A Neutral Model for Low-Severity Fire Regimes[1]

Don McKenzie[2] and Amy E. Hessl[3]

Abstract

Climate, topography, fuel loadings, and human activities all affect spatial and temporal patterns of fire occurrence. Because fire occurrence is a stochastic process, an understanding of baseline variability is necessary in order to identify constraints on surface fire regimes. With a suitable null, or neutral, model, characteristics of natural fire regimes estimated from fire history data can be compared to a “null hypothesis.” We generated random landscapes of fire-scarred trees via a point process with sequential spatial inhibition. Random ignition points, fire sizes, and fire years were drawn from uniform and exponential family probability distributions. For this paper we focused on two sets of statistics commonly computed in fire history studies. Composite fire records and Weibull median probability intervals (WMPIs) were calculated at multiple spatial scales for random subsets of each landscape, and parameters of the Weibull distribution were estimated for each simulated “fire history” and tested for significance. We compared results from simulations to fire-history data from a watershed in eastern Washington. Strong nonlinear relationships were evident between and area sampled and WMPIs for a range of fire sizes for both real and simulated data. Patterns of significance of Weibull “shape” parameters were distinctly different between real and simulated landscapes. The clear patterns on neutral landscapes suggest that deviations from them in empirical data represent real constraints on fire regimes (e.g., topography, fuels) rather than sampling artifacts. Neutral models show promise for investigating low-severity fire regimes to separate intrinsic properties of stochastic processes from the effects of climate, fuel loadings, topography, and management.

Introduction

Fire-history reconstructions provide the empirical basis for fine- and coarse-scale modeling of fire regimes and for informed management and restoration of ecosystems (Landres and others 1999, Schmoldt and others 1999, Swetnam and others 1999, McKenzie and others 2004). Reconstructions use different methods depending on objectives, the nature of the fire regimes being studied, and the spatial and temporal scales of analysis (Clark 1990, Agee 1993, Heyerdahl and others 1995, Lynch and others 2003, Prichard 2003). Although estimates of fire frequency from different methods are often combined for modeling and management, they are not always equivalent (Heyerdahl and others 1995, McKenzie and others 2000, Li 2002).

In dry low-elevation forest ecosystems of the western United States, living trees provide a long-term record of low-severity fire from fire scars (Agee 1993, Swetnam 1993, Everett and others 2000, Veblen and others 2000, Heyerdahl and others 2001). Existing reconstructions are of varying quality; some were developed from very

---

[1] An earlier version of this paper was presented at the 2002 Fire Conference: Managing Fire and Fuels in the Remaining Wildlands and Open Spaces of the Southwestern United States, December 2–5, 2002, San Diego, California.

[2] Research ecologist, Pacific Northwest Research Station, 400 N. 34th Street, Suite 201, Seattle, WA 98103. e-mail: donaldmckenzie@fs.fed.us.

[3] Assistant professor, Department of Geology and Geography, West Virginia University, Box 6300, Morgantown, WV 26506. e-mail: ahessl@geo.wvu.edu.

small samples; others were not crossdated against a master chronology (Madany and others 1982, Heyerdahl and others 1995). Crossdating errors can substantially change estimates of the statistical properties of fire regimes (McKenzie and others 2000). In addition, fire-history reconstructions are sensitive to the area sampled, because too small an area may miss fires entirely, whereas too large an area may record separate fire events as one (Agee 1993, Heyerdahl and others 1995, Baker and Ehle 2001). Research is needed to quantify how fire regime statistics change across spatial scales and how these changes may differ in different ecosystems (Falk and Swetnam 2004).

Neutral models

In formal experiments, in which a null hypothesis is tested against an alternative, “controls” and “treatments” are ideally identical except for the treatment effect. If this effect is statistically significant, the null hypothesis is rejected. “Neutral models” in community and landscape ecology generalize the concept of a null hypothesis to an array of patterns and processes that capture relevant details of a system but eliminate constraints or mechanisms of interest (Caswell 1976, Kimura 1983, Gardner and O’Neill 1991, Hubble 2001). When a complex stochastic process (e.g., landscape disturbance or community assembly) is being studied, identification of the appropriate neutral model is difficult, and much controversy exists in the literature (e.g., Weiher and Keddy 1999).

