CONSERVATION ISSUES

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Monitoring Fire Effects for Managed Burns and Wildfires: Coming to Terms with Pseudoreplication

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ABSTRACT: Collecting unbiased monitoring data on fire effects is often problematic. Samples collected for assessing the effects of managed (prescribed) fires and wildfires are often "pseudoreplicated" because it is impossible to replicate the disturbance event. Furthermore, monitoring data for managed fires and wildfires may be confounded because it is difficult to randomize the effects of fires not under strict experimental control. It is not possible to replicate or randomize large-scale events such as wildfires and many prescribed fires, yet there are techniques that can account for some of the bias introduced by these problems. Since monitoring usually involves repeated observations, this paper discusses simple time-series analysis, along with two common modifications: impact/reference designs and before/after comparisons. While there are many possible monitoring strategies, most monitoring efforts are covered by these broad categories. In this paper we attempt to outline the assumptions, strengths, and limitations of these methods. We recommend four primary strategies to improve the confidence of findings when assessing fire effects: (1) acknowledge pseudoreplication in the data when it exists; (2) expand the use of managed fire and wildfire data for quantifying fire effects; (3) increase the use of unburned reference sites to improve the confidence of analyses of fire effects; and (4) in some instances, consider treating data taken from multiple fires as independent replicates. The concepts discussed in this paper are illustrated by examples taken from data sets for prescribed fire effects in Sequoia and Kings Canyon National Parks, California, USA.

Monitorendo los Efectos del Fuego Intencional y el Natural: Llegando a Término con Pseudo-replicación

RESUMEN: Colectar datos no sesgados de los efectos del fuego es a menudo problemático. Las muestras colectadas para medir el efecto del fuego manejado y los naturales son a menudo 'pseudo-réplicas' porque es imposible replicar el evento que causó el disturbio. Más aun, monitorear los datos para los fuegos manejados y los naturales puede ser confuso porque es difícil aleatorizar los efectos cuando el fuego no está bajo estricto control experimental. No es posible replicar o aleatorizar eventos a gran escala, tales como fuegos naturales y muchos fuegos intencionales, sin embargo existen técnicas que pueden tener en cuenta algunos de los sesgos introducidos por esos problemas. Ya que el monitoreo involucra observaciones repetidas, este trabajo discute análisis de series de tiempo simples, junto con dos modificaciones comunes: diseño de impacto/referencia y comparaciones antes/después. Mientras existen muchas estrategias posibles, la mayoría de los esfuerzos de monitoreo están cubiertos con esas amplias categorías. En este trabajo intentamos detallar esas asumpciones, fuerzas y limitaciones de esos métodos. Recomendamos cuatro estrategias primarias para mejorar la fiabilidad de los resultados cuando se miden efectos del fuego: (1) reconocer la pseudo-replicación en los datos si esta existe; (2) expandir el uso de datos de fuegos intencionales y naturales para cuantificar los efectos del fuego; (3) aumentar el uso de sitios de referencia no quemados para aumentar la confianza del análisis de los efectos del fuego; (4) en algunas instancias, los datos tomados de fuegos múltiples pueden ser usado como réplicas independientes. Los conceptos discutidos en este paper están ilustrados con ejemplos tomados de sets de datos de fuegos intencionales en los parques nacionales de Sequoia y Kings Canyon, California, E.E.U.U.

Index terms: Before-After/Control-Impact (BACI) designs, fire effects, monitoring, pseudoreplication, species diversity

INTRODUCTION

Some critical questions in ecology defy the requirements of standard statistical analysis because it is impossible or unethical to collect well-replicated and randomized samples. Assessing disturbance effects can fall into this category when the disturbance is unplanned or occurs over large spatial scales. There are, however, methods that may reduce bias introduced by these problems. While these methods are in wide use in aquatic biology and toxicology (Stout and Rondinelli 1995, Lee and Pritchard 1997, Lopes et al. 1997, Roberts et al. 1998, Kedwards et al. 1999), they have yet to be fully exploited for the study of fire ecology.

There is a clear need for alternative analytical models for the study of fire ecology. The literature is rife with conflicting reports for very basic fire effects. For example, biotic responses to fire, such as chang-

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ing productivity, plant community diversity, and animal populations, have been shown to increase, decrease, or remain stable following fire (Collins and Wallace 1990, Moreno and Oechel 1991, Singh 1993, Whelan 1995, Bond and van Wilgen 1996, Collins et al. 1998, Swengel 1998). Reports of fire effects on abiotic resources also conflict (Agee 1993). To a large degree, the varied outcomes of these studies reflect unique fire-mediated responses of the organisms and resources under study. However, in some cases this inconsistency is a result of the difficulty in assessing impacts of fire using traditional statistical approaches. Producing accurate assessments with as little bias as possible is especially important for the resolution of contentious issues such as fire management. The Yellowstone fires of 1988 serve as a reminder of the political fallout that can occur in the aftermath of controversial fire management decisions (Baskin 1999).

Randomization, the use of an unbiased pattern for collecting observations, is important because it ensures independence among the sampling units (i.e., individual organisms, plots, or landscapes). Independent samples ensure that there is no systematic difference between the burned and unburned groups. Without randomization it is possible that observed differences between groups are due entirely to uncontrolled and unmeasured natural factors rather than any treatment effects (e.g., one set of plots receives more light than the other plots). This prevents us from placing confidence intervals around our results, making the extension of findings to other areas conceptually difficult. Fequently, when using a nonrandomized sampling design, many researchers do not attempt to generalize their results to other areas, because the results could be mediated by site differences.

