MANAGEMENT AND ANALYSIS OF 30-YEAR
CONTINUOUS FOREST INVENTORY DATA
ON THE SIX RIVERS NATIONAL FOREST

by

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ABSTRACT

The purposes of this research were to test hypotheses concerning potential changes in the structure of the undisturbed portions of the Six Rivers National Forest between the period 1961-1963 and 1993-1995, and to create a user-friendly PC database of the Six Rivers Continuous Forest Inventory data.

Data from 166 plots located throughout the Six Rivers National Forest were put into Microsoft ACCESS, a relational database management system. The stand density index (SDI) values for individual plots, as well as for individual species, were calculated, as were the contributions of particular species or groups of species to overall SDI.

Analysis of the data indicates that overall SDI has increased during the study period. SDI for tolerant species has increased, while no change could be detected for intolerant species. The proportion of the SDI attributed to tolerant species as a group has increased relative to other species, and the proportion of SDI attributed to intolerant species has decreased. No significant change was found in the SDI for any individual intolerant species. Among the intolerant species, significant decreases were found for the proportion of SDI attributed to sugar pine, western white pine, and California black oak relative to all other species. Among more tolerant species, significant increases were recorded in the SDI for Douglas-fir, white fir, tanoak and madrone. Douglas-fir was the only tolerant species to have significantly increased its proportion of SDI relative to all other species.

The results of this study lend credibility to the hypothesis that changes in stand density are due to the interruption of a frequent low-intensity fire interval. These results do not rule out the possibility that the interval of stand-replacing fires has not been
interrupted and that the increases in stand density may primarily be due to natural succession. This work demonstrates that SDI is a very powerful tool in detecting changes in forest community ecology.

Keywords: stand density index, community ecology, forest health, fire exclusion, fire interval, succession, shade tolerance, Continuous Forest Inventory, Forest Inventory and Analysis, Six Rivers National Forest.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Forest Health</td>
<td>1</td>
</tr>
<tr>
<td>Continuous Forest Inventory</td>
<td>2</td>
</tr>
<tr>
<td>Objectives</td>
<td>3</td>
</tr>
<tr>
<td>STUDY SITE</td>
<td>5</td>
</tr>
<tr>
<td>Location</td>
<td>5</td>
</tr>
<tr>
<td>Climate</td>
<td>5</td>
</tr>
<tr>
<td>LITERATURE REVIEW</td>
<td>7</td>
</tr>
<tr>
<td>Stand Density</td>
<td>7</td>
</tr>
<tr>
<td>Shade Tolerance</td>
<td>11</td>
</tr>
<tr>
<td>Fire History of Six Rivers National Forest</td>
<td>13</td>
</tr>
<tr>
<td>Community Ecology</td>
<td>14</td>
</tr>
<tr>
<td>Succession</td>
<td>14</td>
</tr>
<tr>
<td>Atmospheric Carbon Dioxide</td>
<td>16</td>
</tr>
<tr>
<td>Forest Inventory Data</td>
<td>17</td>
</tr>
<tr>
<td>Justification for Evaluating Changes in Stand Density and Species</td>
<td>18</td>
</tr>
<tr>
<td>Composition Using SDI Calculated from CFI Data</td>
<td>20</td>
</tr>
<tr>
<td>METHODS</td>
<td>20</td>
</tr>
</tbody>
</table>

vi
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Results of a matched-pairs t-test of the hypotheses Ho: stand density (SDI) has not changed, Ha: stand density has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.</td>
</tr>
<tr>
<td>2</td>
<td>Results of a matched-pairs t-test of the hypotheses Ho: stand density (ΣSDI) of shade tolerant species has not changed, Ha: stand density of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.</td>
</tr>
<tr>
<td>3</td>
<td>Results of a matched-pairs t-test of the hypotheses Ho: stand density (ΣSDI) of shade intolerant species has not changed, Ha: stand density of shade intolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.</td>
</tr>
<tr>
<td>4</td>
<td>Results of Wilcoxon signed-rank test of the hypotheses Ho: the proportion (%SDI) of shade tolerant species has not changed, Ha: the proportion of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.</td>
</tr>
<tr>
<td>5</td>
<td>Results of a matched-pairs t-test of the hypotheses Ho: the proportion (%SDI) of shade intolerant species has not changed, Ha: the proportion of shade intolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots</td>
</tr>
</tbody>
</table>
measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

6 Results of a matched-pairs t-test of the hypotheses $H_0$: stand density (SDI) of individual shade intolerant species has not changed, $H_a$: stand density of shade intolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

7 Results of a matched-pairs t-test of the hypotheses $H_0$: the proportion (%SDI) of individual shade tolerant species has not changed, $H_a$: the proportion of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

8 Results of a matched-pairs t-test of the hypotheses $H_0$: stand density (SDI) of individual shade tolerant species has not changed, $H_a$: stand density of individual shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

9 Results of matched-pairs t-test of the hypotheses $H_0$: the proportion (%ΣSDI) of shade tolerant species has not changed, $H_a$: the proportion of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Study site location and vicinity map (adapted from USDA 1982). Shaded area is the Six Rivers National Forest, northwestern California, USA.</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Theoretical changes in biomass (or stand density) over time. Corresponding successional stages as defined by biomass trends are also depicted (after Bormann and Likens 1979, Oliver 1981, Guldin 1996).</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Stem and leaf diagram depicting the age distributions of site trees measured on 161 Continuous Forest Inventory plots established in the Six Rivers National Forest, northwestern California, USA. Ages were established from ring counts in 1993-1995. Corresponding periods of possible stand-replacing events are also depicted.</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>Histogram of the distribution of stand density index (SDI) values calculated for Continuous Forest Inventory plots remeasured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.</td>
<td>35</td>
</tr>
</tbody>
</table>
INTRODUCTION

