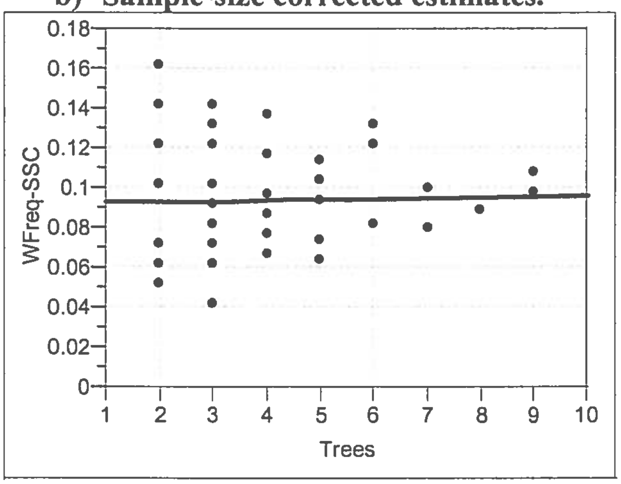


2) Weibull fire frequency (f_{WM}).

a) Uncorrected estimates.



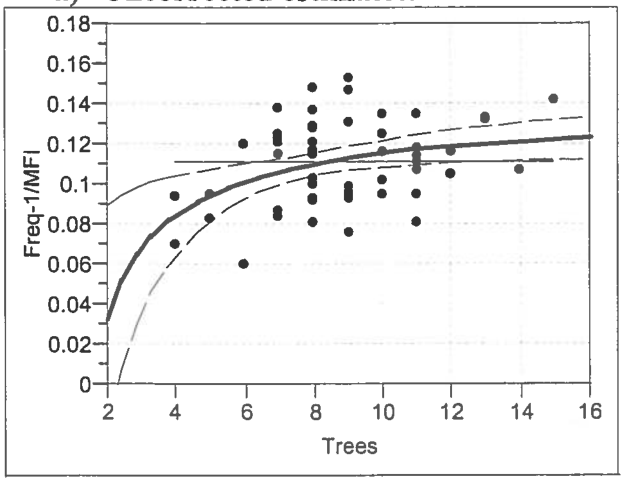
b) Sample-size corrected estimates.



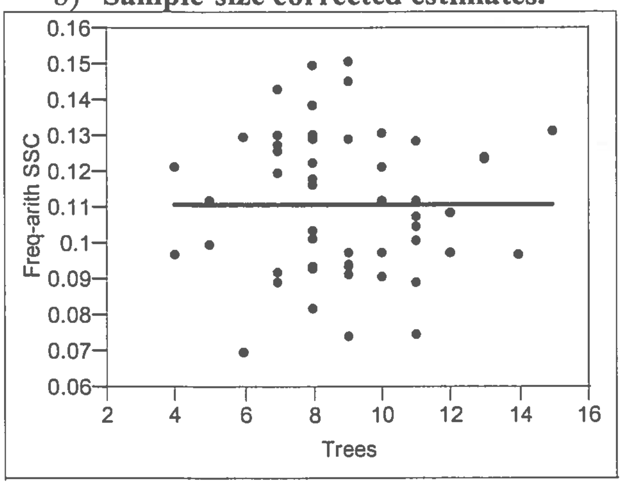
8 ha composite.

1) Arithmetic frequency ($\overline{f}$).

a) Uncorrected estimates.

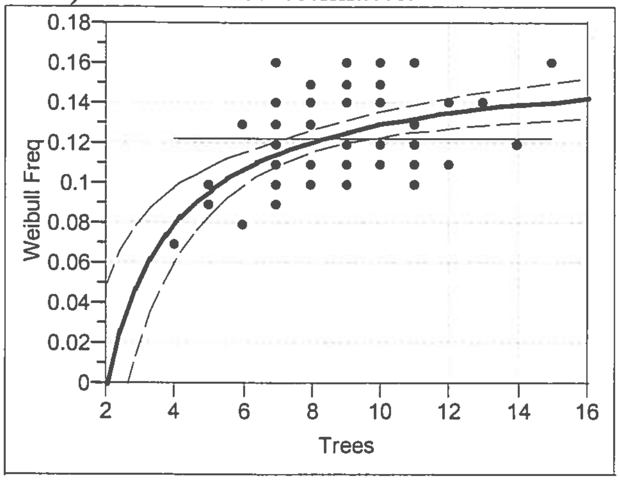


b) Sample-size corrected estimates.

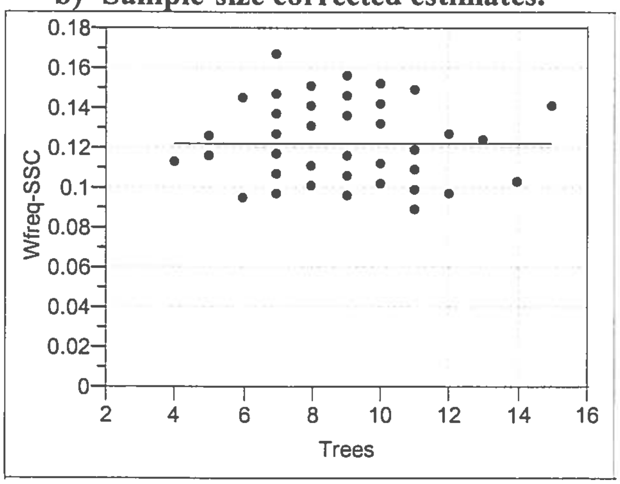


2) Weibull fire frequency (f_{WM}).

a) Uncorrected estimates.



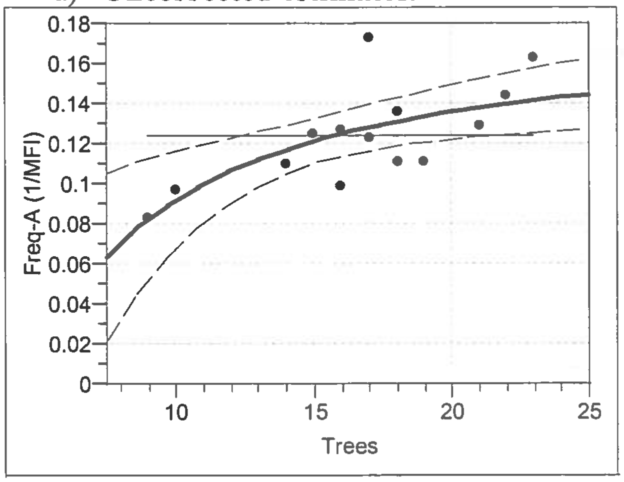
b) Sample-size corrected estimates.



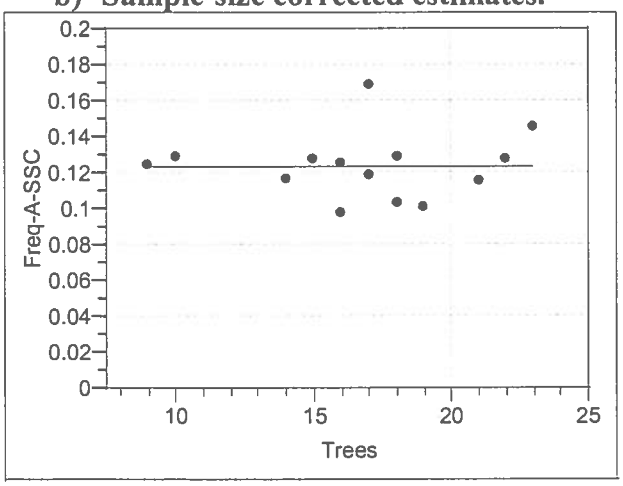
16 ha composite.

1) Arithmetic frequency ($\overline{f}$).

a) **Uncorrected estimates.**

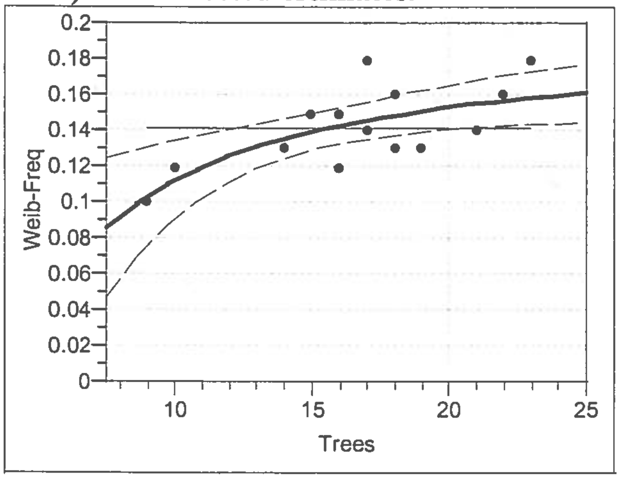


b) **Sample-size corrected estimates.**



2) Weibull fire frequency (f_{WM}).

a) Uncorrected estimates.



b) Sample-size corrected estimates.

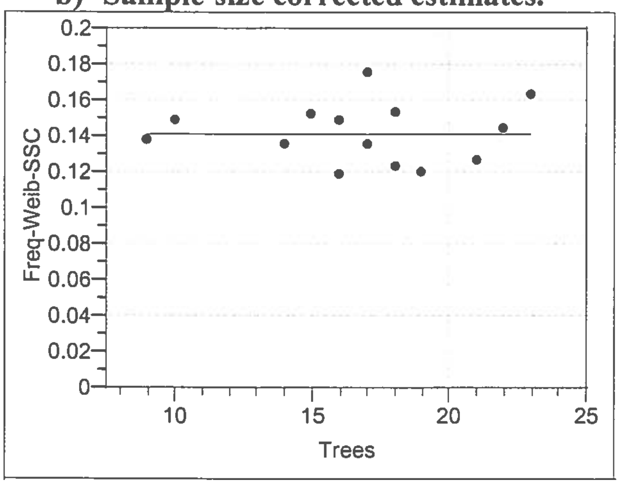
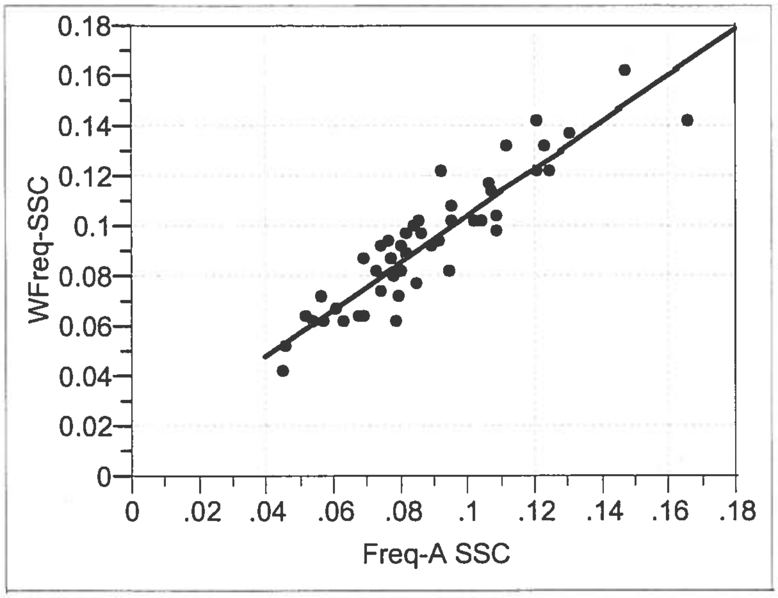


Figure 2. Correlation of arithmetic (MFI^{-1}) and Weibull ($WMPI^{-1}$) fire frequency for Monument Canyon Research Natural Area study area.