Replication is the application of the treatment (e.g., fire) over many independent sampling units. Samples that are improperly replicated such that samples are not fully independent are considered pseudoreplicated (Hurlbert 1984). Pseudoreplication in fire ecology typically occurs when a series of subsamples nested within a single burned area are treated as independent samples. Nested subsamples are not independent, given that the treatment, fire, is not independently applied and the samples probably share critical factors affecting the response variable(s). For example, subsamples taken from a single burn unit will probably have comparable levels of fire severity and share similar environmental conditions (e.g., slope, aspect, average precipitation, etc.). Such samples provide a reduced estimate of error in subsequent statistical analyses. Usually, this bias leads to an overestimation of treatment (fire) effects and increases the likelihood of committing a type I error (the chance of detecting a significant effect of fire when no meaningful effect has occurred) (Hurlbert 1984). While this is highly undesirable when generalization is desired, some studies are simply concerned with site-specific effects of a particular fire, so the use of pseudoreplicated samples is appropriate. This is different from basic scientific questions that are concerned with "typical" or average responses to burning.

Fire effects studies can be divided into three broad categories based on the amount of planned intervention in the application of the fire: experimental fires, managed (or prescribed) fires, and wildfires. Different types of studies have variable amounts of control over the amount of randomization, replication, and outside factors that may bias results (Table 1). Source of fire treatment will therefore determine both the most effective monitoring protocol and power of subsequent analyses. While these categories are not mutually exclusive (e.g., a managed fire may be treated as an experimental treatment), this division is useful in the present discussion. Experimental fires are performed under tightly controlled conditions, typically to answer specific questions about fire responses (e.g., Trabaud and Lepart 1981, Platt and Schwartz 1990, Moreno and Ochel 1991, Collins et al. 1998). These fires are usually small and the burning treatments are more easily replicated and randomly applied.

Managed, or prescribed, burns are performed as resource management actions, usually to reduce fuel loads or to remove undesirable species. Although managed fires typically lack replication in the strict sense (see below), they may often be conducted over larger spatial scales than experimental burns. Although managed burns are not as controlled as experimental burns, in many cases it is possible to collect data prior to the managed burn. Wildfires are by definition unplanned and any study of their effects is opportunistic. It is particularly difficult to collect unbiased wildfire effects data due to the unlikelihood of adequate randomization and replication. Despite these difficulties the study of wildfires remains a critical avenue of research

Table 1. Summary of typical experimental design attributes that vary among experimental fires, managed fires (prescribed burns), and wildfires. See text for details.

Aspect of Fire	Experimental Fire	Managed Fire	Wildfire
Randomization	yes	no	no
Replication	yes	no[a]	no[a]
Typical spatial extent	patch	community	landscape
Fire intensity	low	low to high	low to high
Amount of experimental control			
Severity	moderate	moderate	low
Frequency	high	high	low
Season	high	high	low

[a] Fire cannot be replicated in the strict sense for managed fires and wildfires; however, multiple separate fire events may be used as replicates with caution (see text).

because wildfires often represent the extremes in fire size and severity. There are indications that some important fire effects only occur during extreme events. For example, Stephenson et al. (1991) and Turner et al. (1997) show that recruitment of some dominant tree species occurs primarily following fire events that are sufficiently intense or large to create forest canopy gaps.

There are opportunities and drawbacks to each approach. Although standard features of experimental design are well known to fire ecologists, there seems to be a bias against using data from managed fires or wildfires. Data from these sources may not be as "clean" as data from experimental burns, but these various types of fires are common and provide unique perspectives on fire effects. At the very least, managed burns and wildfires represent underused sources of information for studying fire effects. Below we discuss techniques that help account for statistical problems in the study of managed fires and wildfires. Although in most cases it is not possible to entirely eliminate problems associated with lack of randomization and replication, it is possible to create monitoring protocols that reduce these difficulties.

COMPENSATING FOR STATISTICAL DIFFICULTIES

In the following sections we describe the methods and assumptions of several typical fire effects monitoring designs. Although many particular designs are possible, we discuss three broad design categories: time-series designs, impact/reference designs, and before/after comparisons. Each design type affects the strength of the resulting statistical inferences and carries different assumptions. Many fire effects studies contain some element of temporal data, so we use time-series designs as a general template for designing fire effects studies. From this basis we consider use of reference sites and also the differences between monitoring a single fire and monitoring several fires. Throughout we attempt to identify methods that are particularly useful for studying managed burns and wildfires. Concepts are illustrated by examples taken from a long-term data set of prescribed fire effects in Sequoia and Kings Canyon National Parks, California, USA.

Time-Series Designs

The most elementary type of fire effects study is the time-series design. Simply put, time-series assessments involve monitoring a single burn area over time; changes in resources or populations are noted. Analyses of temporal change are then used to infer subsequent change or recovery. Time-series designs are common in fire effects monitoring due to the relative ease of data collection and analysis (Whelan 1995).