Forest Health

Recent analysis of forest health in the inland western forests has characterized those forests as being "unhealthy" or susceptible to catastrophic loss. Stands which have historically been maintained in a disturbance-dependent climax state are thought to be undergoing changes in structure. Forest scientists cite increases in stand density (number of trees/acre) beyond the sustainable carrying capacity of the site due to the interruption of recurring disturbances as the primary probable cause leading to widespread tree mortality in the inland west (Adams 1994, Steele 1994, Graham 1994). Disruption of the natural fire recurrence interval due to the policy of fire exclusion is considered to be a major factor. "On the best sites, fire prevents invasion by the relatively tolerant...Douglas-fir and true firs" (Smith 1986). Sites historically dominated by shade intolerant species may now be evolving toward shade tolerant species which would normally be destroyed by frequent low-intensity fires (Adams 1994).

Consequences of fire exclusion include increases in stand density, increased stress due to competition, and weakened trees that are more susceptible to insect and pathogen invasions. Fire exclusion also leads to the accumulation of fuels, resulting in fuel ladders to the stand overstory and increasing the vulnerability of mature stands to catastrophic stand-replacing fires (Adams 1994, Auclair and Bedford 1994, Harvey 1994, Helms 1994). If the undisturbed forested stands of the Six Rivers National Forest are increasing in density, and if those increases favor the more tolerant species, the Six Rivers' stands may be moving toward the same type of problems now occurring in the inland west. Long term data are necessary to detect changes in stand density of slow-growing forests.
Continuous Forest Inventory

The USDA Forest Service has conducted forest surveys nationally with the purpose of "...the determination, nationally and regionally, on a continuing basis, the extent, character, and condition of the forest resource, and of rates of timber growth, mortality, and use as authorized by the McSweeney-McNary Forest Research Act of May 22, 1928, and subsequent amendments" (USDA 1962). In 1961-1963, 278 Continuous Forest Inventory (CFI) plots were established in what are now the four districts of the Six Rivers National Forest. Aerial photo point locations were designated on a systematic grid. Points were classified by land use/ownership patterns and stratified by cubic volume classes. The 278 ground plots were randomly selected from the photo point locations, resulting in a stratified sample with proportional allocation with the larger size strata receiving more plots than the smaller size strata (USDA 1962).

Ground plots were recorded by location, elevation, aspect, and slope. Each plot consisted of four nested circular plots with increasing tree diameter parameters. Trees of all species were individually assigned numbers, marked with metal tags, and inventoried by DBH, percent live crown, crown position, and defect (Appendix A). These data were somehow misplaced and not rediscovered until recently. A project to re-inventory the plots was undertaken jointly by the USDA Forest Service and the Forestry Department of Humboldt State University. Plots were re-inventoried in 1993, 1994 and 1995. Plots were screened to exclude areas which had been disturbed, such as those which had been clearcut or which have had all vegetation removed for road or log-landing construction. As of spring, 1996, 166 plots had been re-measured.

Data from CFI plots are traditionally analyzed "in-house" by the USDA Forest Service using the Forest Inventory and Analysis (FIA) system. The FIA system is not considered user-friendly and is thought of as specific to timber production. The FIA
system requires specialized training to enter data and to run the program. The Forest Service Data General computers require special user accounts before access is permitted. FIA processes inventory data and calculates information such as relative volume, number of trees per acre, basal area, basal area growth for 10 and 20 years, average site class per stratum and stratum expansion factors, species percentages, volume and growth, number of seedlings per acre, average basal area weighted age for commercial measured trees, cubic volume, Scribner volume for an 11" DBH to a utilized top, average annual growth, and mean diameter. FIA creates graphs depicting relative values of basal area per acre, cubic feet per acre, basal area growth per acre, and cubic volume growth per acre. Options are available for various printout displays which are used almost exclusively for preparing stand prescriptions (USDA 1988).

A major problem with that approach is that it is very difficult for users to access the data and use it for other purposes not originally envisioned by the FIA developers. A more "user-friendly" and accessible database would facilitate scientific and academic research and broader use of CFI data. For example, scientists and graduate students could investigate research hypotheses with familiar hardware and software using high quality data collected over significant time periods.

Objectives

This study was designed to meet the following objectives:

(1) to create a user-friendly PC relational database of the Six Rivers CFI data; and

(2) to illustrate the utility of the database by testing hypotheses concerning potential changes in the structure of the undisturbed portions of the
Six Rivers National Forest during the measurement interval. Specifically, the following null hypotheses were tested:

(a) $H_0$: stand density has not changed;
(b) $H_0$: stand density of shade tolerant species has not changed;
(c) $H_0$: stand density of shade intolerant species has not changed;
(d) $H_0$: the proportion of shade tolerant species has not changed;
(e) $H_0$: the proportion of shade intolerant species has not changed;
(f) $H_0$: stand density of individual shade intolerant species has not changed;
(g) $H_0$: the proportion of selected individual shade intolerant species has not changed;
(h) $H_0$: stand density of selected individual shade tolerant species has not changed; and
(i) $H_0$: the proportion of selected individual shade tolerant species has not changed.
STUDY SITE

Location

The sites surveyed for this study were located in the Six Rivers National Forest in northwestern California within Del Norte, Humboldt, Trinity, and Siskiyou counties (Figure 1). The 958,480 acres of the National Forest stretch nearly 160 miles along the Klamath Mountains and the Coast Range and are divided into three Ranger Districts (Mad River, Lower Trinity, and Orleans) and the Smith River National Recreation Area (formerly the Gasquet Ranger District).