A. Correlation plot for 47 individual grid cells (linear fit, $r = 0.92$).



B. Correlation plot for all window sizes (square root fit $r = 0.99$).

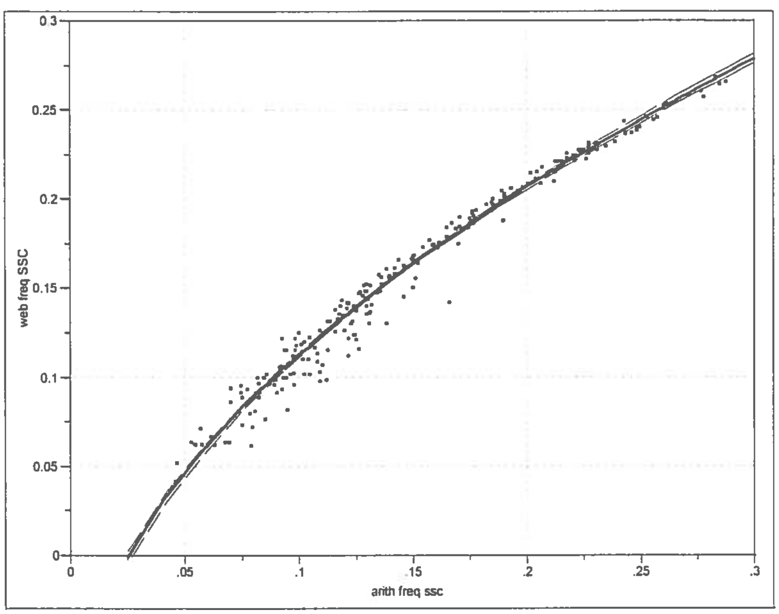
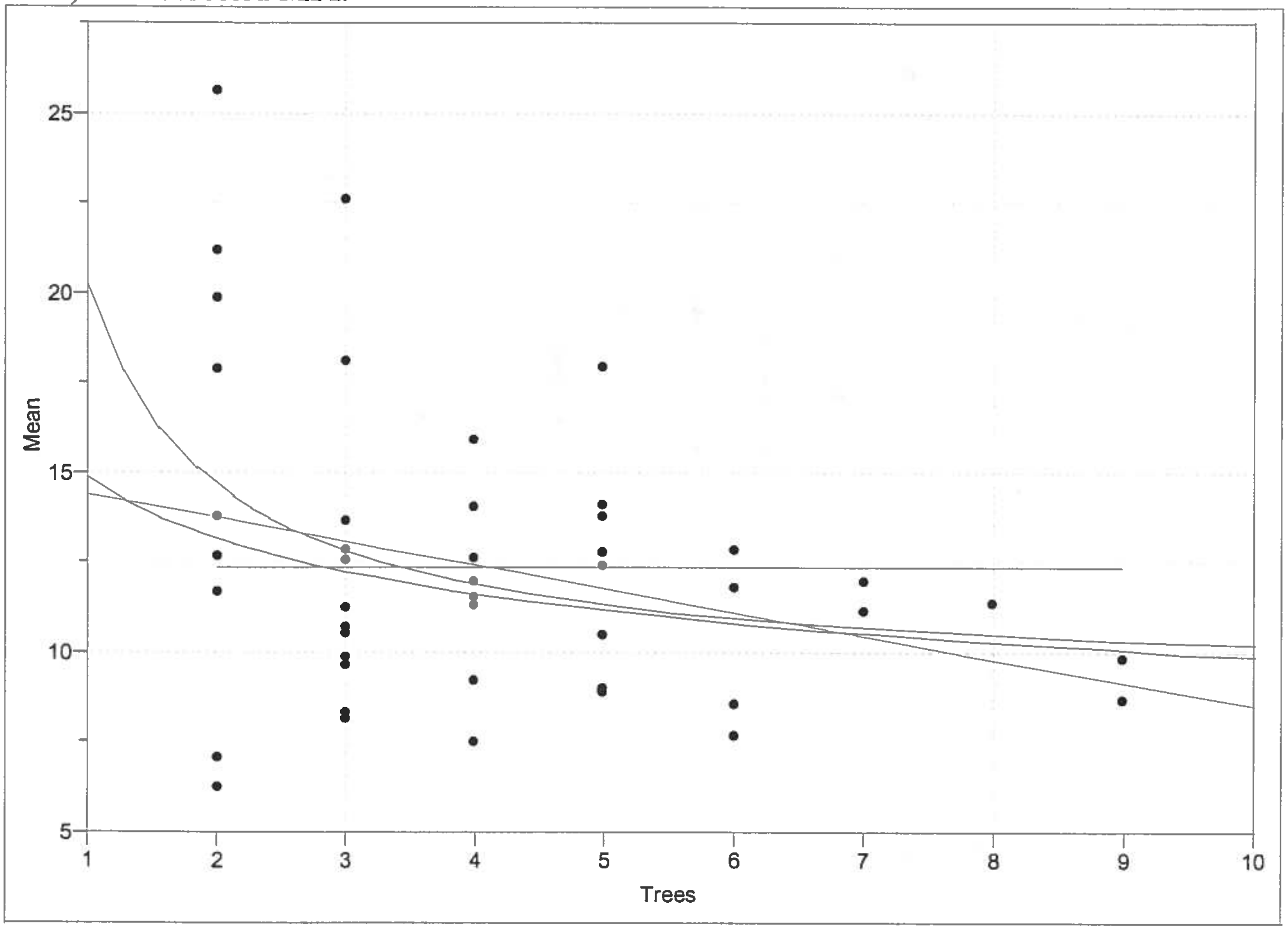
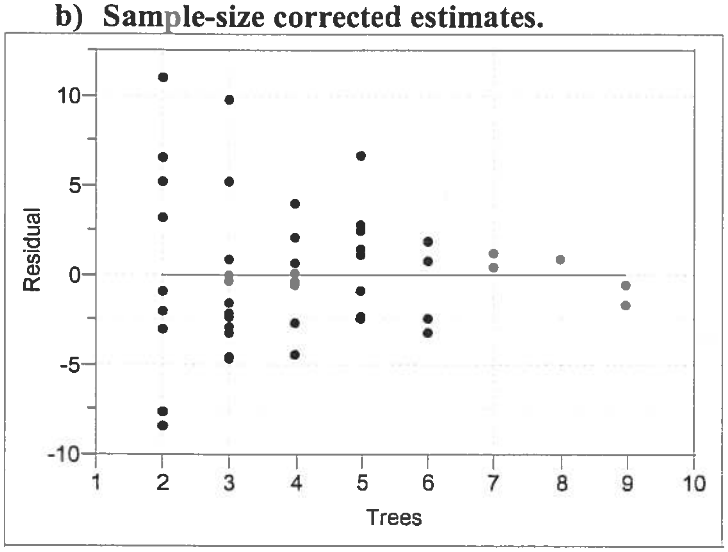


Figure 3.