Neutral models have been used in landscape ecology to study species co-occurrence (Milne 1992, Palmer 1992), formation of ecotones (Milne and others 1996), metapopulation models and conservation (With 1997), and connectivity and disturbance spread (Green 1994, Keitt and others 1997). In this paper, we present a neutral model of low-severity fire regimes – those for which the fire history is preserved via fire scars on living trees. The model was designed to represent stochastic properties of fire regimes in that fire sizes, fire-free intervals, and fire locations are considered to be random variables. We examine two statistical properties of the neutral model: how estimates of fire frequency change with changing spatial scale, and how temporal trends in the hazard of burning change with area and number of trees sampled. We compare results to the same statistical properties on a real landscape, and make qualitative inferences about the usefulness of pursuing this method for identifying constraints on fire regimes.

Methods

Fire history data

The fire-history data are from a dry forest ecosystem in eastern Washington, USA. Everett and others (2000) produced a detailed, spatially explicit dataset of fire history data from 17,700 fire-scarred trees collected in five study sites (3,116 to 12,747 ha) extending from the Okanogan-Wenatchee National Forest in central Washington to the Colville National Forest in northeastern Washington (*fig. 1*). These study sites occupy a 500 km northeast to southwest gradient across the Okanogan Highlands and down the east side of the Cascade Range.

Fire-history sites are located within forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Loud.). These forests in Washington typically occur between 600 and 1,200 m elevation and change into Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), grand fir (*Abies grandis* [Dougl.] Lindl.), western larch (*Larix* *occidentalis* Nutt.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) at higher elevations and grassland or sagebrush (*Artemisia tridentata* Nutt.) at lower (*fig. 2*).

This spatially distributed network of geo-referenced, cross-dated fire scar chronologies is ideal for spatial and temporal analysis of regional surface-fire history. To date, chronologies have been developed for five study sites (*fig. 1*). Within each site, all fire-scarred trees were mapped, and a spatially stratified random sample of high-quality trees (with a large number of scars) was collected.

For this paper, we focus on the 11,088-ha Swauk watershed (inset in *fig. 1*), with a total of 7,048 fire scars on 671 recorder trees. The composite fire interval for the watershed (counting only fires that scarred >10 percent of the trees) is 8 yr, and the Weibull median probability interval (WMPI) for these same fires is 7 yr (Hessl and others 2004). The frequency of occurrence of a fire somewhere in the watershed (possibly fewer than 10 percent of trees scarred), however, was just under 2 yr.

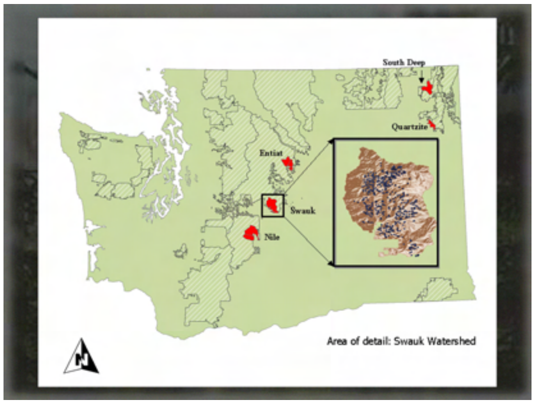

Figure 1–Location of fire-history study in eastern Washington

Figure 2–Study locations in ponderosa pine forests.

Simulation model

The "neutral" landscape consisted of a square grid with unitless X and Y coordinates, in emulation of a watershed. We randomly located 200 points to represent trees that could record fires over the course of the simulations. Sequential spatial inhibition (Ripley 1987) was used to ensure that no two trees overlapped. A 300 yr fire history was simulated for two watershed-scale mean fire frequencies (MFRIs): 2 and 5 yr. These numbers represent the average interval between the occurrence of fire somewhere in the watershed and correspond to the 2 yr value computed from the Swauk watershed. Time steps (years until the next fire) were drawn from an exponential distribution, with mean=MFRI and rounded to the nearest integer, until their sum was >300. At each time step, a circular fire was simulated with its center randomly located in the watershed. Mean fire sizes were defined within a range of proportions of the total watershed area, between 0.1 and 0.4, with steps of 0.05. These proportions were chosen to approximate proportional sizes of composite fire records in real watersheds. For each round of simulations, the size of each fire was drawn from a gamma distribution whose mean was the mean fire size.