Climate

Northwestern California is subject to a Mediterranean climate with hot, dry summers and cool, wet winters. Precipitation is carried from the Pacific Ocean by the jetstream and deposited upon the Six Rivers National Forest in response to the orographic effect of the coastal mountains. Average annual precipitation totals up to 90-150 inches are recorded for the northern areas (USDA 1995). Elevations above 4000 feet receive precipitation as snow during much of the winter. Due to changes in latitude, elevation, and aspect, the Six Rivers National Forest is subject to highly diverse micro-climates, being generally warmer and drier in the southern range, wetter on western aspects and cooler at higher elevations.

Annual precipitation for California since 1600 has been estimated using tree ring analysis (Fritts and Gordon 1980) indicating two unusually long periods of drought, from 1755 to 1825 and from 1860 to 1885.
Figure 1. Study site location and vicinity map (adapted from USDA 1982). Shaded area is the Six Rivers National Forest, northwestern California, USA.
LITERATURE REVIEW

Stand Density

Foresters have long been charged with maximizing production of wood from forested lands. To this end, the concept of full or "normal" stocking was developed to indicate where trees occupy a site to the extent that no sunlight or soil resources are "wasted." Too few trees leave resources wasted; too many trees utilize the resources inefficiently, leading to stagnation or losses due to stem exclusion mortality. Production of wood could be increased if stocking were maintained at optimum levels. Just what these optimum levels should be remained elusive (Davis and Johnson 1987, Avery and Burkhart 1994).

Descriptions of stand density were developed to better quantify site utilization. Stand density can be regarded as "an estimate of an 'average' competition level in stands" and can be expressed in absolute or relative terms (Avery and Burkhart 1994). The number of trees per acre can be used as a measure of stand density in young planted stands but is inadequate for older stands with a developed diameter distribution. Basal area per acre, the cross-sectional area of tree boles at 4.5 feet from the ground, is a better indicator of stand density than numbers of trees (Kimmins 1987). While basal area is not a direct biological indicator of site occupancy, it is fairly well correlated with the cross-sectional area of the crown (Smith 1986, Zeide 1987). Stocking estimates require comparisons of total basal area of a stand with empirical data from "normal" or fully stocked stands of the same species, age and site quality.

In 1933, L.H. Reineke, while working as Associate Silviculturist for the USDA Forest Service at the California Forest Experiment Station, developed a stand density
index (SDI) for even-aged forests which is independent of age and site quality. SDI is based upon the inverse straight-line relationship between the logarithms of the average stand diameter and number of trees per acre. This line defines the upper limits of tree density as a function of average diameter where mortality due to competition occurs. Reineke (1933) estimated the slope of this line to be -1.605. SDI describes the density of a stand as the number of trees per acre as if each tree were 10 inches in diameter at breast height. SDI "...permits direct comparison between species in addition to expressing varying stand densities within a species" (Reineke 1933).

Reineke calculated maximum densities for redwood (*Sequoia sempervirens* (D Don) endl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var *menziesii*), white fir (*Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr.), and mixed conifer stands in California. While interesting and important for maximizing wood production, maximum stand density indexes are not necessary to compare changes in stand densities.

In 1968, Albert R. Stage derived an equation to partition SDI's "...nonlinear expression into additive components to describe the relative stocking of a stand by species..." This development enabled SDI to "...be used to describe uneven-aged stands better than present methods" (Daniel et al. 1979). Even so, SDI has not been well-used by practicing foresters, who prefer to base thinning and stocking estimates upon simpler basal area measurements.

SDI is traditionally used in forestry, while the "3/2 law" is traditionally used in ecology (Avery and Burkhart 1994). The 3/2 law of self thinning is described by Yoda et al. (1963) as a straight "self-thinning line" which is formed when the logarithm of average mass is plotted against the logarithm of plant density for crowded even-aged plant populations. This line defines the limits of plant density, as a function of plant mass, where mortality occurs due to competition. The slope of this line is -1.5 (-3/2). Since the
3/2 law is based upon plant mass rather than stem diameter, it is not independent of site. Because diameter is better correlated with crown width than is plant mass (Zeide 1987), SDI may be a better predictor of tree self-thinning limits. The 3/2 law of self thinning is the mathematical equivalent of Reineke's SDI (Avery and Burkhart 1994). The 3/2 law equivalent of Reineke's SDI "maximum density line" is Yoda's "self-thinning line."