To demonstrate this technique we present data taken from monitoring protocols of prescribed burns conducted by the National Park Service (National Park Service 1992). Fire effects data were collected from permanently marked 20-m x 50-m plots, randomly established within a larger area designated for prescribed burning. Included in the monitoring program are two 50-m herbaceous vegetation transects per plot. From this information we calculated understory species richness. Data were collected from three separate plots within a single burn unit in a low-elevation ponderosa pine (*Pinus ponderosa* Douglas) forest in Sequoia National Park, California. Data were collected 1 month postfire, and 1, 2, and 5 years postfire (Figure 1). Preburn and unburned reference site data were also collected, but we consider this information in later sections.

If we consider only the trend seen in the burned plots, it is apparent that time-series designs are troublesome with respect to data interpretation. The first, and perhaps most difficult, problem with time-series designs of a single burn is the lack of replication across the treatment (i.e., fire). While the trend shown for the burned plots in Figure 1 is suggestive of an increase in species richness following the first 5 years after fire (F test; $P < 0.01$, df = 9), it is not possible to draw general conclusions from these data. As stated earlier, variance associated with each observation time in a pseu-

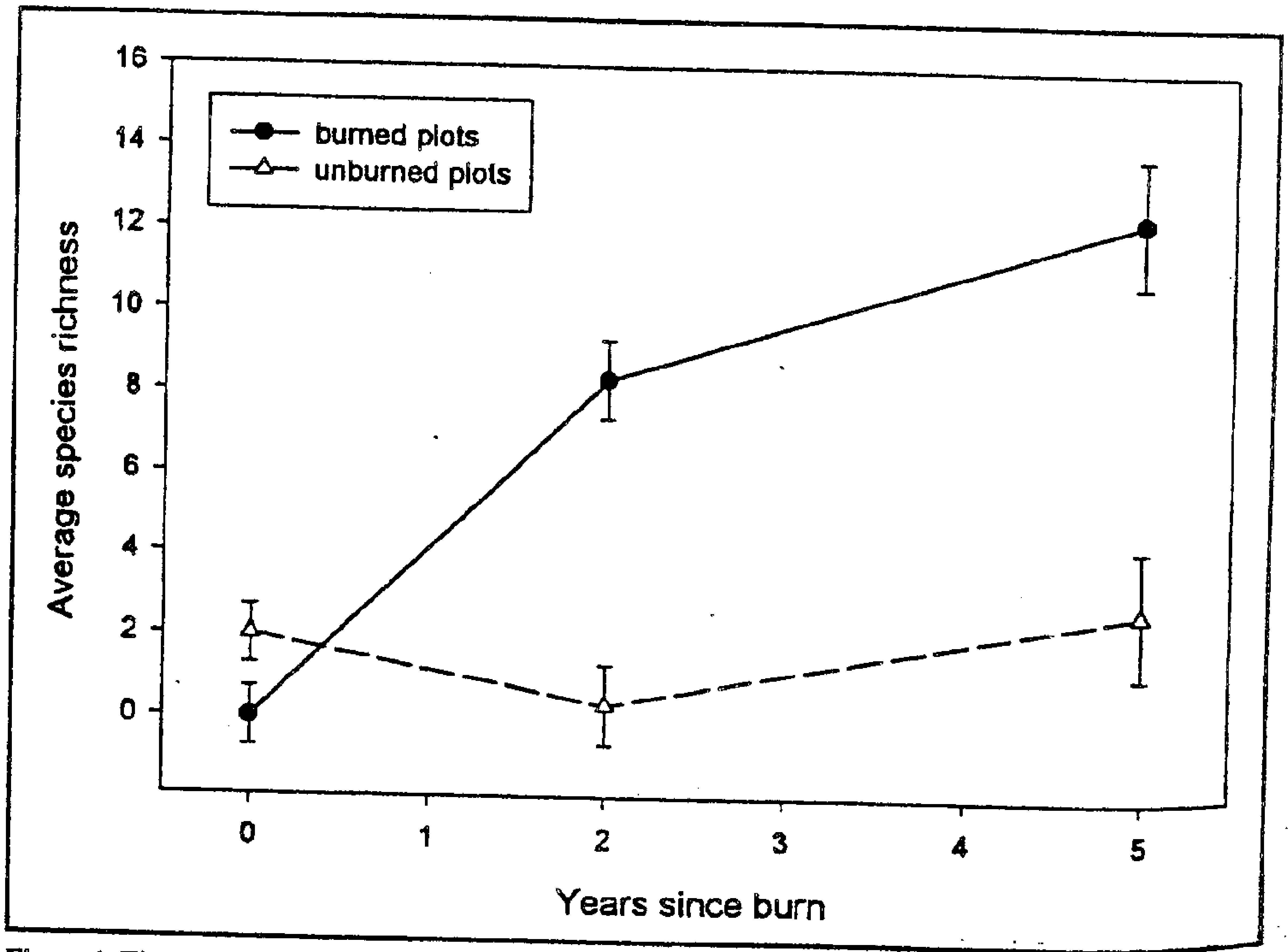

Figure 1. Time-series data for understory species richness following fire in a ponderosa pine forest. The data were collected from three burned plots (within a single burn unit) and three unburned plots in a ponderosa pine forest. The data for both the burned and unburned plots were collected immediately postfire, and 1, 2, and 5 years postfire. Repeated measures analysis shows a significant increase in species richness over time for the burned plots, while the unburned plots remained unchanged.

doreplicated study only describes plot differences within the burn itself, and the results should not be used to predict the effects of fire in other areas.