Composite fire records

The coordinates of each recorder tree were noted and a data matrix created (300 rows=years, 200 columns=trees) to hold the "fire history" of the simulated watershed. We then simulated fire-history reconstructions within the watershed, using a "neutral" method whereby one tree was selected as a starting location. Using this tree as a center, we computed composite fire intervals (CFIs) for search radii from 0.1 to 0.6 proportions of the watershed (at intervals of 0.01–50 total) and fit each time series of fire-free intervals to the two-parameter Weibull distribution. For each search radius, 20 replicate CFIs were computed (*fig. 3*).

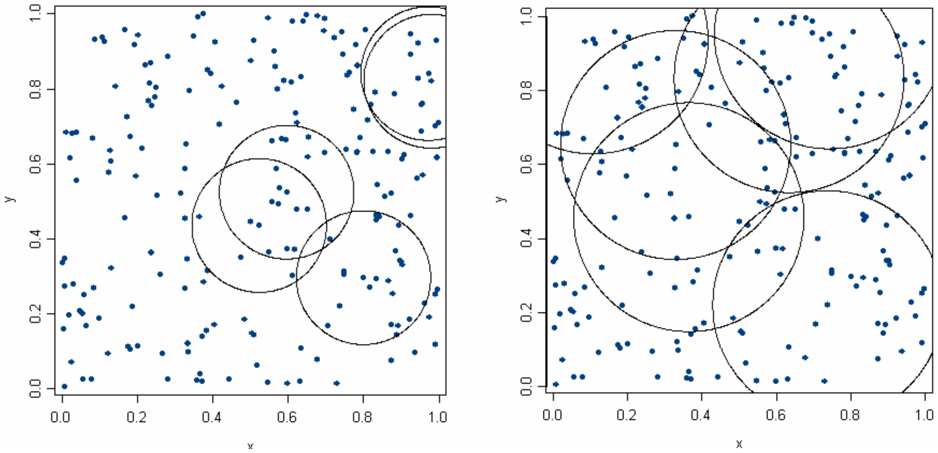

Figure 3–Simulated areas for fire-history reconstructions with search radii equal to 0.1 and 0.3 of the watershed.

Two features of the Weibull distribution make it well-suited to modeling both high- and low-severity fire regimes (Clark 1989, Johnson and Gutsell 1994, Grissino-Meyer 1999): the Weibull median probability interval (WMPI) is a robust measure of central tendency, and the shape parameter and associated hazard function allow changes in the hazard of burning over time to be identified (*figs. 4 and 5*). For each of the composite fire records (20 replicates x 50 search radii), we computed the WMPI and the Weibull shape parameter, the latter as a surrogate for the slope of the hazard function (Clark 1989, Johnson and Gutsell 1994). For each search radius, the mean of 20 replicates was stored for WMPI and the shape parameter. We applied the same iterative process to fire history for the Swauk watershed, but restricted sample years to the period 1651 to 1900. By 1650, most trees had recorded one fire. Before 1900, fire exclusion had not drastically changed fire frequency (*fig. 6*, Hessl and others 2004). We created a set of composite fire records (20 replicates x 50 search radii) similar to the simulated watershed, using a 250 yr fire record.

We compared simulated to empirical results qualitatively for changes in WMPI and shape parameters with changing spatial scale. The exploratory analysis presented here was designed to provide insight as to whether the neutral model of fire regimes is a useful concept that can be applied to inferences about the constraints (e.g., fuels, topography, land use) on low-severity fire regimes. Formal statistical tests and extrapolation to other geographic areas will be the subject of future research.