Plant ecologists have attributed great theoretical and practical importance to the self-thinning rule, variously praising it as the best documented generalization (White 1981) and most general principle (Westoby 1981) of plant demography, a central concept of population dynamics that may link ecosystem function with evolutionary demography (Westoby 1981, 1984); a uniquely precise mathematical formulation in a science where most generalities are qualitative, not quantitative (Hutchings and Budd 1981a); a scientific law (Yoda et al. 1963, Dirzo and Harper 1980, Lonsdale and Watkinson 1982, Malmberg and Smith 1982, Hutching 1983); or even the only law in plant ecology (Harper, cited in Hutching 1983). McIntosh (1980) agreed that, if substantiated, a self-thinning law could well be the first basic law demonstrated for ecology.

In 1987, Zeide reported:

....the claim made already in the original article (Yoda et al. 1963, p. 123) about "the universal applicability of the 3/2 power law" has been not only widely accepted but amplified as well. At present the law is regarded as "one of the most robust and widely applicable theoretical models for describing intraspecific density-dependent regulation in plant populations" (Pitelka 1984, p. 442), "a most general principle of plant population biology" (Long and Smith 1984, p. 195), "a true law instead of the mere rule" (Wittington 1984, p. 217), and as "the first basic law demonstrated for ecology (Harper as cited by McIntosh 1980, p. 234). Moreover, Westoy (1984) believes that it may come to occupy a central place in our understanding of ecosystems (Zeide 1987).

While both Weller and Zeide raised questions involving the universal application of the -3/2 slope to specific species and datasets (Weller 1987, Zeide 1987), both appeared to be in agreement on the interspecific application of the 3/2 law reported by Gorham
(1979). "Despite the failure of the thinning rule for individual populations, the combined data for all populations are still consistent with an interspecific relationship of slope -3/2...." (Weller 1987). Similarly, H. Sterba and R.A. Monserud (1993) report that "R.O. Curtis (personal communication) is probably right when he states that 'Reineke's -1.605 is a reasonable average over all species but is probably not quite right for any individual species'."

Because plant biomass is difficult to measure or estimate, ecologists traditionally use percent cover as an indicator of site utilization. Field personnel become skilled and consistent in their ocular estimates of per cent cover although estimates may vary among technicians. This technique, while appropriate for many management applications where sampling is severely limited by funding, adds a layer of variability to datasets and may be less powerful in detecting significant differences in tree species composition than stand density techniques with higher levels of accuracy and precision such as SDI. "In order to insure scientific credibility, a quantitative approach toward ecological indicators is preferred when feasible" (O'Laughlin 1994).

In summary, SDI is an indicator of the latent variable, site utilization. It is an appropriate measure of tree stand density and community ecology in undisturbed mixed-species uneven-aged stands, and may be superior to other indicators of site utilization because:

(1) SDI is independent of species, site quality, and age (Reineke 1933, Daniel et al. 1979);

(2) the contributions of individual trees or species to stand density can be calculated and are additive (Stage 1968);

(3) SDI is mathematically equivalent to the 3/2 law of self-thinning (Avery and Burkhart 1994) which,
(a) is widely recognized in the field of ecology;
(b) is most consistent as a measure of interspecific relationships (Gorham 1979, Weller 1987, Zeide 1987), and
(4) diameter is better correlated with crown width than is plant mass (Zeide 1987). So SDI may be a better predictor of tree self-thinning limits than the 3/2 law.

**Shade Tolerance**

While "...much of the difference in shade tolerance is related to differences in the ability of the photosynthetic apparatus to adapt to low light intensity" (Kramer and Kozlowski 1979), shade tolerance is now known to be "...as much a matter of availability of and competition for moisture and nutrients as competition for light" (Kimmins 1987). "Levels of optimum basal area tend to be greater for shade-tolerant species than for intolerant ones and greater for evergreens than for deciduous species" (Smith 1994). This is consistent with predictions of increasing stand densities and a shift to more tolerant species. SDI is a function of basal area (Rieneke 1933). Since shade tolerant species tend to have higher optimum basal areas than shade intolerant species, it would be appropriate to detect overall SDI increases along with increases in the proportion of SDI contributed by shade tolerant species. The ability of shade tolerant species to become established in the shade leads to a shift to more tolerant species in the succession to climax communities (Kramer and Kozlowski 1979).

Species analyzed in the Six Rivers National Forest are classified with the following shade tolerances:

intolerant; ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), California black oak (*Quercus kelloggii*

In the northern hemisphere, trees of the same species tend to be relatively more tolerant in the southern portion of their range, on good sites, or when young. They tend to be relatively less tolerant in the northern portion of their range, when growing on poor sites or when old (Baker 1950). For the purpose of comparing changes in densities of intolerant and tolerant species, the species with intermediate tolerances were designated as either intolerant or tolerant. Sugar pine, western white pine and red alder were designated as intolerant and Douglas-fir was designated as tolerant. This designation was based upon
their relative tolerance compared to their associates in the Six Rivers National Forest as well as upon their location relative to their natural range.

**Fire History of Six Rivers National Forest**

There is some evidence that a historic disturbance interval has been disrupted in the Six Rivers National Forest. Adams and Sawyer (1980), using tree ring data covering the period of 1750-1910, determined that "...the mean fire interval for the mixed evergreen forests on Six Rivers National Forest" was approximately 16.5 years. Whether these fires were caused by lightning or by native Americans is difficult to determine except near certain villages where elders remember burning to improve acorn crops (L. Salazar, personal communication). Helms (1994) states that:

> Historically, fire has played an important role in the mixed-conifer type. Many small fires, occurring at a frequency of 4 to 20 years, kept the forest open and helped maintain a mosaic of vegetation. With fire exclusion, California white fir and incense-cedar were encouraged, canopies tended to close, shrubs and herbs declined, and intense fires were encouraged due to buildup of fuels.