The second challenge common to time-series analyses is temporal autocorrelation. Observations of the same site taken at separate times are not fully independent because the same unit is being sampled, necessitating use of repeated measures analysis. For example, a plot that has demonstrated severe fire effects at one observation will still show relatively strong fire effects in subsequent observations. Figure 1 shows a significant increasing trend in species diversity in the burned plots over time immediately following fire, even with statistical adjustments for temporal autocorrelation (adjusted Huynh-Feldt; $P < 0.01$, df = 9), with a strong linear trend in species richness over time ($P < 0.05$, df = 9). A complete discussion of repeated measures analysis is beyond the scope of this paper. However, it is important to remember that in addition to the standard assumptions of ANOVA (normal distributions, equal variances among groups, independent samples), repeated measures designs assume compound symmetry (i.e., the covariances between all possible pairs of repeated measures are equal). If this assumption does not hold, less powerful multivariate repeated measures calculations are available (von Ende 1993).

Interpreting trends in time-series data (such as fire effects) demands some very restrictive assumptions. We must assume that any observed trends are in response to fire effects, not due to random, unmeasured environmental influences (e.g., increasing yearly precipitation). That is, if we construe the data for the burned plots in Figure 1 to represent a fire-caused increase in species richness, we must assume that the diversity in the plots would not have changed over the 5 years of observation if the plots had not burned. The essential problem with simple time-series data is that we have no information about areas that were not burned. One solution to this problem is to include monitoring data from unburned reference sites.

Impact/Reference Designs

Impact/reference designs are comparisons between a burned site and an unburned reference site. Differences between impact and reference sites are treated as evidence of disturbance effects, with the magnitude of these differences understood to be a measure of fire severity. Reference sites do not necessarily have to be unburned. Comparisons could be made between two or more sites of varying fire intensity or severity. Numerous standard methods to assess fire intensity could be used to carry out this comparison (Alexander 1982, Johnson and Miyanishi 1995).

To create powerful comparisons using impact/reference designs it is necessary to carefully choose reference sites. While occurrence of wildfire and the conditions that dictate use of managed prescribed burning are out of our direct control, we are free to select reference sites that closely match the burned site. If sites are matched with respect to important biotic and abiotic factors (e.g., community composition, slope, aspect, etc.), one can minimize resulting differences due to natural features. If a seemingly perfect reference site selection could be achieved, the need for randomly assigning treatments between sites would be unnecessary. Choosing appropriate reference sites may be considerably easier in systems that are fairly uniform in terms of biotic and environmental conditions (e.g., some boreal forests). Ideally, these sites should also be in close geographic proximity, otherwise differences in local weather patterns could confound the comparisons. Observations taken at burned and reference sites should also be taken close together in time. Rainfall patterns or seasonal differences may cause spurious differences if too much time elapses between measurement of the impact and reference sites. In addition, for wildfires, researchers must assess the reason the unburned site remained unburned. If environmental differences drove a particular site to remain unburned, these same site differences could affect response dynamics and make the area an inappropriate reference site.

A common statistical procedure that can increase the precision of comparisons between impact and references sites is the analysis of covariance or ANCOVA (Snedecor and Cochran 1967). ANCOVA can account for measurement biases due to site influences, so long as these site differences are accurately measured. ANCOVA is a relatively straightforward way to factor out measurable environmental noise when it is not possible to randomly select plot location. A second option to control these differences would be to select and observe more than one reference site. These "asymmetrical designs" (Underwood 1994) allow for a more precise estimation of background patterns in undisturbed sites, and allow the investigators to test differences in temporal patterns of resource variance in burned and unburned sites, rather than just mean abundances. This increased precision is of course gained at a cost, namely, the effort of selecting and monitoring additional reference sites.

Included in the unburned reference plots in Figure 1 is an example of an impact/reference design. Changes in species richness are compared against monitoring data collected in the same way from three unburned reference plots. One reference plot is from a low-elevation ponderosa pine stand, while the other two reference plots are from mixed conifer stands at slightly higher elevations. The reference plot data do not contain observations at year one, so the burned plot data for this time period are removed in this analysis. The data are compared using repeated measures ANOVA testing the time × burn interaction. The interaction term allows us to observe how the plot types diverge over time. In this case the burned plots increase significantly in species richness over time, while the unburned plots remain essentially unchanged (year × burn interaction, adjusted Huynh-Feldt; $P < 0.001$, df = 12).

Fire remains unreplicated in this example and it would not be possible to place statistical bounds on generalizations based on this particular fire. Adding a reference site to the analysis, however, overcomes some of the more troubling aspects in the interpretation of the results. With this comparison we can rule out the possibility that observed changes are due entirely to environmental fluctuations and assign fire a causal role in the observed changes. Here, we need only assume that the impact and reference sites are responding in the same direction to environmental fluctuations (Wiens and Parker 1995). Nevertheless, the possibility remains that the plot types have a different magnitude of response to environmental fluctuations, and changes over time are still entirely environmentally mediated (i.e., without the burn the reference plots would have added fewer species than the burned plots given the same environmental changes). Because both burned and reference plots are in roughly the same forest type and in close geographic proximity, there is no a priori reason to believe this to be true.