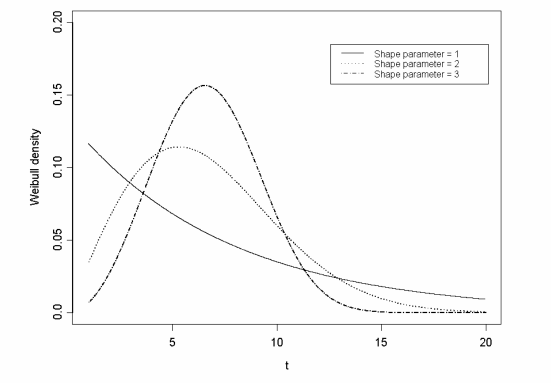

Figure 4–Shape of the Weibull density for different values of the shape parameter, with scale parameter held constant..

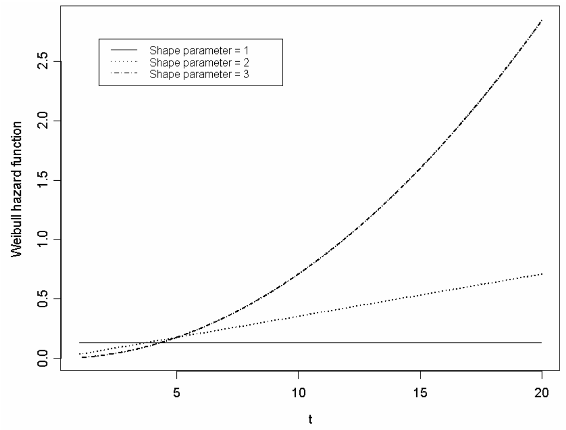

Figure 5–Shape of the Weibull hazard function for different values of the shape parameter, with scale parameter held constant..

Results and Discussion

Scaling relationships for the estimated fire-free intervals (WMPI) between simulated (neutral) and real watersheds are clearly similar (*figs. 7 and 8*). In both cases a log-linear model best predicted the relationship between the search radius, equivalent to sample area in a fire-history study, and WMPI, with R2 of 0.96 and 0.89, for simulated and real data, respectively. When the watershed-scale mean FRI was 2 yr in simulated data, point-level WMPI ranged from 9 yr, for simulated mean fire sizes of 0.15 of the watershed area, to 5 yr for a simulated size of 0.35. For watershed-scale means of 5 yr, point-level WMPI ranged between 23 yr (0.15 of watershed) down to 12 yr (0.35 of watershed). For the Swauk watershed, mean point-level WMPI was 13 yr (*fig. 8*).

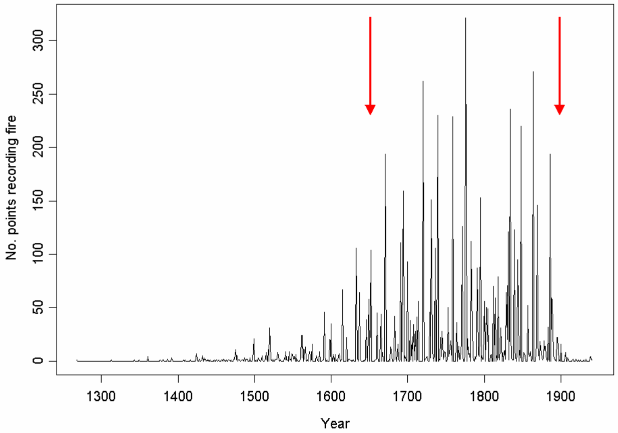

Figure 6–Fire history record in the Swauk watershed. Arrows represent the beginning and end of the period used in this paper.