1) **Single grid cells.**
   a) **Uncorrected MFI.**

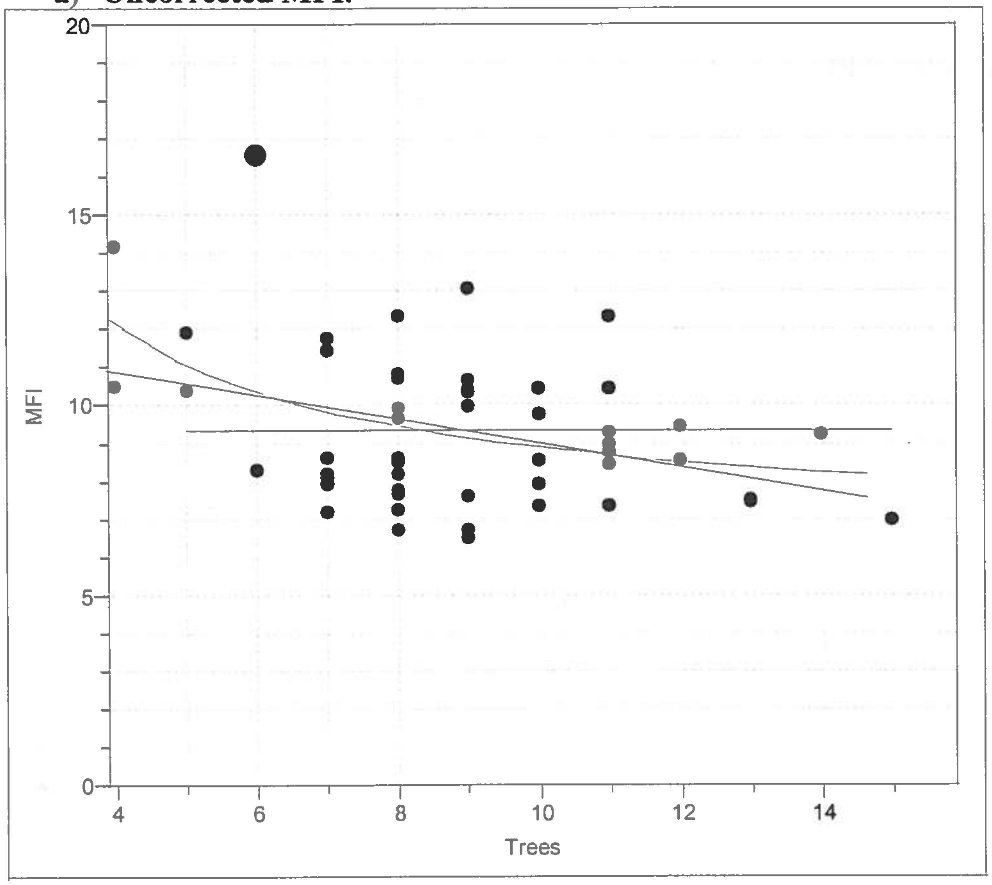


b) **Sample-size corrected estimates.**

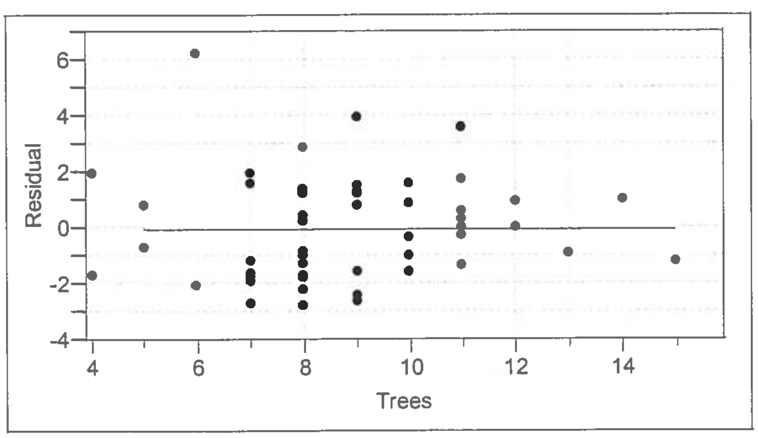


2) 2 grid-cell combinations.

a) Uncorrected MFI.

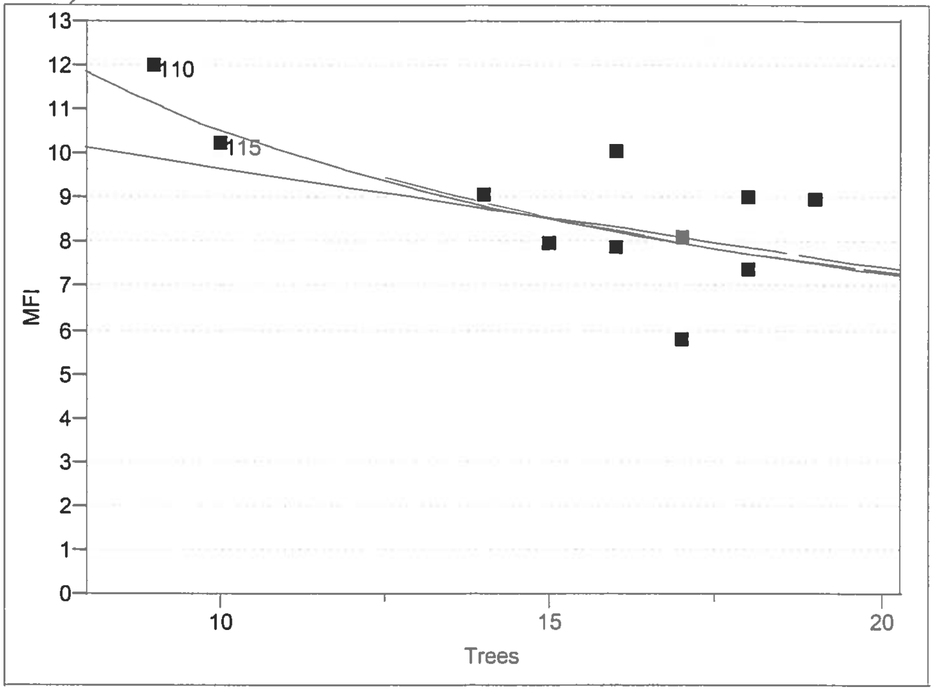


b) Sample-size corrected estimates.



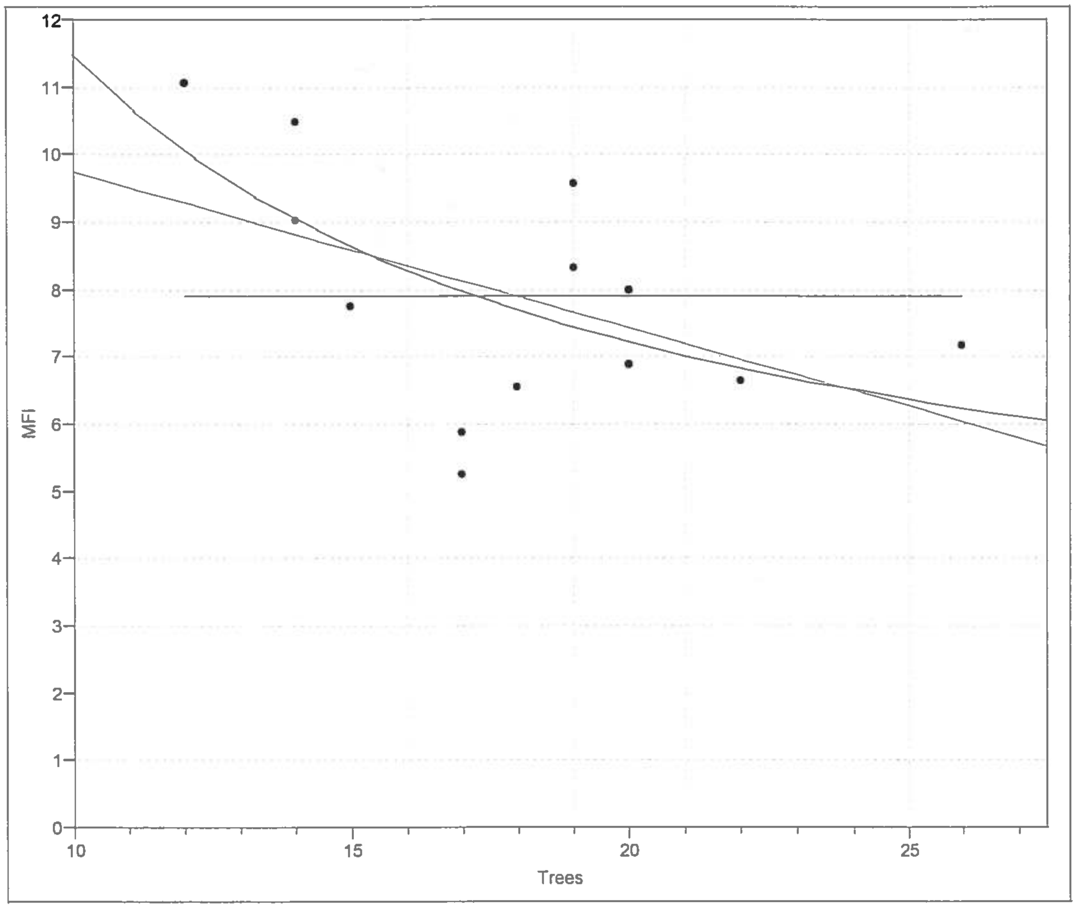
3) 4 grid-cell combinations.

a) Uncorrected MFI.

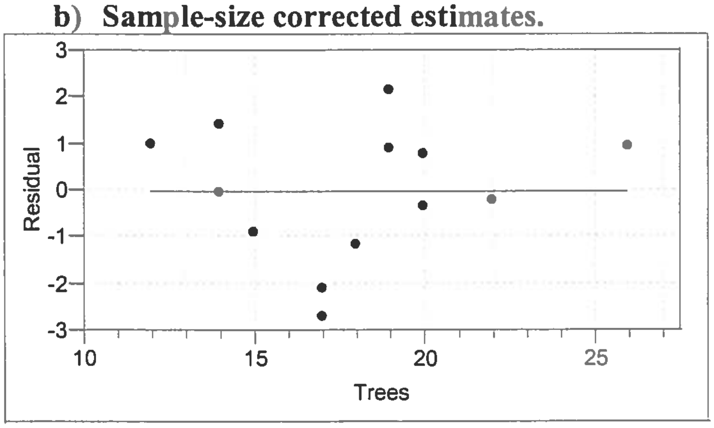


4) 5 grid-cell combinations.

a) Uncorrected MFI.

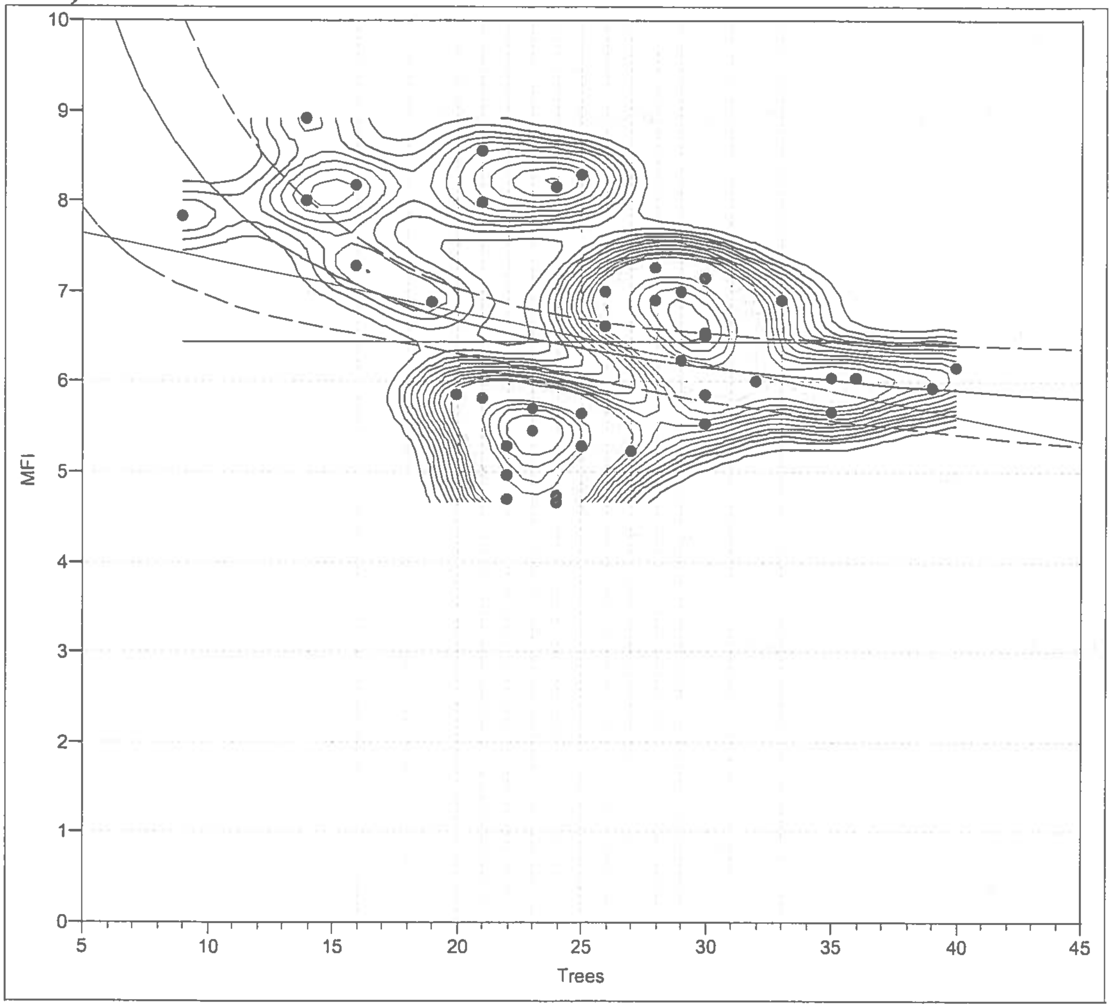


b) Sample-size corrected estimates.