Between 1870 and 1920, many large-scale stand-replacing wildfires burned areas primarily along the upper third of ridges (USDA 1995). In 1910 organized fire suppression began in the area which is now the Six Rivers National Forest. Although a matter of public policy, the appropriateness of fire suppression was still debated. Snow and Kotok (1924) described their vision of pine forests if fire were to be excluded:

> Were it possible for the observer to visualize the entire area upon which pine has grown, and to behold it truly fully stocked, he would then see by comparison that the present California pine forests represent broken, patchy, understocked stands, worn down by the attrition of repeated light fires.

In 1931, an excerpt from the Siskiyou National Forest diary notes that "...The *Curry County Reporter*, a Gold Beach newspaper, was still advocating '...'light burning of the
forests.' The Six Rivers National Forest fire records do indicate that most fires in that period were extinguished fairly quickly and limited to small acreages. There were, however, several fires which consumed large acreages before being controlled or burning themselves out.

Community Ecology

Species composition is a dynamic part of forest structure. "The natural composition is...not static or well-defined; it is instead dynamic and subject to continual changes resulting from the developmental processes that are usually initiated by competition or regenerative disturbances" (Smith 1986). The area an individual species is physiologically capable of occupying is called its fundamental niche (Kimmins 1987). A species' fundamental niche is reduced to its realized niche by interspecific competition. If two species are competing for the same resource, one will eventually dominate due to the competitive exclusion principle or "Gause's hypothesis" (Gause 1934, 1935, Hardin 1960). The range of species is a function of gradients of competitive behavior, physical gradients (moisture, soil, climate, temperature), and disturbance intervals. Changes in any factor may change the realized niche. Conversely, changes in the realized niche of a species may indicate a change in physical gradients and/or disturbance interval.

Succession

Succession is the "...process of change by which...biotic communities replace each other...over a period of time" (Kimmins 1987). Forest stand development is theorized to undergo four stages or phases (Figure 2) beginning from some catastrophic disturbance (Bormann and Likens 1979, Oliver 1981, Guldin 1996). The first stage is the stand initiation stage (reorganization phase) where, after stand biomass declines, fast-growing
Figure 2. Theoretical changes in biomass (or stand density) over time. Corresponding successional stages as defined by biomass trends are also depicted (after Bormann and Likens 1979, Oliver 1981, Guldin 1996).
herbs, shrubs and trees colonize the site. Biomass continues to increase through the second stage, known as the stem exclusion stage (aggradation phase), in which the canopy closes, intolerants dominate the overstory, and tolerants occupy the understory. Mortality due to self thinning begins during this stage. The natural mortality of older trees in the overstory marks the third stage, known as the understory re-initiation stage (transition phase), in which small gaps are created in the canopy. The old-growth stage (steady-state phase), the fourth of these idealized stages, marks the stabilization of the stand's proportion of species, sizes and age classes. The stand continues to be dynamic, with older trees dying and creating gaps which foster regeneration of intolerants, while the overall stand structure remains relatively constant.

Atmospheric Carbon Dioxide

Total atmospheric levels of carbon in the form of carbon dioxide (CO₂) have increased from levels of 580 x 10¹⁵ grams in 1780, estimated from ice core data, to levels of 745 x 10¹⁵ grams in 1990, estimated from Mauna Loa direct measurements (Mueller and Kramer 1994), an increase of over 28 percent. Carbon dioxide enhancement has been shown to increase net photosynthesis in some forest species (Tinus 1970, Wright and Woodwell 1970, Green and Wright 1977). Increased net photosynthesis may be a contributing factor to increases in stand density. Increased temperature had either no effect (Green and Wright 1977) or increased response to enhanced CO₂ (Wright 1974). Increased levels of CO₂ caused Coulter (Pinus coulteri D. Don) and knobcone pine seedlings to maintain net photosynthesis at lower soil water potentials (Hurt and Wright 1976) and responsiveness of in situ ponderosa pine to enhanced CO₂ was not altered by decreasing soil water potential (Green and Wright 1977). Green and Wright (1977) also
reported that for ponderosa pine, enhanced levels of CO$_2$ compensated for a reduction of 50 percent in light intensity.

**Forest Inventory Data**

There is some debate as to the appropriateness of using forest inventory data other than "....for purposes for which the sampling design and measurement techniques were designed" (Stout 1991). Attempts to use forest survey data to establish cause-effect relationships have been met with varying responses.

Bechtol et al. (1991) argued that:

FIA data are observational rather than experimental-originally designed to monitor timber inventories, growth, and removals at the population level on a regional scale. They therefore reflect the net results of all factors influencing regional populations of trees and timber stands. These include shifting land-use patterns, timber harvesting and management practices, natural disturbances, stand dynamics, moisture stress, pollution, and a host of other forces. Interpretations must therefore be made cautiously.

It was the opinion of Stage (1991) that:

A major limitation of Forest Survey data for establishing cause-effect relationships may be the sparse spatial distribution of sampling locations. If the hypothesized cause covers enough area to affect a number of locations sufficient to provide statistical power, the matching controls will be almost impossible to find outside the area of effect. Conversely, if the geographic extent of the cause is small enough to find controls in the immediate neighborhood, then there will be little chance of sampling both affected and control locations that are otherwise similar.