Before/After Designs

If one is fortunate enough to have monitoring information preceding the fire, "before" data can serve as part of a powerful comparison to determine fire-related impacts and recovery. Often postdisturbance changes are expressed as differences between the pre- and postdisturbance conditions. Using differences helps to standardize the response variables (species richness in our example), making plots easier to compare. Figure 2 shows postfire differences in ponderosa pine forest understory species richness for the data shown previously for the burned plots in Figure 1. As in Figure 1, there is a significant increase in species richness over time (adjusted Huynh-Feldt; $p < 0.01$, df = 9), and the trend is essentially linear ($p < 0.05$, df = 9). While the results of statistical tests for the burned plots in Figure 2 and Figure 1 are similar, these data are much easier to interpret than simple time-series data. Because data points represent changes in species richness following a fire, the initial reduction and recovery of understory species diversity can be most logically attributed to a response to burning.

A widely used combination of before/after comparisons and time-series analysis are known as "BACI" designs (Before-After/Control-Impact designs; Stewart-Oaten and Murdoch 1986, Stewart-Oaten et al. 1992, Underwood 1994). The aim of these methods is to detect impacts by comparing the differences associated with impact and reference sites. Multiple observations are performed both before and after the impact, and the difference between the control and impact sites is typically assessed using a t-test. Significant differences between impact and reference sites following a perturbation are taken as evidence of disturbance. Figure 3 shows an example of a BACI design taken from data presented in Mutch and Parsons (1998), who observed annual tree mortality rates in four plots in mixed conifer stands 5 years before burning and 5 years after burning at Sequoia National Park, California. The data plotted on Figure 3 represent differences in annual tree mortality rates for all species and size classes between the burned and unburned plots before burning (years 1–5) and after burning (years 6–10). The t-test of average pre- and postburning conditions is not significant at $P < 0.05$ (t = 2.05, $P = 0.07$, df = 8), because tree mortality rates quickly return to near baseline levels. In this example it may be better to examine regression slopes of tree mortality rates before and after burning. Regression shows that there is no trend in tree mortality rates over time prior to burning ($r^2 = 0.01$, $P = 0.87$, df = 4). In contrast, postburn conditions show high levels of mortality directly following the fire with a significant linear decrease in tree mortality rates as time progresses ($r^2 = 0.85$, $P = 0.02$, df = 4).