5) **9 grid cell combinations (36-ha extent).**

a) Uncorrected MFI.



b) Sample-size corrected estimates.

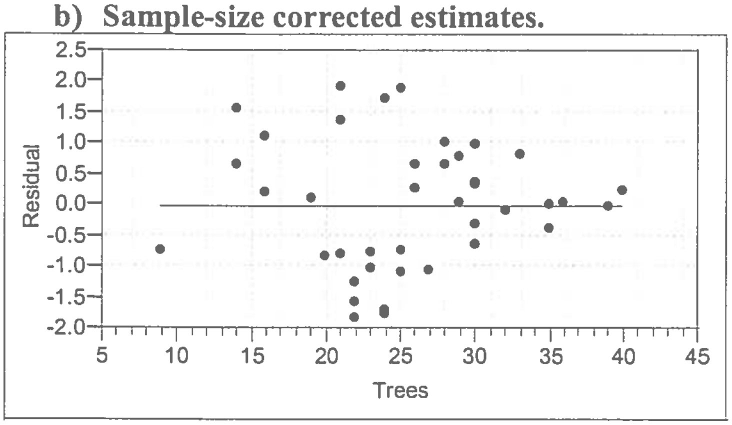
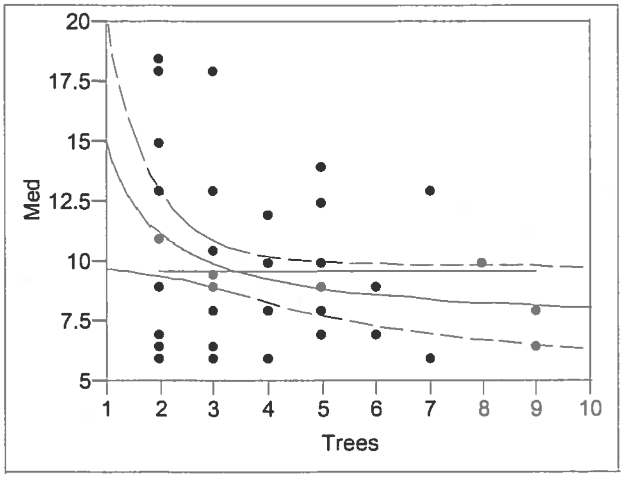


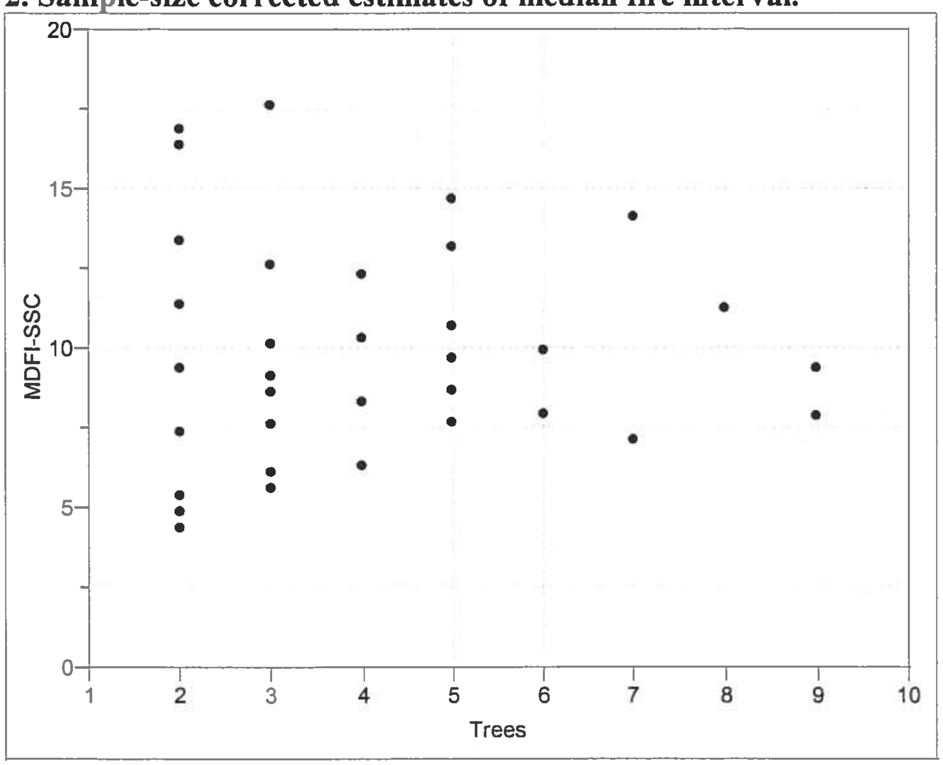
Figure 4. Effects of sample size on estimates of the composite median fire interval.

1 grid cell.

1. Uncorrected estimates of median fire interval.

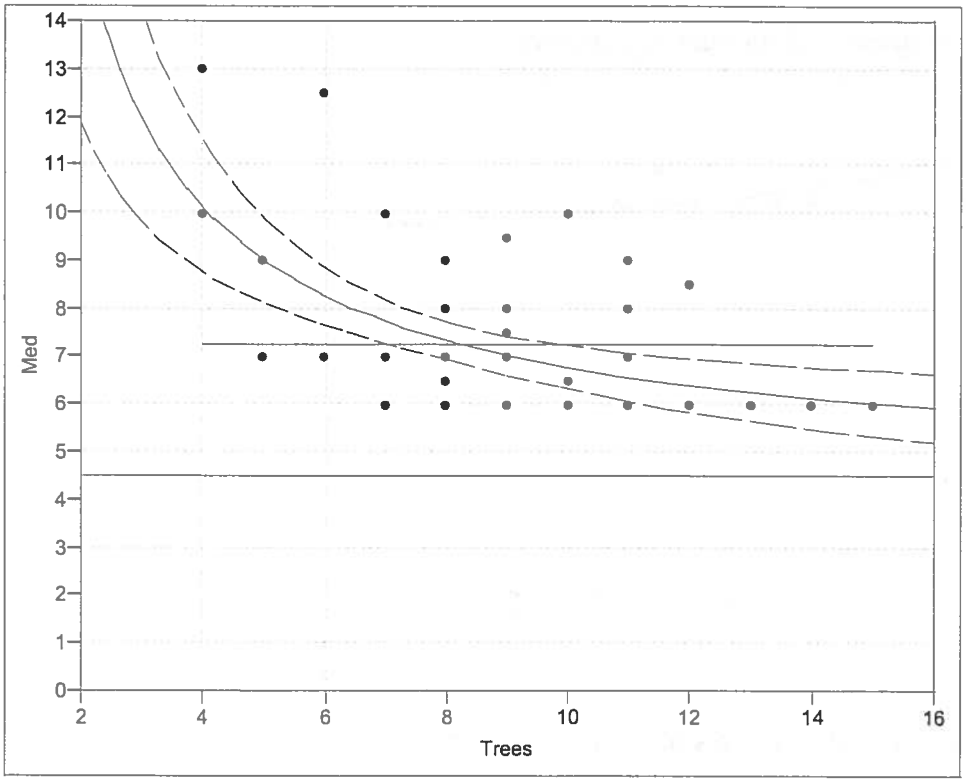


2. Sample-size corrected estimates of median fire interval.

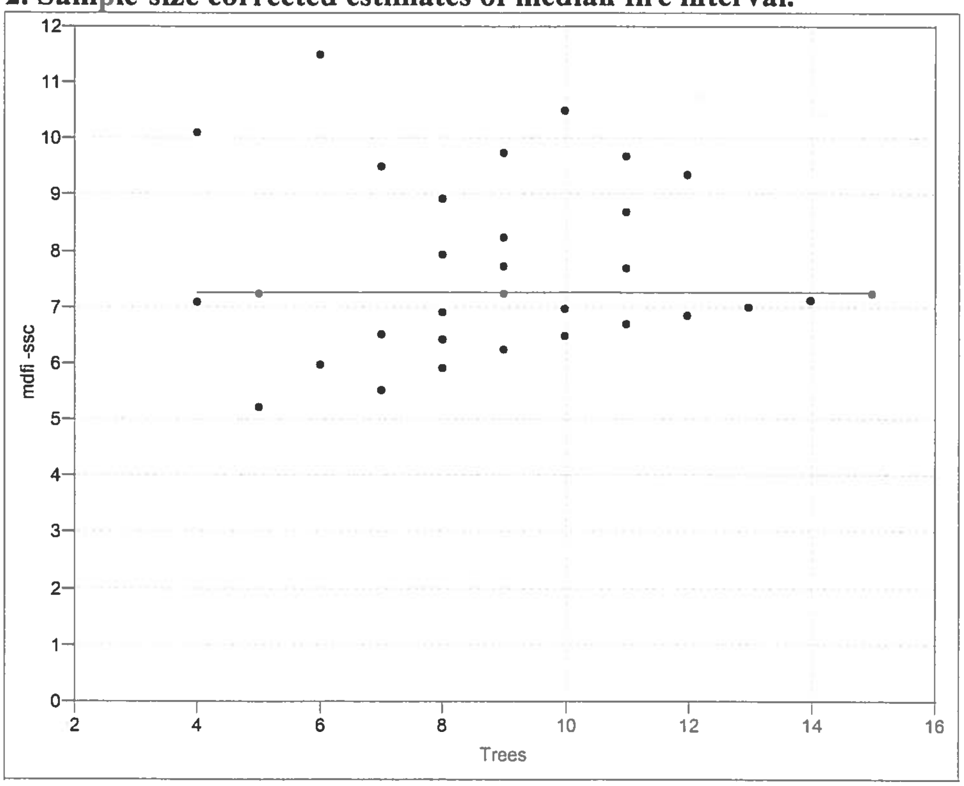


2 grid cells.