In their effort to "....dispel in some measure the extreme distrust of those databases by scientists interested in establishing cause and effect relationships on important forest types and conditions...," Schreuder and Thomas (1991):

......conclude that cause-effect may be established, if both the potential cause and effect variables are measured in the Survey provided the variables are measured accurately, estimated properly, and are based on a large enough
sample. Otherwise, Forest Survey data can be used, however, to establish growth trends for large areas, suggest and identify potential cause-effect hypotheses, and identify supplemental data sets to be collected to bolster or reject potential hypotheses.

Brooks (1994) adds:

Nevertheless, national and regional forest surveys are an important source of information for many unintended purposes because of their unique and extensive temporal and spatial coverage.

Stage (1991) wrote that "...one should be looking for effects of causes rather than looking for causes of effects." It is, therefore, not the purpose of this research to establish any single cause of increases in stand densities, but rather to detect and quantify those increases if any, and to suggest possible causes and implications.

Justification for Evaluating Changes in Stand Density and Species Composition Using SDI Calculated from CFI Data

The Six Rivers National Forest plans to use historic range of variability (HRV) as a tool “....to develop management schemes that mimic natural processes and functions...The assumption...is that maintaining representative examples of various community types will protect viable populations of most species...and maintain biological diversity” (USDA 1995). If the HRV of tree communities has been maintained by recurring periodic disturbances because those disturbances arrested natural succession, an interruption of those disturbances would cause a shift in tree communities toward later (more shade tolerant) successional climax communities. While detection of a cause-and-effect relationship is beyond the scope of this dataset, quantifying predicted changes in community ecology may be an important indicator of changes in the factors which maintain those historical ranges, and of potential problems resulting from continuing changes.
CFI data are appropriate for ecological hypotheses testing because:

(1) plot locations are assigned through stratified random sampling;

(2) "...measurements of the traditional tree and plot data by FIA are of high quality" (Schreuder and Thomas 1991).

(3) SDI can be accurately and precisely calculated using direct measurements of tree circumference and counts of trees per plot;

(4) individual tree numbers and placement of diameter nails ensure comparability of repeated measurements; and

(5) changes in stand density can be detected using repeated measurements over time.
METHODS

CFI plot and tree data were inputted from the original plot records into the USDA Forest Service DG/FIA system at the Supervisor's Office of the Six Rivers National Forest. The data were then downloaded to floppy disks in ASCII text. A sorting program was created (Wright 1995) to separate the "A" lines which describe general plot information, from the "F," "N," and "D" lines which describe the data for individual trees. This sorting program facilitated loading the data into ACCESS, a relational database management system developed and marketed by Microsoft, Inc. (Microsoft 1993).

The database design process required five basic steps. First, the purpose of the database was determined; specifically, to facilitate the data organization required to test scientific hypotheses. Second, the information was divided into separate subjects. Each subject became a table in the database. Third, the information about each subject was divided into categories called "fields," each of which became a column in the table. Fourth, the relationships between the data in each table were specified. For example, the relationship between any individual tree in tables containing tree records and the plot containing that tree was indicated by joining the tree's plot number with another table containing the information about the plot such as aspect, elevation, date of measurement, ranger district and so on. Finally, the database was analyzed for errors.

The sorted data were imported into ACCESS. Separate tables were created that contained data from plot records, tree records, log records, measure tree records, and snag records for each year of measurement by ranger district. Plot ID numbers and tree numbers were designated as primary key fields. The database required primary key fields be selected to uniquely identify each record stored in the table by ranger district, plot
number and tree number. Relationships between the data contained within different tables were specified by "joining" the related fields. Questions were asked about the data by creating queries. Queries were designed by designating criteria desired from specific fields from selected tables and specifying calculations to be performed. Tables were queried to sort data by plot and species and calculate trees per acre and basal area per tree using DBH and plot factors. SDI calculations were performed using compatible spreadsheet software (EXCEL, Microsoft 1992).

Stand density index was calculated for each plot using the following equation:

$$SDI = 10^{(\log N + 1.605 \log D - 1.605)}$$

where N is trees per acre and D is the quadratic mean diameter (QMD) in inches.

SDI for each individual tree (i) per plot was calculated using the following equation:

$$SDI_i = a + bd_i^2$$

where a and b are coefficients depending on the QMD of all trees and are determined from the QMD by the following equations:

$$a = 10^{-k} (1 - k/2) (\Sigma d_i^2/N)^{k/2}$$

$$b = 10^{-k} (k/2) (\Sigma d_i^2/N)^{(k/2)-1}$$

in which k is a constant equal to 1.605. This enables the partitioning of any specified component of SDI (Stage 1968).

The contribution of a particular species or group of species to the plot SDI was calculated as:

$$\Sigma SDI_i$$ for that species or group of species.
The proportion of site utilization of a particular species was calculated as:
\[ \sum SDI_i \text{ for that species} / SDI_{total}. \]
The proportion of site utilization of a group of species was calculated as:
\[ \sum SDI_i \text{ for that group of species} / SDI_{total}. \]
Proportions x 100 were designated percent SDI (%SDI).