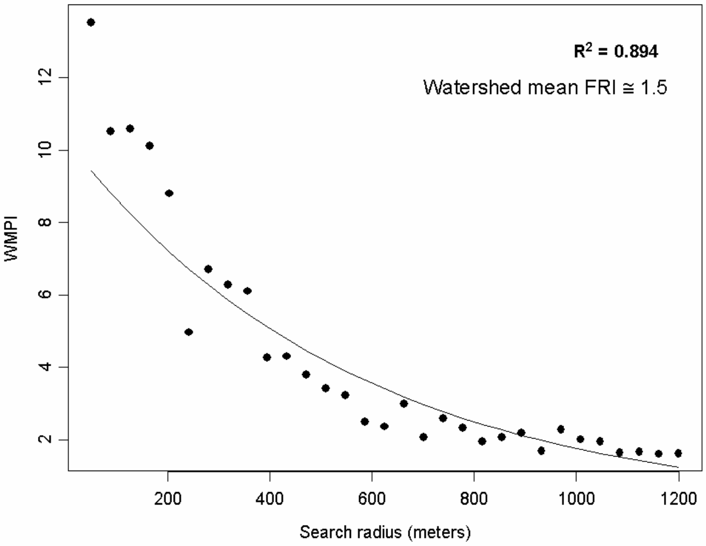

Figure 7–Relationship between area sampled and WMPI for simulated data.

Results from the neutral model suggest that non-linear scaling laws are an intrinsic property of the spatial relationships among points subject to this particular stochastic process (low-severity fire) (Falk and Swetnam 2004). The log-linear relationship holds for a variety of mean fire sizes and fire frequencies. In the composite fire record for the Swauk watershed, there are no local influences that invalidate the scaling relationship, despite the variety of fire sizes and the relatively complex, dissected topography (*fig. 1*). Given that fire regimes vary over seemingly homogeneous landscapes (e.g., Baker 1989) and that topography has been shown to provide strong constraints on fire regimes (e.g., Taylor and Skinner 2003), more research is needed in a range of low-severity fire regimes before a global scaling law can be said to exist.

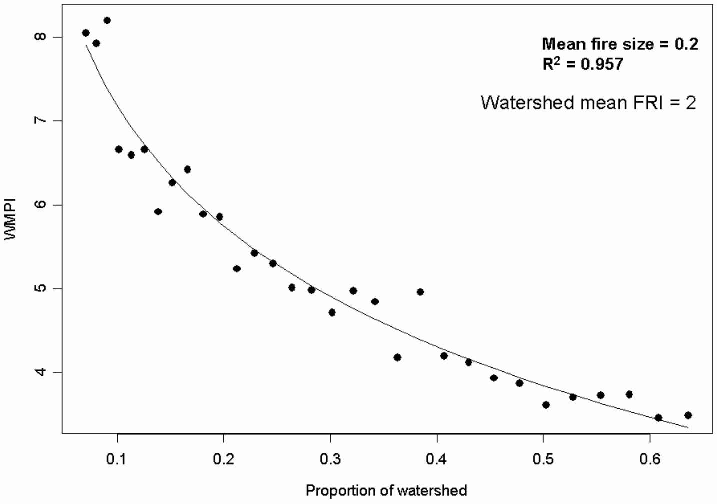

Figure 8–Relationship between area sampled and WMPI for the Swauk watershed.

Estimates of the Weibull shape parameter differed substantially between simulated and real watersheds, both in mean value and trends over increasing search radii. For simulated watersheds, mean estimates were between 1.10 and 1.45 for a variety of mean fire sizes (0.1 to 0.5 of watershed) and search radii (0.15 to 0.45) (*fig. 9*). Search radii below 0.15 contained too few fires to estimate shape parameters successfully. In contrast, shape parameters estimates in the Swauk watershed ranged between 1.5 and 2.5, with a sharp descent between the point level and a search radius of 200 m (*fig. 10*). Initial bootstrap estimates of significance for the shape parameters suggested that for a 95 percent confidence interval for both simulated and real watersheds to exclude 1.0 (corresponding to a flat hazard function), shape parameters should have a minimum between 1.3 and 1.6. A more refined bootstrap algorithm for these distributions, to more precisely compute p-values, is under development.