1. Uncorrected estimates of median fire interval.

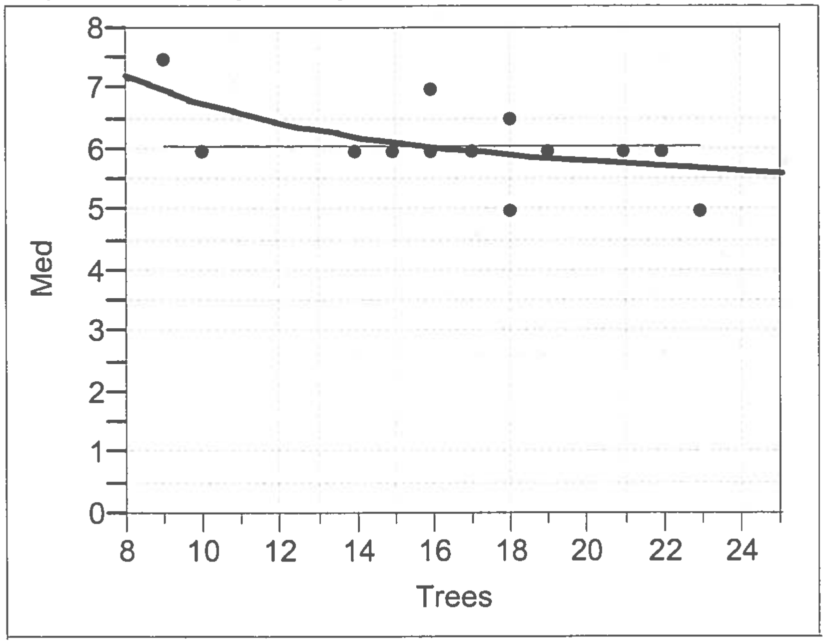


2. Sample-size corrected estimates of median fire interval.

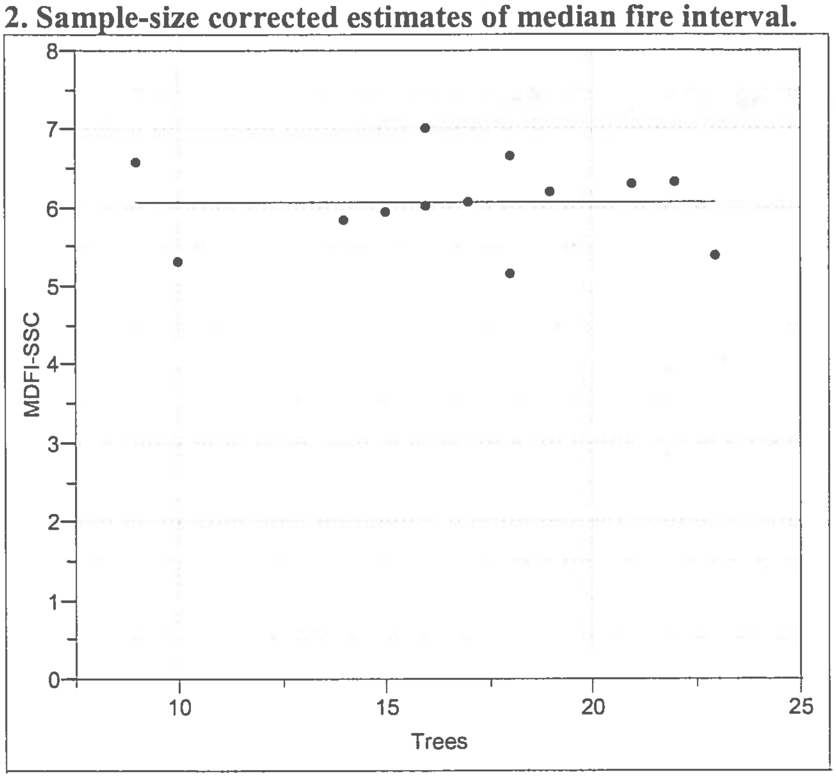


4 grid cells.

1. Uncorrected estimates of median fire interval.

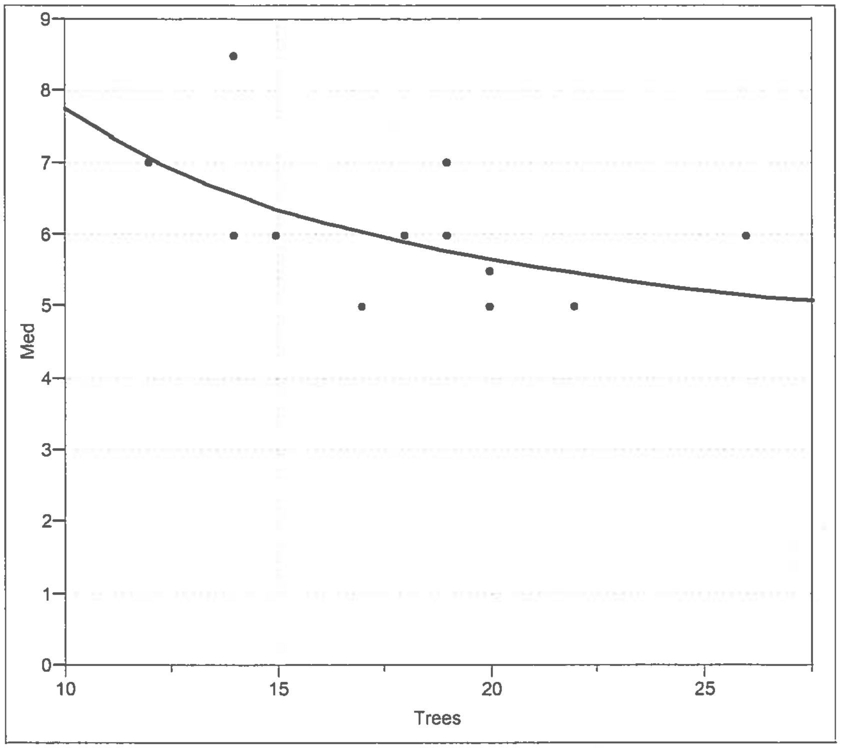


2. Sample-size corrected estimates of median fire interval.



5 grid cells.

1. Uncorrected estimates of median fire interval.



2. Sample-size corrected estimates of median fire interval.

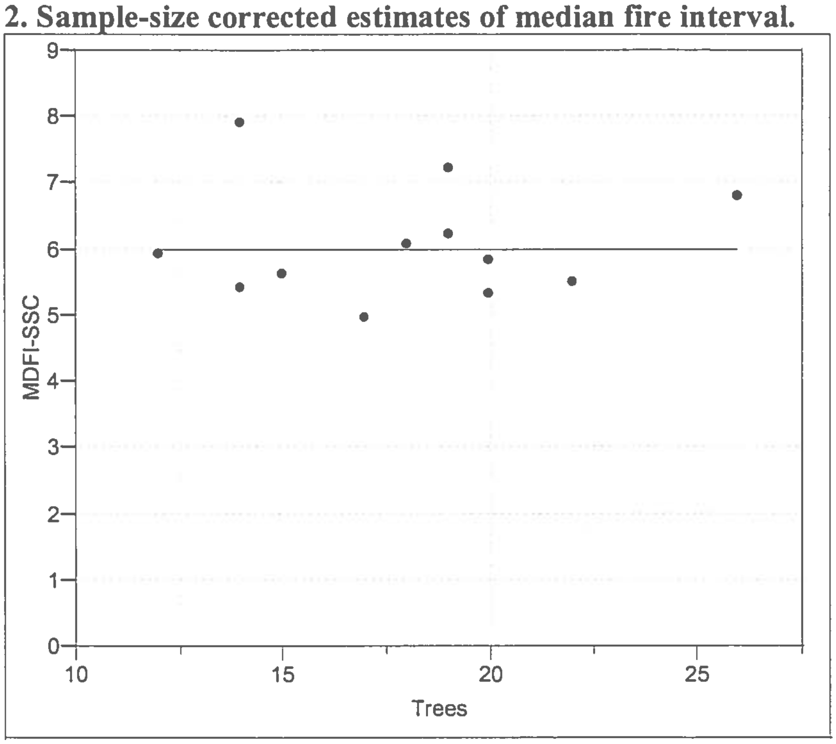
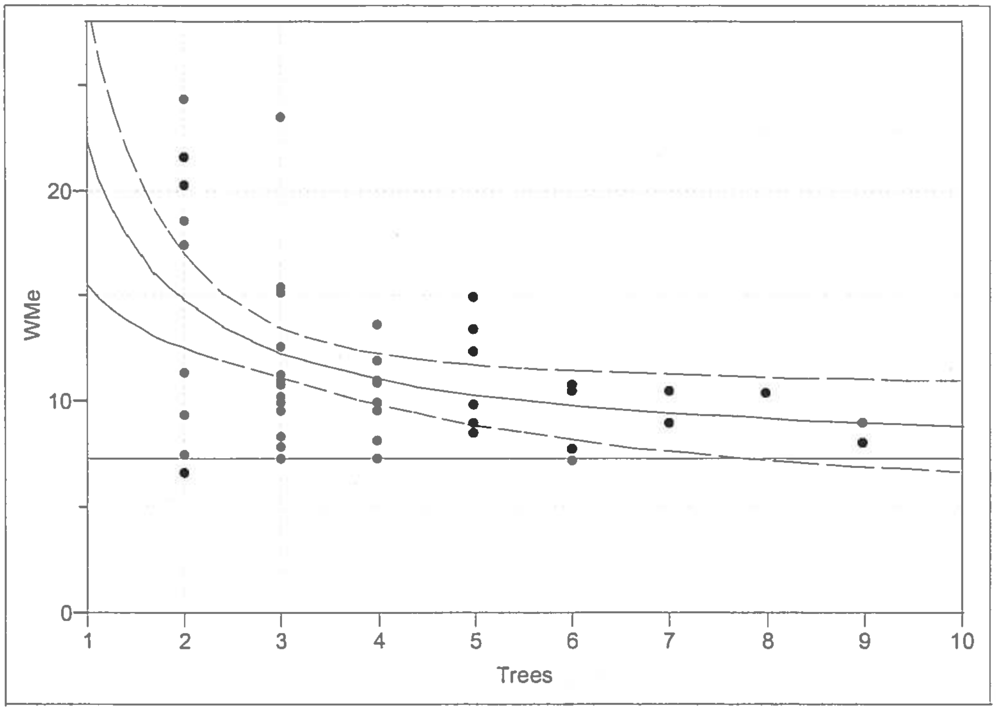