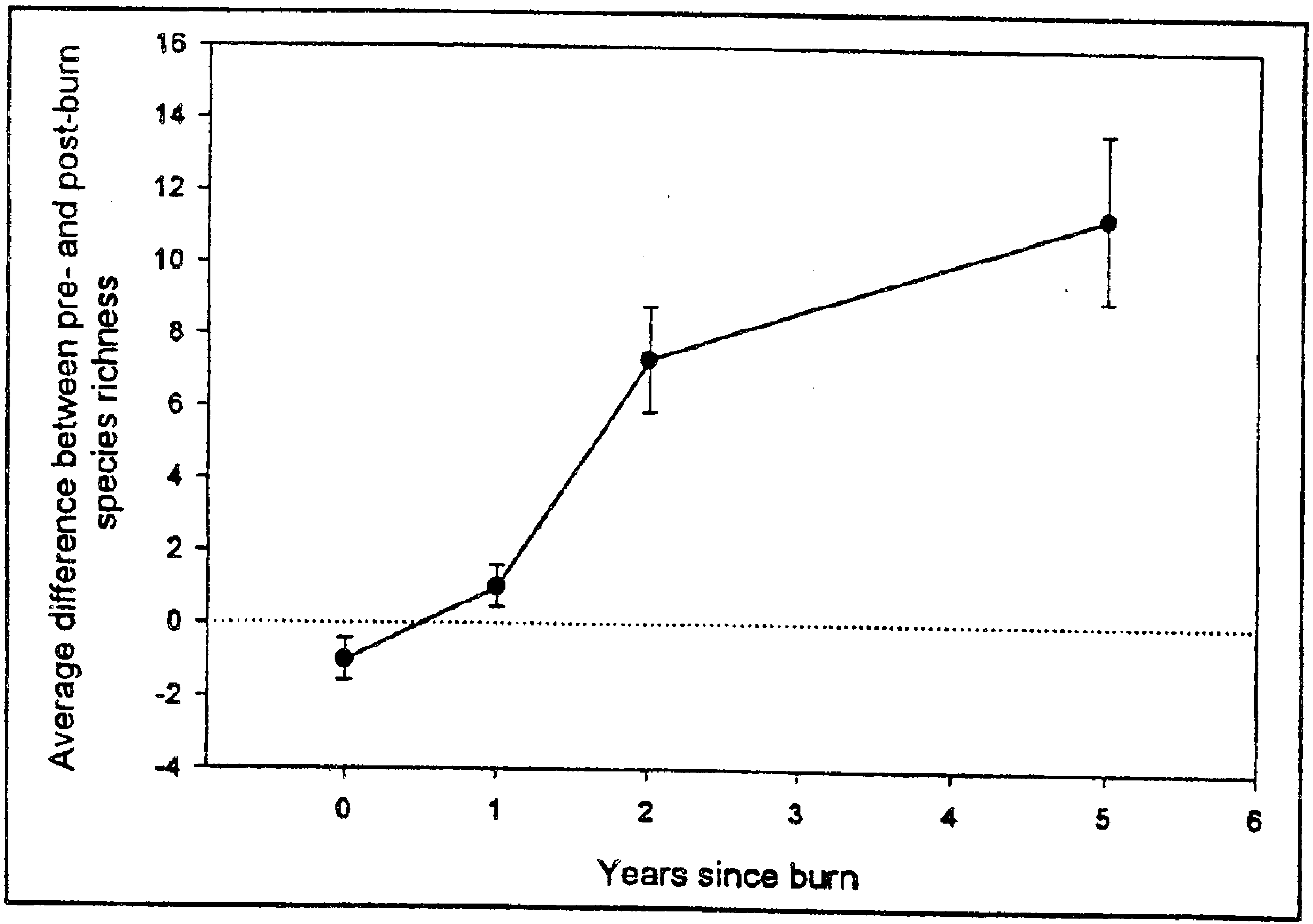

Figure 2. Before/after comparisons of species richness after burning. Burned plots are the same as in Figure 1. Species richness is expressed as the difference between preburn and postburn conditions. The dashed line is the unburned condition, and differences from zero represent changes from baseline conditions. The results are similar to those presented in Figure 1 when considering the burned plots alone, but the changes in species diversity can be directly assigned to fire effects.

BACI designs are relatively easy to interpret, and they take temporal variation explicitly into account when comparing disturbance effects. The resources of interest are measured for long periods of time both before and after the fire so environmental fluctuations over time are taken into account. This method may be most appropriate for resources that can be measured over short time intervals such as changes in water quality or insect population sizes. Detecting differences in long-term processes (e.g., forest succession) may not be feasible due to the time investment necessary in collecting both pre- and postburn data. In addition, as with any other impact/reference design, the choice of an appropriate reference site is critical and problems with replication of fire treatments remain unsolved.

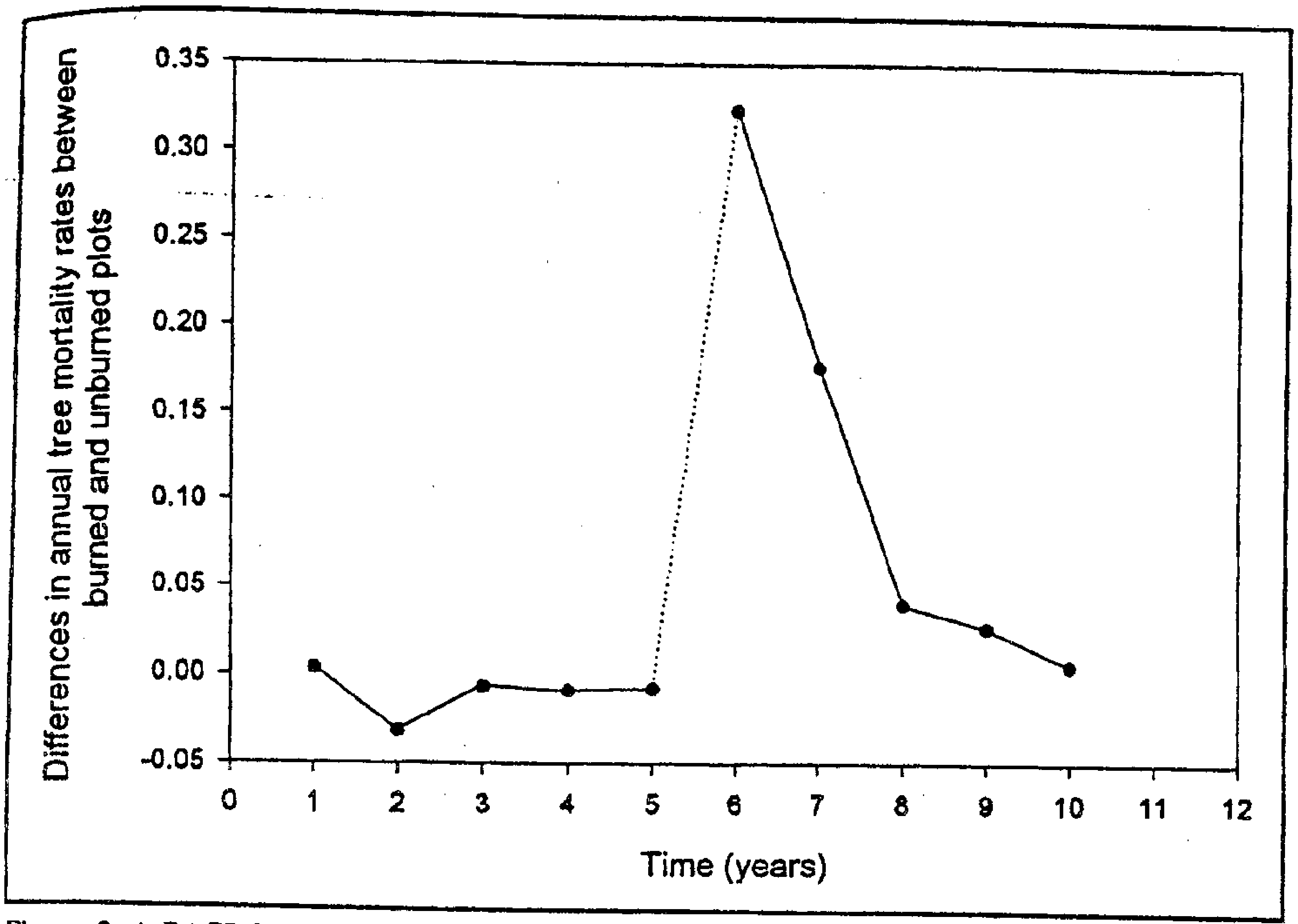

Figure 3. A BACI design showing differences in tree mortality rates between unburned and burned plots. All plots were unburned until year 5, when a prescribed burn was applied to half of the plots. The burned plots recovered rapidly, so the *t*-test between pre- and postfire conditions is insignificant. Linear regression shows that the burned plots quickly approached preburn levels of tree mortality. Data are from Mutch and Parsons (1998).