Changes in shape parameter are surrogates for changes in the slope of the hazard function (Clark 1989, Johnson and Gutsell 1994, *fig. 5*). The neutral model, shape parameters gradually increased with the search radius (*fig. 9*), though changes were slight and probably not statistically significant. However, similar behavior for a variety of simulated fire sizes suggests that this gradual increase may be an intrinsic

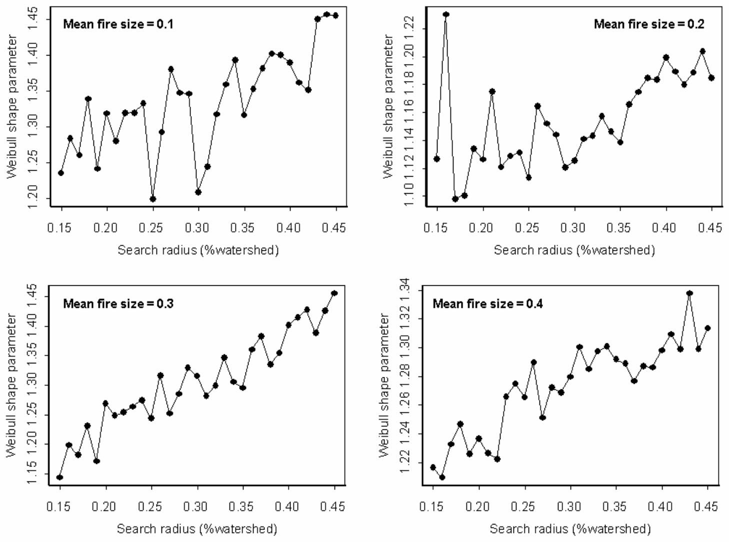

Figure 9–Trends in the Weibull shape parameter with increasing search radii on simulated landscapes with different mean fire sizes.

property of the stochastic process being modeled, and needs to be distinguished from any processes of interest when the neutral model is compared with real data.

In contrast, in the Swauk watershed the shape parameters drop very quickly with increasing spatial scale, up to 240 m search radius, then begin a gradual ascent similar to those in the neutral model, although values are higher (approximately 1.5 to 1.8 in Swauk vs. a maximum of 1.45 for neutral model). We infer that a constraint on fires in rapid succession is operating on the Swauk landscape up to, on average, an area of 18 ha (240^2 * PI / 10^4), and that the increasing hazard function over time at this scale is a reflection of it. Beyond this search radius, the shape parameter behaves very similarly to that from the neutral model. In the Swauk and similar landscapes, composite fire records from study areas of different sizes, for example 10 ha vs. 40 ha, could therefore yield very different interpretations about fire history. Baker (1989) observed that different statistical models were appropriate for different-sized study areas in a landscape with high-severity fire. Key processes controlling fire frequency may change, or at least appear different, when data are collected and analyzed at different spatial scales.

An obvious candidate for the small-scale constraint on historical fire frequency in the Swauk watershed is buildup of fine fuels after fire. Time is required for a spatially continuous fuelbed, and therefore sufficient potential fire spread for trees to record fire, to accrue. When viewed at scales much greater than 18 ha, this constraint on fire occurrence is no longer observed. The 18 ha threshold would appear to be a surrogate for a modal, or characteristic, fire size, in that it defines the spatial extent over which the constraint of fuel buildup can be observed. When the search radius becomes much greater than typical fire size, it would be expected to include multiple fires, burning different patches over time, and confounding the fuel constraint.

The threshold for change in behavior of the hazard function would clearly change with changes in characteristic fire size, but only on landscapes on which a mechanism exists that controls fire occurrence (not neutral landscapes). Constraints on fire size, then, will be another factor controlling fire frequency. Other results from this exercise—the log-linear models of WMPI as a function of search radius (and fire size)—indicate that on both neutral landscapes and the Swauk watershed, scaling relationships among all factors are clearly defined. If proven to be robust on a variety of landscapes, particularly those on which topography provides strong constraints on fire spread, these scaling relationships could be useful for predicting characteristics of fire regimes for which extensive, spatially explicit data are not available.