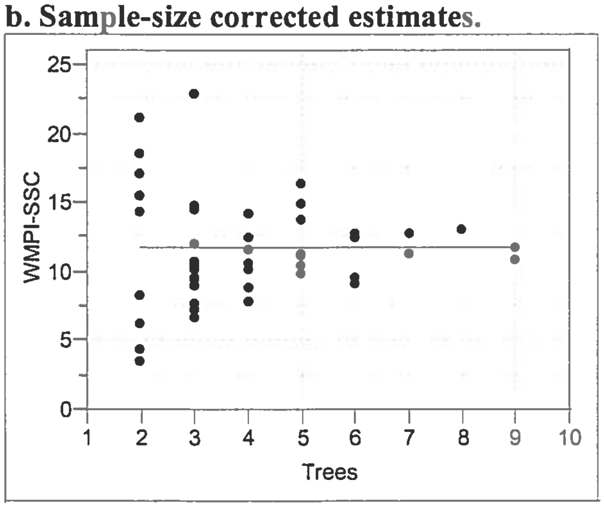
Figure 5. Effect of sample size on estimates of Weibull Median Probability Interval (WMPI).

1 grid cell.

a. Uncorrected estimates.

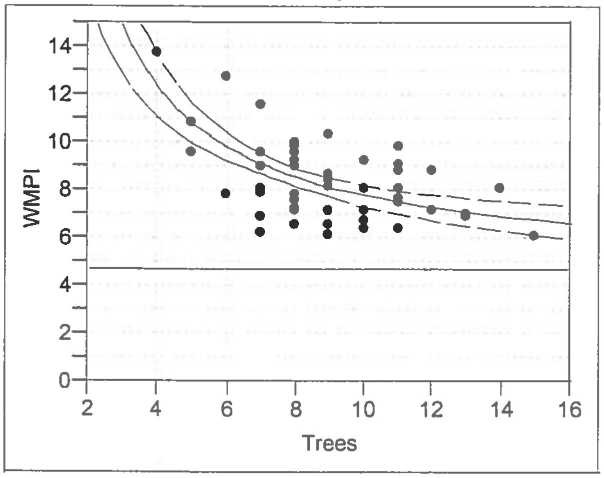


b. Sample-size corrected estimates.

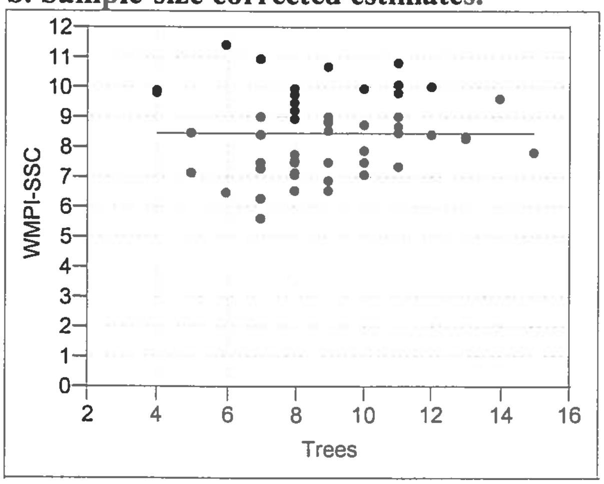


2 grid cells

a. Uncorrected estimates.

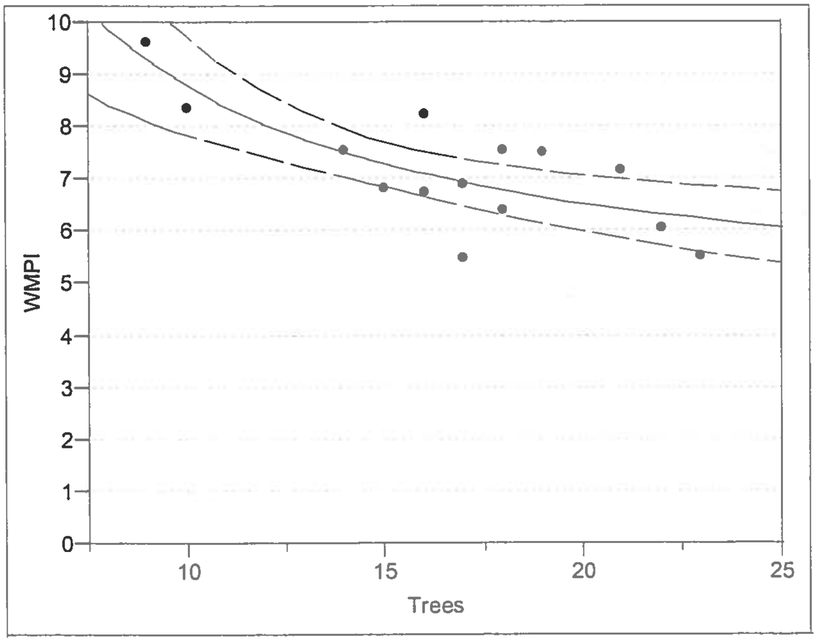


b. Sample-size corrected estimates.

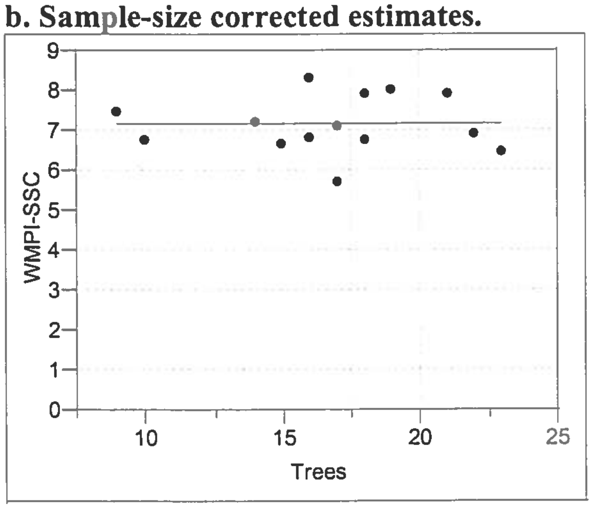


4 grid cells.

a. Uncorrected estimates.

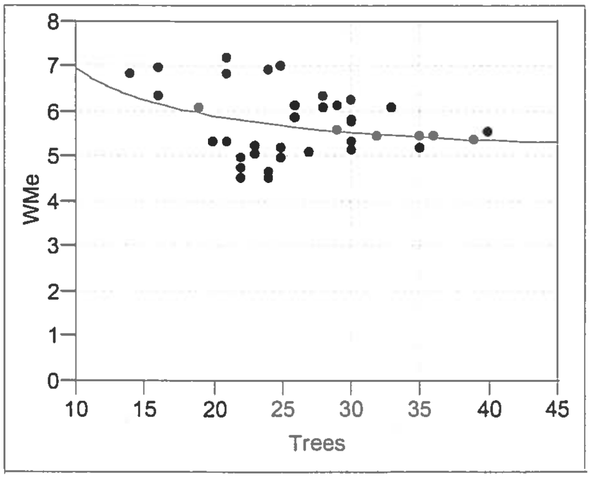


b. Sample-size corrected estimates.

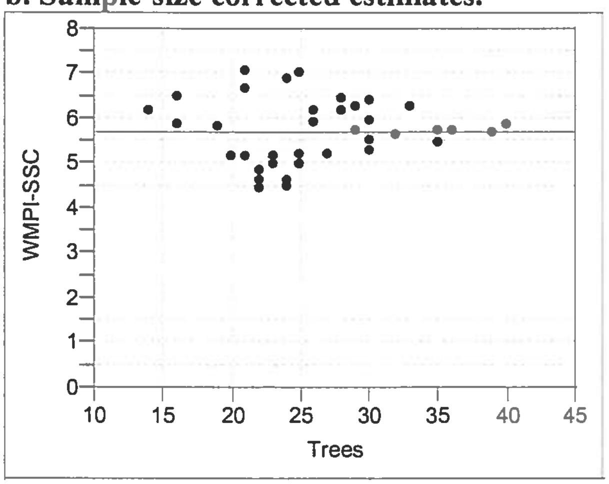


9 grid cells.

a. Uncorrected estimates.

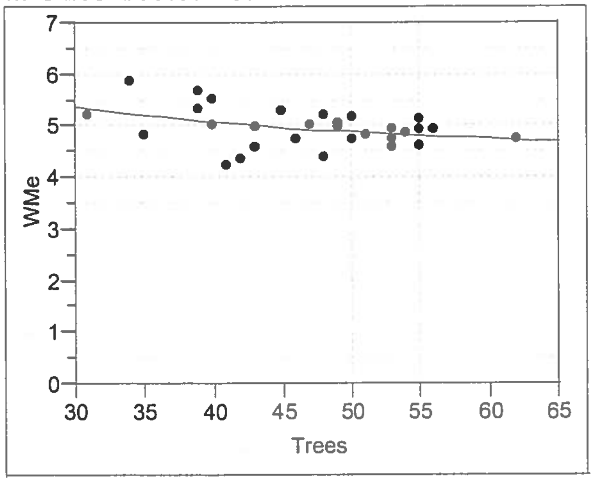


b. Sample-size corrected estimates.



16 grid cells.

a. Uncorrected estimates.



b. Sample-size corrected estimates.