The plots were designated as the experimental units for each test (Hurlbert 1984). For example, when testing the intolerants, the SDI$_i$'s for every species designated as an intolerant were summed for each plot, and then the change in the totals over time for each plot were tested. The SDIs, \(\sum SDI_i\) for each species, and \(\sum SDI_i / SDI_{total}\) from plots measured in 1961-1963 were paired with SDIs from re-measurements of the same plots in 1993, 1994, or 1995. California white oak and Oregon white oak were tested as a single species because their characteristics are similar and their individual sample sizes were small.

Data were tested for skewness, kurtosis and omnibus normality. Data which did not meet normality assumptions were screened for outliers and possible outliers were removed and the data re-tested. If the subsequent test results met the normality assumptions and did not differ significantly from the original results, the original results were reported. If the normality assumptions could not be met, nonparametric tests were applied. Hypotheses were tested using matched-pairs t-tests or Wilcoxon signed-rank tests with Number Cruncher Statistical System software (Hintze 1995). To maintain overall \(\alpha\) at 0.05, test results for individual species were considered significant at \(\leq 0.05/(\text{number of tests within that group})\) as suggested by Bonferroni (Stevens 1992). Descriptive statistics were run on site tree ages and current plot SDI's.

The original plot cards are permanently stored in the Ecoplot Library of the Ecology Department of the Supervisors Office, Six Rivers National Forest, 1330 Bayshore
Way, Eureka, CA 95501. Electronic files are maintained on the USDA Forest Service DG/FIA system: side: I.S; directory: D11; level: Other Staff; staff name: TM; drawer: Runtams; folder: CFI, command line: Tams, inventory; FIA program; under filenames 30YCFIMR.TEXD, 30YCFILT.TEXD, 30YCFIOR.TEXD, 30YCFIGA.TEXD, 93CFIMR.TEXD, 94CFI.LT.TEXD, 94CFIOR TEXD, and 95CFIGA.TEXD. These files are also maintained at the Timber Management Service Center, National Forest Systems, USDA Forest Service, 3825 E. Mulberry Street, Fort Collins, CO 80524-8597. The PC database and copies of the original plot cards are maintained in the Schatz Tree Farm Office, Forestry Building, College of Natural Resources and Sciences, Humboldt State University, Arcata, CA 95521.
RESULTS

Analysis of the data indicates that SDI has increased (P < 0.000001, Table 1). SDI for tolerant species has increased (P < 0.000001, Table 2) and no change could be detected for intolerant species (Table 3). The proportion of the SDI (%SDI) attributed to tolerant species as a group has increased (P = 0.000013, Table 4) relative to other species, and the proportion of the SDI (%SDI) attributed to intolerant species has decreased (P < 0.000001, Table 5).

No significant change was found in the SDI for any individual intolerant species (Table 6). Sugar pine (P = 0.005225), western white pine (P = 0.001317), and black oak (P = 0.003588) had significantly decreased their proportion of SDI (%SDI) relative to other species (Table 7). Among the tolerant species, Douglas-fir (P = 0.000000), white fir (P = 0.002481), tanoak (P = 0.000031), and madrone (P = 0.001927) have a significantly increased SDI (Table 8). Douglas-fir (P = 0.000194) was the only tolerant species to have significantly increased its proportion of SDI (%SDI) relative to all other species (Table 9). Individual species with small sample sizes (n < 10) were not tested.

Ages for dominant or codominant site trees on each plot were determined from ring counts and analyzed (n = 161). The median age was 130 years with a 95 percent confidence interval of 115 to 144 years. The mean age was 158 years with a 95 percent confidence interval of 144 to 172 years. The distribution of ages is shown in a stem and leaf diagram (Figure 3). The mean SDI value for plots remeasured during the period of 1993-1995 was 406 (n=166) with a 95 percent confidence interval of 379 to 432 and the median value was 393 with a 95 percent confidence interval of 367 to 423. The distribution of SDIs is depicted in a histogram (Figure 4).
Table 1. Results of a matched-pairs t-test of the hypotheses Ho: stand density (SDI) has not changed; Ha: stand density has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: SDI</th>
<th>Ha: SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>166</td>
<td>No change</td>
<td>Increased</td>
<td>&lt;0.000001*</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$. 
Table 2. Results of a matched-pairs t-test of the hypotheses $H_0$: stand density ($\Sigma SDI_i$) of shade tolerant species has not changed; $H_a$: stand density of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>$H_0$: $\Sigma SDI_i$</th>
<th>$H_a$: $\Sigma SDI_i$</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOLERANT**</td>
<td>165</td>
<td>No change</td>
<td>Increased</td>
<td>$&lt;0.000001*$</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$.

**Douglas-fir, redwood, white fir, red fir, grand fir, incense-cedar, Port-Orford-cedar, pacific yew, big-leaf maple, coast live oak, canyon live oak, interior live oak, tanoak, California laurel, madrone, giant chinkapin, and pacific dogwood.
Table 3. Results of a matched-pairs t-test of the hypotheses Ho: stand density (ΣSDIi) of shade intolerant species has not changed; Ha: stand density of shade intolerant species has decreased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: ΣSDIi</th>
<th>Ha: ΣSDIi</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTOLERANT**</td>
<td>93</td>
<td>No change</td>
<td>Decreased</td>
<td>0.354204</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$.
**Ponderosa pine, Jeffrey pine, sugar pine, western white pine, lodgepole pine, knobcone pine, red alder, California black oak, California white oak, and Oregon white oak.
Table 4. Results of a Wilcoxon signed-rank test for difference in medians of the hypotheses Ho: the proportion (%SDI) of shade tolerant species has not changed; Ha: the proportion of shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: %SDI</th>
<th>Ha: %SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOLERANT**</td>
<td>165</td>
<td>No change</td>
<td>Increased</td>
<td>0.000013*</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$.