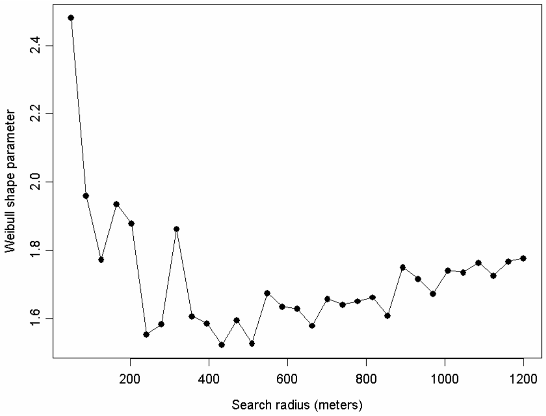

Figure 10–Trends in the Weibull shape parameter in the Swauk watershed with increasing search radii.

Conclusions

Neutral models hold promise for understand complex behavior in low-severity fire regimes. Fire is a stochastic process, of which each fire-history record is just one of many potential realizations (Lertzman and others 1998). Because fire-history reconstructions are made with finite resources, each can discover only an incomplete sample of even the one realization that it observes (Baker and Ehle 2001). A template is needed for intrinsic statistical properties of fire regimes, against which specific realizations can be compared to distinguish their individual properties (for example, constraints on fire size and frequency).

In this paper, we begin to explore the ways in which neutral models can help distinguish these individual properties of real landscapes from the "neutral" background. More research is needed as to what to include in the neutral background. For example, many fire-history reconstructions develop collector's curves to determine the first point in time at which a representative sample of the total population of recorder trees has recorded at least one fire (Hessl and others 2004). Should a neutral model incorporate an increasing population of trees over time? Similarly, many researchers include only significant fire events (greater than a certain percentage of recorder trees scarred) in models of the association between fire occurrence and fuel or climatic constraints (Swetnam and Betancourt 1990, Grissino-Meyer 1995, Heyerdahl and others 2001, Hessl and others 2004). How would neutral model behavior differ with these additional attributes? Finally, more comparisons with data from real landscapes are needed, both to test the usefulness of the concept and to identify consistent patterns, if any, in scaling relationships and departures from "neutrality" in real fire regimes.

Acknowledgments

We thank Donald Falk, Carol Miller, and Steven McKay for review comments that improved the manuscript. Research was funded by a grant from the Joint Fire Sciences Program #01-1-6-01.

References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press; 493 p.

Baker, W.L. 1989. Effect of scale and spatial heterogeneity on fire-interval distributions. Canadian Journal of Forest Research 19: 700–706.

Baker, W.L.; Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 1205–1226.

Caswell, H. 1976. Community structure: a neutral model analysis. Ecological Monographs 46: 327–354.

Clark, J.S. 1989. Ecological disturbance as a renewal process: theory and application to fire history. Oikos 56: 17–30.

Clark, J.S. 1990. Fire and climate change during the last 750 years in northwestern Minnesota. Ecological Monographs 60: 135–159.

Everett, R.L.; Schellhaas, R.; Keenum, D.; Spurbeck, D.; Ohlson. P. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129: 207–225.

Falk, D.A., and Swetnam, T.W. 2004. Scaling rules and probability models for surface fire regimes in ponderosa pine forests. In Omi, P.N., and Joyce, L.A., technical editors. Fire, fuel treatments, and ecological restoration: Conference proceedings, 2002 16–18 April, Fort Collins, Colorado. Proceedings RMRS-P-29, Fort Collins, CO: Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture; 475 p.

Gardner, R.H., and R.V. O'Neill. 1991. Neutral models for landscape analysis. Chapter 11 in Turner, M., and R. Gardner eds. Quantitative methods in landscape ecology. Springer-verlag, New York, NY; 289–307.

Green, D.G. 1994. Connectivity and complexity in landscapes and ecosystems. Pacific Conservation Biology 1: 194–200.

Grissino-Mayer, H.D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Tucson: University of Arizona, 407 p. Ph.D. dissertation.

Grissino-Mayer, H.D. 1999. Modelling fire interval data from the American Southwest with the Weibull distribution. International Journal of Wildland Fire 9: 37–50.

Hessl, A.E.; McKenzie, D.; Everett R.; Schellhaas, R.. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14: 425–442.