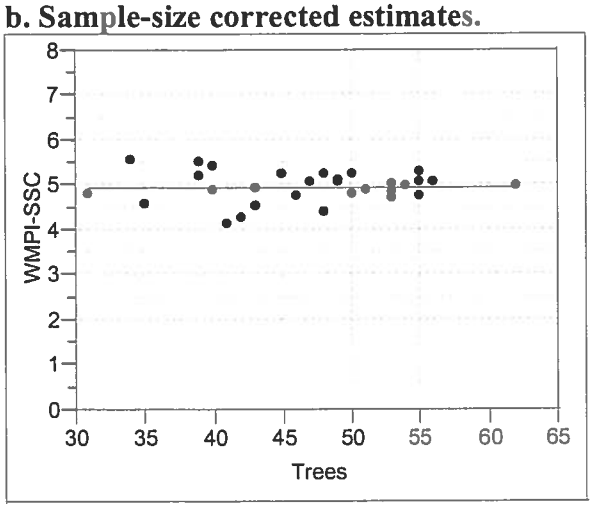


FIG. 6

Figure SAMPDEPTH. Sample depth (percent of locations recording) by year.

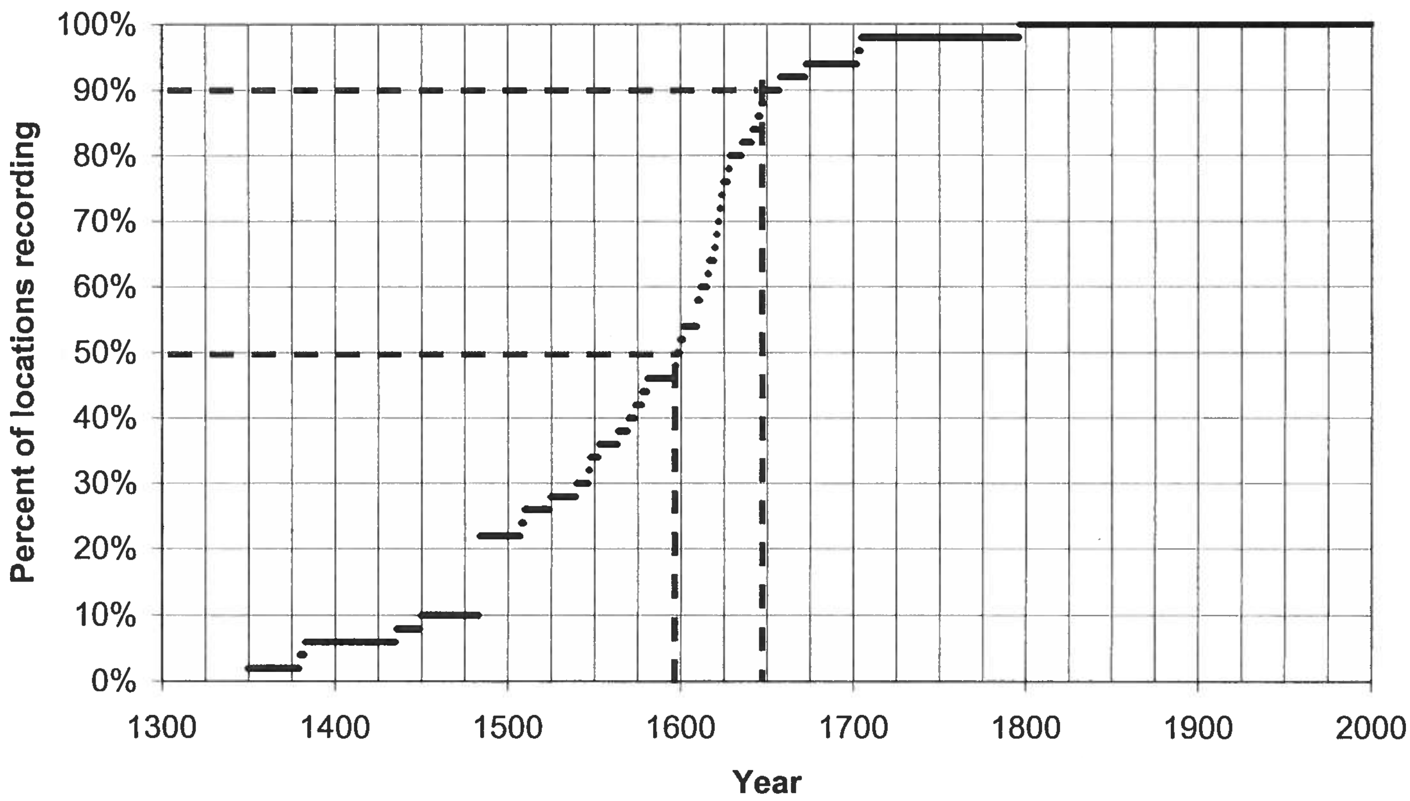
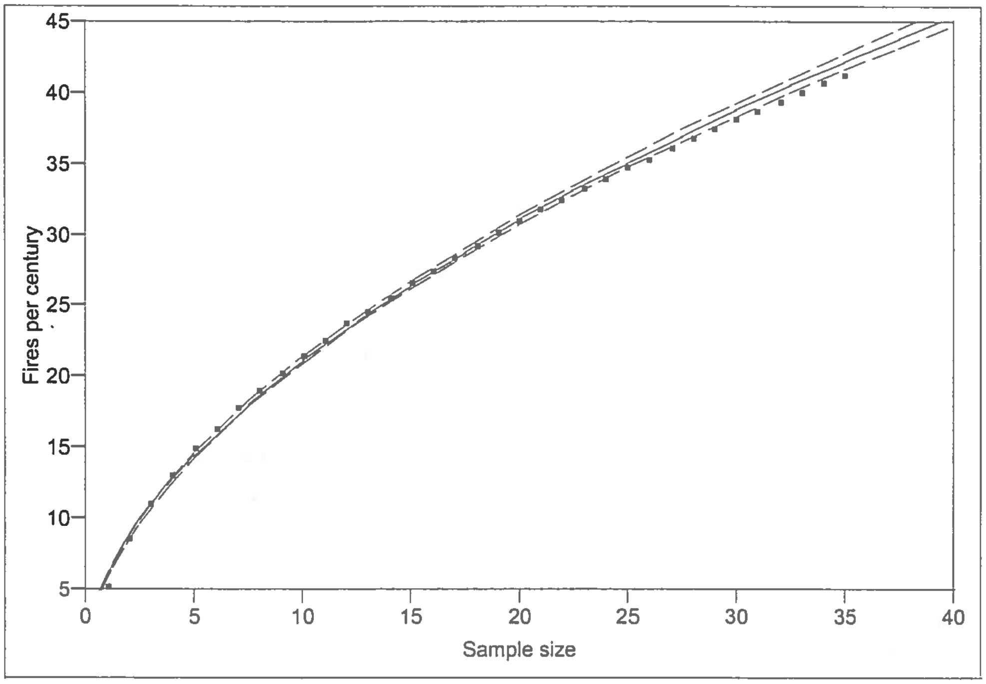
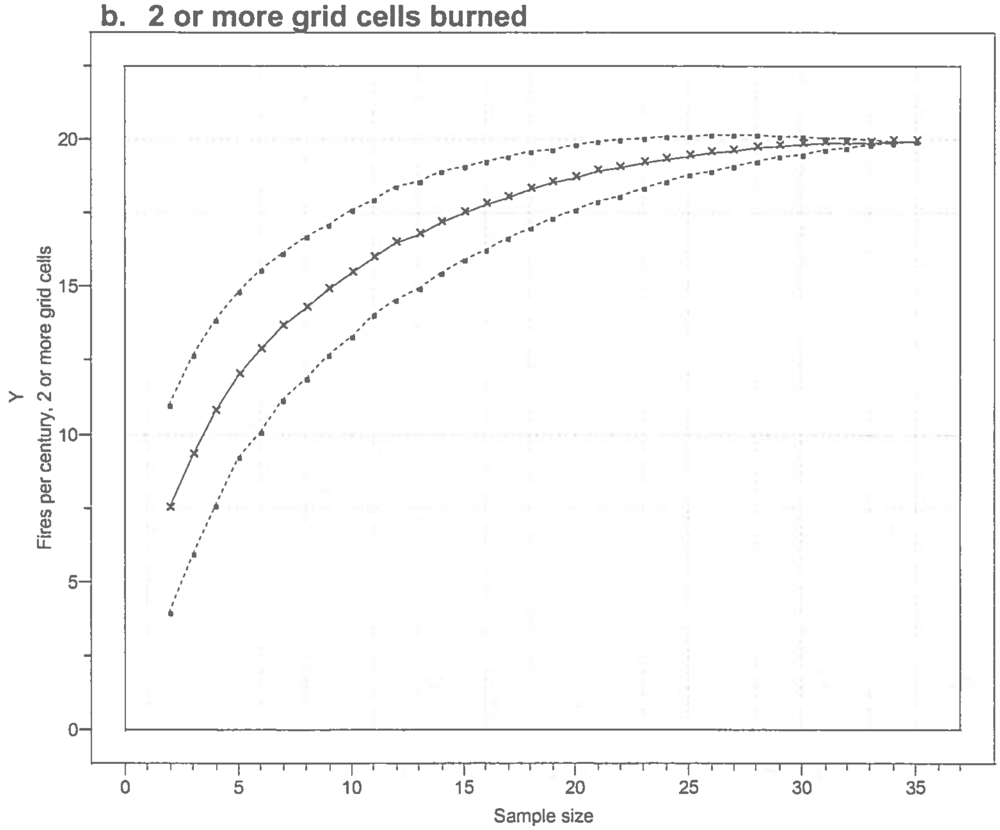


Figure 7. Bootstrap estimates of fire frequency using composite fire records for each grid point.