Because BACI relies very heavily on collecting a rather large amount of preburn data, it is probably of limited value for unpredictable events such as wildfires. However, in some instances data pre-dating the wildfire may be available. It is critical that postfire data are collected using the same methods for the before/after comparisons to be valid. This may be difficult if the methods used to collect the data were not well documented. Often data gathered for other studies will be for different purposes than current monitoring priorities. For example, if preburn data on total browse cover were collected in a wildlife study they may not be useful for studying the effects of fire for a particular nonbrowse shrub species. In addition, if historical data are old, they may not provide a good basis of comparison due to successional changes in the community.

Multiple Fires

Because disturbance is often assessed as a single discrete event, problems with the lack of replication of fire effects naturally follow. Although we assume (and hope) that spectacular environmental disasters such as the Exxon Valdez oil spill do not frequently repeat themselves, in many environments fire is a naturally recurring event. Often the presence of fire is essential for the maintenance of populations, communities, and ecosystems (Collins and Wallace 1990, Whelan 1995, Bond and van Wilgen 1996). It may be possible to treat separate fires in a given system as replicates and avoid many analytical problems.

If separate fire events can be treated as independent replicates, it would then be valid to use standard statistical analyses such as ANOVA or linear regression. However, several potential problems may arise in conducting these analyses. The most obvious is that separate fires cannot be considered replicates in a strict sense. Replicates used for statistical tests should be standardized before treatments (fire) are applied. However, this is only possible under a highly controlled experimental study design. Between-site differences will always be present as well as differences in the fire event itself. For example, using spring and fall fires together in the same analysis may obscure real patterns of fire effects as a result of differences in site moisture conditions and plant phenologies. Where burns can be grouped together, ANCOVA may overcome some intersite differences. A secondary problem is that multiple fire events will most likely occur in different years. The data from such a comparison would likely have a large amount of unexplained variation due to different yearly abiotic conditions. However, if the results are clear even when the error associated with interannual variation is included, it adds some confidence to our inferences.

The analysis of several different fires may be aided by grouping fires by vegetation type, fire intensity, or some other logical system. In order to facilitate cross-site comparisons it is necessary to collect monitoring data in the same way at each site. While this type of coordination is not simple, at the very least intra-agency monitoring techniques could be standardized. Figure 4 shows an example of using multiple fires in a single analysis. The data represent changes in understory species richness following eight different prescribed fires in the giant sequoia-mixed conifer forests of Sequoia and Kings Canyon National Parks. Each data point is the average understory richness taken from between one to three monitoring plots for each fire. Again, there is a significant increase in species richness 5 years following fire (adjusted Huynh-Feldt; $P < 0.01$, df = 24), and the trend is linear ($P < 0.01$, df = 8). Although the data trends are similar to those seen in Figure 2, we can place much more confidence in our results because the analysis uses multiple fire events. It is also more plausible to extend these findings to other similar forest types in the Sierra Nevada.

CONCLUSIONS

Although experimental studies are invaluable for understanding fire effects, we can make faster progress if we make better use of all available data. Often, these data will be from some kind of monitoring program. The fact that the monitoring of fire effects often does not neatly fit into the