Heyerdahl, E.K.; Berry, D.; Agee, J.K. 1995. Fire history database of the western United States. EPA Office of Research and Development: Report EPA/600/R-96/081. Washington, DC.

Heyerdahl, E.K.; Brubaker, L.B.; Agee, J.K. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology 82: 660–678.

Hubble, S.P. 2001. A unified neutral theory of biodiversity and biogeography. Princeton, NJ: Princeton University Press; 448 p.

Johnson, E.A.; Gutsell, S.L. 1994. Fire frequency models, methods, and interpretations. Advances in Ecological Research 25: 239–287.

Keitt, T.H., Urban, D.L.; Milne, B.T. 1997. Detecting critical scales in fragmented landscapes. Conservation Ecology http://www.consecol.org/ vol1/iss1/art4

Kimura, M. 1983. The neutral theory of molecular evolution. Cambridge, UK: Cambridge University Press; 367 p.

Landres, P.; Morgan, P.; Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9: 1179–1188.

Lertzman, K.; Fall, J.; Dorner, B. 1998. Three kinds of heterogeneity in fire regimes: at the crossroads of fire history and landscape ecology. Northwest Science (special issue) 72: 4–23.

Li, C. 2002. Estimation of fire frequency and fire cycle: a computational perspective. Ecological Modelling 154: 103–120.

Lynch, J.A.; Clark, J.S.; Bigelow, N.H.; Edwards, M.E.; Finney, B.P. 2003. Geographic and temporal variations in fire history in boreal ecosystems of Alaska. Journal of Geophysical Research; 108 p.

Madany, M.H.; Swetnam, T.W.; West, N.E. 1982. Comparison of two approaches for determining fire dates from tree scars. Forest Science 28: 856–861.

McKenzie, D.; Peterson, D.L.; Agee, J.K. 2000. Fire frequency in the Columbia River Basin: building regional models from fire history data. Ecological Applications 10: 1497–1516.

McKenzie, D.; Prichard, S.; Hessl, A.E.; Peterson, D.L. 2004. Empirical approaches to modelling wildland fire: methods and applications to landscape simulation. Chapter 7; In: Perera, A. J.; and L. Buse, eds., Emulating natural forest landscape disturbances. New York, NY: Columbia University Press.

Milne, B.T. 1992. Spatial aggregation and neutral models in fractal landscapes. American Naturalist 139: 32–57.

Milne B.T.; Johnson, A.R.; Keitt, T.H.; Hatfield, C.A.; Hraber, D.J.; Hraber, P.T. 1996. Detection of critical densities associated with pinon-juniper woodland ecotones. Ecology 77: 805–821.

Palmer, M.W. 1992. The coexistence of species in fractal landscapes. American Naturalist. 139: 375–397.

Prichard, S.J. 2003. Spatial and temporal dynamics of fire and forest succession in a mountain watershed, North Cascades National Park. University of Washington, Seattle, Washington. Ph.D. Dissertation.

Ripley, B.D. 1987. Stochastic simulation. Wiley and Sons, New York, NY 237 p.

Schmoldt, D.L.; Peterson, D.L.; Keane, R.E.; Lenihan, J.M.; McKenzie, D.; Weise, D.R.; Sandberg, D.V. 1999. Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management. Gen. Tech. Rep. PNW-GTR-455., Portland, Oregon: Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture; 104 p.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262: 885–889.

Swetnam, T.W.; Betancourt, J.L. 1990. Fire-Southern Oscillation relations in the southwestern United States. Science 249: 1017–1020.

Swetnam, T.W.; Allen, C.D.; Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9: 1189–1206.

Taylor, A.H.; Skinner, C.N. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13: 704–719.

Veblen, T.T.; Kitzberger, T.; Donnegan, J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications 10: 1178–1195.

Weiher, E.; Keddy, P. 1999. Ecological assembly rules: perspectives, advances, retreats. Cambridge University Press, Cambridge, UK; 438 p.

With, K.A. 1997. The application of neutral landscape models in conservation biology. Conservation Biology 11: 1069–1080.

This page intentionally left blank.