1. **Without replacement (stochastic permutation)**
   a. **All fires.**

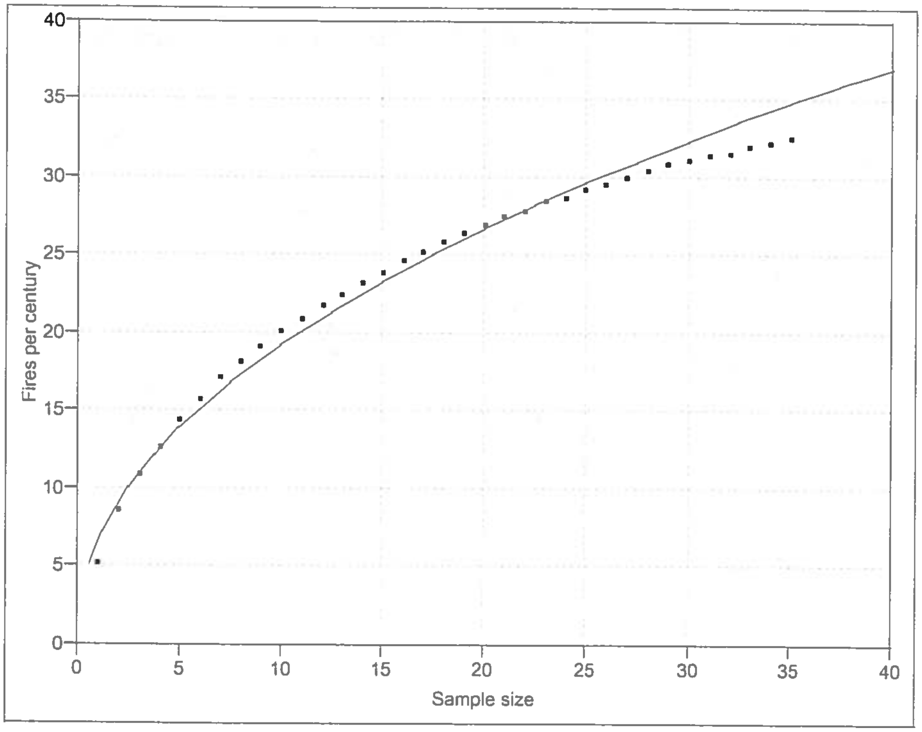


   b. **2 or more grid cells burned**



2. With replacement.

a. All fires.



b. With replacement, 2 or more grid cells:

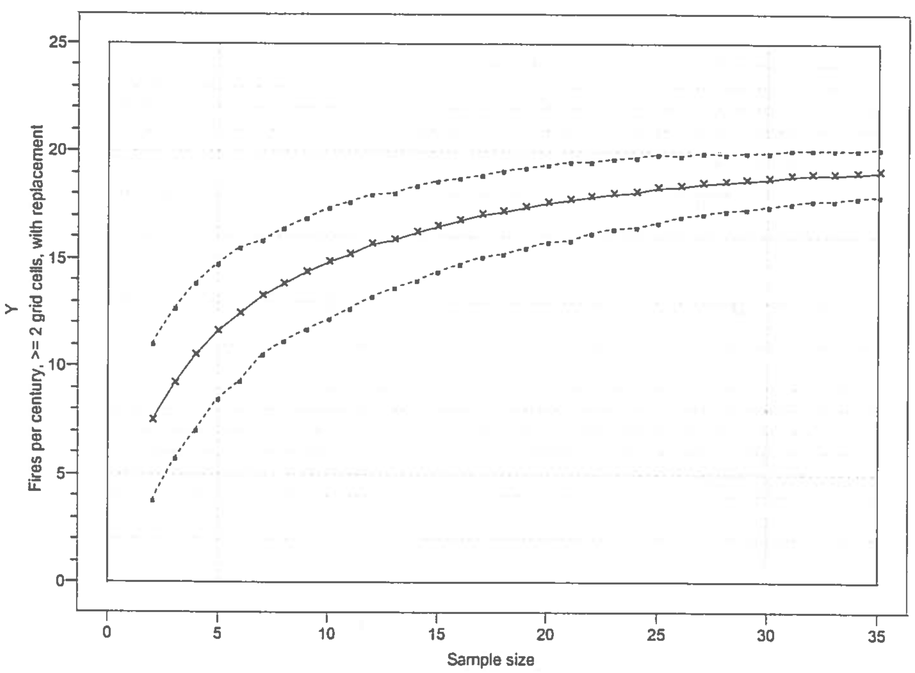


Table 1. Summary of collections and temporal extent of fire history at sampled grid cells at MCN.

Grid cell	Number of trees sampled	Inner and outer ring years	Temporal extent of record (yr)	Earliest fire year	Last fire year
101	4	1642-1999	358	1665	1933
102	3	1612-1999	388	1684	1933
103	2	1574-1999	426	1648	1880
105	2	1624-2000	377	1648	1887
106	5	1622-2001	380	1680	1942
107	3	1602-1999	398	1691	1880
109	2	1705-1999	295	1801	1929
111	5	1354-2000	647	1450	1880
112	9	1581-2001	421	1648	1961
113	6	1564-2001	438	1639	1905
115	4	1621-2000	380	1648	1912
116	5	1628-2001	374	1664	1876
117	3	1484-2000	517	1729	1887
119	2	1636-1999	364	1664	1893
121	4	1525-1999	475	1600	1929
122	4	1610-2001	392	1654	1893
123	3	1620-1999	380	1648	1936
125	2	1647-1999	353	1716	1880
127	2	1625-2000	376	1658	1893
129	3	1600-2000	401	1664	1955
130	3	1629-1999	371	1704	1929
131	5	1383-1999	617	1505	1937
132	6	1610-2001	392	1639	1887
133	2	1797-1999	203	1836	1899
135	6	1484-2000	517	1648	1911
137	4	1510-2000	491	1542	1951
138	9	1450-2001	552	1509	1893
140	1	1540-2000	461	1745	1801
141	4	1616-2000	385	1654	1893
142	5	1547-2001	455	1610	1942
143	3	1548-1999	452	1576	1915
144	5	1484-2000	517	1618	1929
145	3	1703-1999	297	1729	1896
146	7	1508-1999	492	1659	1899
147	2	1598-1999	402	1705	1896
148	7	1436-2001	566	1467	1937
149	2	1645-2000	356	1724	1876
151	3	1597-1999	403	1684	1893
153	8	1380-2001	622	1597	1904
154	3	1617-1999	383	1729	1921
156	3	1570-1999	430	1622	1893
157	2	1658-2001	344	1714	1893

158	2	1649-2000	352	1724	1955
160	4	1553-1999	447	1665	1893
162	4	1673-2000	328	1684	1938
164	3	1623-1999	377	1654	1981
166	5	1578-2000	423	1598	1893
170	6	1484-2000	517	1684	1929
180	3	1484-2000	517	1601	1909
188	5	1484-2000	517	1696	1892
Mean ± 1 s.d.	4.0 ± 1.9	1574 ± 87 to 2000 ± 1	427 ± 88	1654 ± 74	1909 ± 30
Study area	198	1354-2001	648	1450	1981

Table 2.

a.

Window size (ha)	Mean of F_A estimates (fires century^{-1})	Reciprocal regression		
		r^2_{adj}	*F*-ratio	*p* (*F*)
4	8.9	0.00	1.21	0.27
8	11.1	0.12	7.83	**0.01**
16	12.4	0.42	10.49	**0.01**
20	13.2	0.15	3.18	**0.10**
36	16.1	0.02	1.78	0.19
64	19.1	0.08	3.47	**0.07**
100	22.2	0.70	45.18	**<0.01**
144	25.2	0.68	24.52	**< 0.01**
196	28.0	0.15	1.88	0.24
256	29.5	*a*	*a*	*a*
288	30.3	NA	NA	NA

b.

Window size (ha)	Mean of F_A estimates (fires century^{-1})	Reciprocal regression		
		r^2_{adj}	*F*-ratio	*p* (*F*)
4	9.4	0.06	3.70	0.06
8	12.2	0.31	23.02	**<0.01**
16	14.2	0.43	10.79	**0.01**
20	15.0	0.23	4.51	0.06
36	17.7	0.01	1.34	0.25
64	20.3	0.08	3.38	0.08
100	22.5	0.70	45.25	**< 0.01**
144	24.5	0.53	13.54	**0.01**
196	26.3	0.15	1.87	0.24
256	27.0	*a*	*a*	*a*
288	28.0	NA	NA	NA

a Too few replicates to conduct test.

Table 3.

Window size (ha)	Mean of CFI estimates (yr $fire^{-1}$)	Reciprocal regression		
		r^2_{adj}	*F*-ratio	*p* (*F*)
4	12.4	0.09	0.25	> 0.96
8	9.4	0.15	0.61	> 0.79
16				
20	7.9	0.30	4.61	**> 0.08**
36	6.5	0.16	1.18	> 0.35
64	6.5	0.13	**get**	**< 0.05**
100	6.6	**0.69**	42.81	**< 0.01**
144	5.9	**0.71**	**get**	**< 0.01**
196	3.6	0.14	1.81	> 0.25
256	3.4	*a*	*a*	*a*
288	3.3	NA	NA	NA

Table 4.

Window size (ha)	Mean of FI_M estimates (fires $century^{-1}$)	Reciprocal regression			
		r^2_{adj}	*F*-ratio	*p* (*F*)	Normality of residuals, *p*(*W*)
4	9.6	0.07	4.38	**0.04**	**0.03**
8	7.3	**0.27**	19.40	**< 0.01**	**< 0.01**
16	6.1	**0.28**	5.93	**0.03**	< 0.78
20	6.0	**0.19**	3.83	0.08	< 0.22
36	5.0	0.05	2.02	0.16	**< 0.01**
64	4.0	**0.16**	6.68	**< 0.02**	**< 0.01**
100	3.4	**0.34**	10.87	**< 0.01**	< 0.85
144	3.0	*a*	*a*	*a*	*a*
196	3.0	*a*	*a*	*a*	*a*
256	3.0	*a*	*a*	*a*	*a*
288	2.0	NA	NA	NA	NA

a Insufficient replication of sample sizes to conduct test.
NA Not applicable.

Table 5.

Window size (ha)	Mean of WMPI estimates	Reciprocal regression		
		r^2_{adj}	F-ratio	p (F)
4	11.7	0.17	10.25	**0.003**
8	8.5	0.43	0.79	> 0.63
16	7.2	0.57	0.45	0.85
20	**6.3**	**0.20**	**3.78**	**0.05**
36	5.7	0.06	3.65	**0.06**
64	5.0	0.12	5.13	**> 0.03**
100	4.4	0.69	43.84	**< 0.001**
144	4.1	0.70	27.12	**< 0.001**
196	3.8	0.17	2.00	> 0.22
256	3.7	*a*	*a*	*a*
288	**3.3**	NA	NA	NA

a Too few replicates to conduct test.
NA Not applicable.

Table 6.

Area (ha)	Frequency		MFI	FI_M	WMPI
	$\bar{f}$	f_{WM}			
4	(3) 4	4	4	(3) 4	4
8	(6) 7	(7) 8	(6) 7	7	(6) 7
16	(13) 14	(13) 14	15	14	(12) 13
20	17	17	13	(15) 16	17
36	22	21	21	21	21
64	36	36	36	37	36