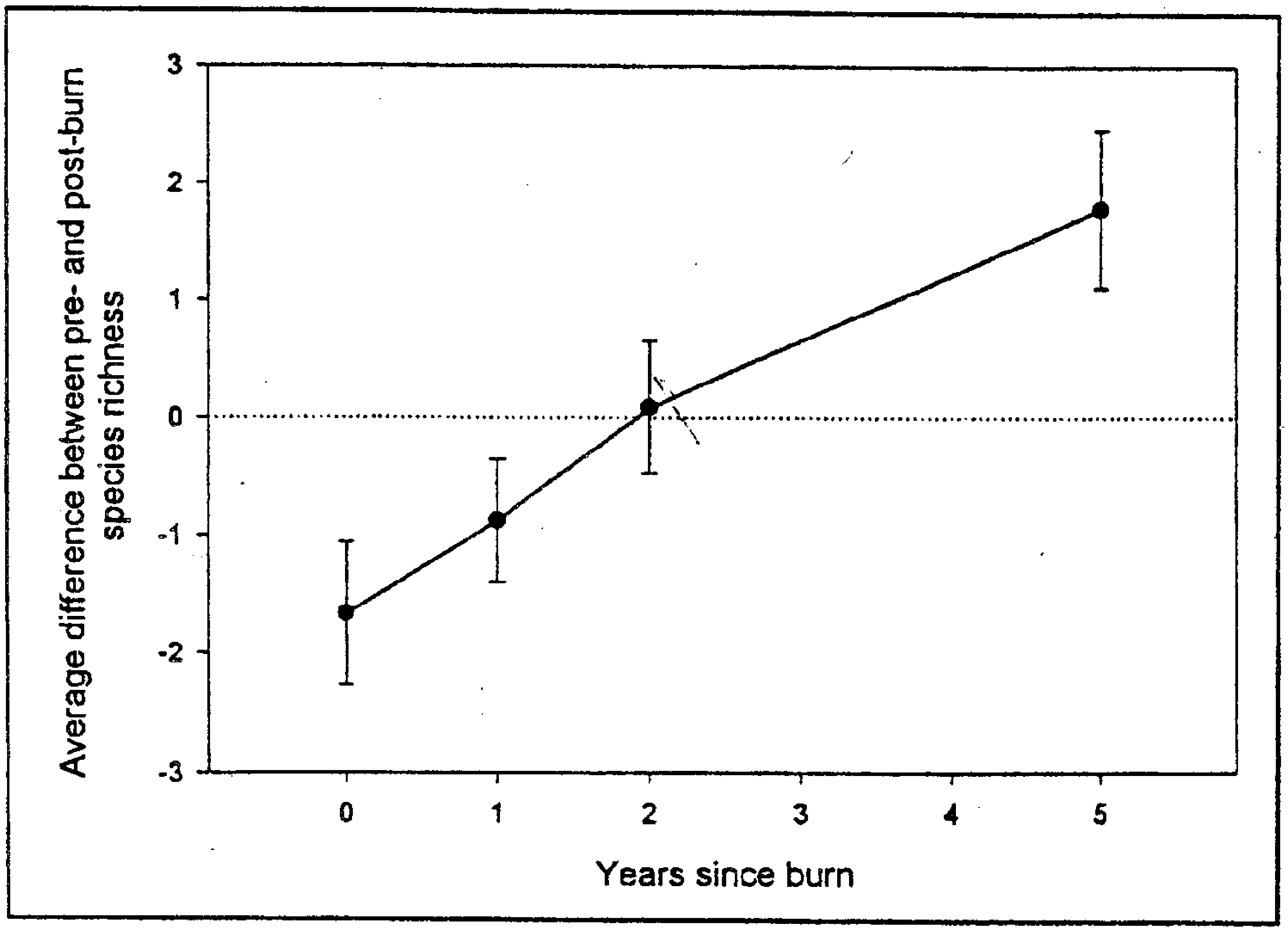

Figure 4. Time-series data showing the response of understory species richness to burning in eight separate fires in the giant sequoia-mixed conifer forests of Sequoia National Park, California. Prefire data were available, so the data points are differences between pre- and postfire conditions. As in Figure 1, there is a significant increase in species richness over time.

requirements of classic statistical analysis does not mean generating accurate assessments of fire effects is impossible. Perhaps the single greatest advantage that fire ecologists have in monitoring fire effects is the fact that fires often occur repeatedly across a given landscape, and can be used as independent replicates. Although there are limitations as to what could be considered a true, independent "replicate," it is clear that use of multiple burns makes for a powerful natural experiment. The challenge for fire ecologists is to design standard monitoring protocols so the integration of these results will be valid.

As fire is increasingly managed in many areas to attain economic or conservation goals, the importance of accurately understanding fire effects grows. Without this information management effectiveness will be uncertain to the same degree that knowledge of fire effects is uncertain. Monitoring will be one of the primary methods by which information is gathered on fire effects. Improvement of monitoring techniques should supply us with better information to make informed decisions in the often controversial arena of fire management. Below we list four recommendations to improve findings of monitoring programs for fire effects.

1. Pseudoreplication, where it occurs, should be acknowledged. The fact that samples are not properly replicated does not invalidate interesting findings. Rather, statistical bounds cannot be set on the results and therefore findings are usually restricted and site specific. If inferences are limited to a particular fire, multiple sampling plots within that area will strengthen the ability to accurately assess fire responses.
2. There should be a greater exploitation of managed burns and wildfires for studying fire effects. Although there is some loss of experimental control (Table 1), these fires occur at scales and intensities that cannot normally be duplicated in experimental fires. The use of preburn data and reference sites helps to compensate for problems associated with the lack of randomization and replication inherent in "natural experiments."
3. When managed burns and wildfires are used there should be an increased use of reference (unburned) site comparisons. Reference site sampling increases the effort needed to study fire effects but is a better investment of time and monitoring dollars than adding additional plots within the burn unit. Although some authors (Underwood 1994) emphasize gathering more prefire data in order to improve monitoring methods, it seems that this information is often difficult to gather. This is particularly true in regions where wildfires constitute a significant proportion of the total area burned. Prefire data are extremely useful, but unless fires are planned resources may be better applied by selecting more and better reference sites. Carefully chosen and monitored reference sites overcome many of the problems of simple time-series data, without having to guess where fire might occur in order to gather prefire data necessary for before/after comparisons.
4. Fire ecologists should take advantage of multiple fires in the analysis of fire effects when such data are available. While multiple fires are not replicates in the strict sense, trends seen across sites and years are a powerful indication that the responses are significant and fire-mediated. As in impact/reference designs, the use of covariance analysis may help remove site-related bias in the data.

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