**Douglas-fir, redwood, white fir, red fir, grand fir, incense-cedar, Port-Orford-cedar, pacific yew, big-leaf maple, coast live oak, canyon live oak, interior live oak, tanoak, California laurel, madrone, giant chinkapin, and pacific dogwood.
Table 5. Results of a matched-pairs t-test of the hypotheses Ho: the proportion (%SDI) of shade intolerant species has not changed; Ha: the proportion shade intolerant species has decreased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: %SDI</th>
<th>Ha: %SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTOLERANT**</td>
<td>93</td>
<td>No change</td>
<td>Decreased</td>
<td>&lt;0.000001*</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$.

**Ponderosa pine, Jeffrey pine, sugar pine, western white pine, lodgepole pine, knobcone pine, red alder, California black oak, California white oak, and Oregon white oak.
Table 6. Results of a matched-pairs t-test of the hypotheses Ho: the stand density (SDI) of individual shade intolerant species has not changed; Ha: the stand density of individual shade intolerant species has decreased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: SDI</th>
<th>Ha: SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa pine</td>
<td>17</td>
<td>No change</td>
<td>Decreased</td>
<td>0.178401</td>
</tr>
<tr>
<td>Jeffrey pine</td>
<td>4</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Sugar pine</td>
<td>27</td>
<td>No change</td>
<td>Decreased</td>
<td>0.116266</td>
</tr>
<tr>
<td>Western white pine</td>
<td>11</td>
<td>No change</td>
<td>Decreased</td>
<td>0.070607</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>2</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Knobcone pine</td>
<td>11</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Red alder</td>
<td>6</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Black oak</td>
<td>37</td>
<td>No change</td>
<td>Decreased</td>
<td>0.117163</td>
</tr>
<tr>
<td>White oak</td>
<td>15</td>
<td>No change</td>
<td>Decreased</td>
<td>0.511750</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$. To maintain overall $\alpha$ at 0.05, test results for individual species are considered significant at $\leq 0.05/(\text{number of tests within that group})$ as suggested by Bonferroni (Stevens 1992). Thus, the significant probability of individual species of intolerants is $\leq 0.05/5 = 0.01$. 
Table 7. Results of a matched-pairs t-test of the hypotheses Ho: the proportion (%SDI) of individual shade intolerant species has not changed; Ha: the proportion of individual shade intolerant species has decreased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: %SDI</th>
<th>Ha: %SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa pine</td>
<td>17</td>
<td>No change</td>
<td>Decreased</td>
<td>0.050434</td>
</tr>
<tr>
<td>Jeffrey pine</td>
<td>4</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Sugar pine</td>
<td>27</td>
<td>No change</td>
<td>Decreased</td>
<td>0.005225*</td>
</tr>
<tr>
<td>Western white pine</td>
<td>11</td>
<td>No change</td>
<td>Decreased</td>
<td>0.001317*</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>2</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Knobcone pine</td>
<td>11</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Red alder</td>
<td>6</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Black oak</td>
<td>37</td>
<td>No change</td>
<td>Decreased</td>
<td>0.003588*</td>
</tr>
<tr>
<td>White oak</td>
<td>15</td>
<td>No change</td>
<td>Decreased</td>
<td>0.202451</td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$. To maintain overall $\alpha$ at 0.05, test results for individual species are considered significant at $\leq 0.05/(\text{number of tests within that group})$ as suggested by Bonferroni (Stevens 1992). Thus, the significant probability of individual species of intolerants is $\leq 0.05/5 = 0.01$. 
Table 9. Results of a matched-pairs t-test of the hypotheses Ho: the proportion (%SDI) of individual shade tolerant species has not changed; Ha: the proportion of individual shade tolerant species has increased, for Stand Density Index values calculated from tree data collected from Continuous Forest Inventory plots measured during the period of 1961-1963 and re-measured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample size (n)</th>
<th>Ho: %SDI</th>
<th>Ha: %SDI</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas-fir**</td>
<td>154</td>
<td>No change</td>
<td>Increased</td>
<td>0.000194*</td>
</tr>
<tr>
<td>Redwood</td>
<td>2</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>White fir</td>
<td>40</td>
<td>No change</td>
<td>Increased</td>
<td>0.038572</td>
</tr>
<tr>
<td>Red fir</td>
<td>6</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Grand fir</td>
<td>2</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Incense-cedar</td>
<td>19</td>
<td>No change</td>
<td>Increased</td>
<td>0.871433</td>
</tr>
<tr>
<td>Port-Orford-cedar</td>
<td>4</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Pacific yew</td>
<td>4</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Big-leaf maple</td>
<td>14</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Coast live oak</td>
<td>9</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Canyon live oak</td>
<td>29</td>
<td>No change</td>
<td>Increased</td>
<td>0.584306</td>
</tr>
<tr>
<td>Interior live oak</td>
<td>21</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Tanoak</td>
<td>67</td>
<td>No change</td>
<td>Increased</td>
<td>0.127112</td>
</tr>
<tr>
<td>California laurel</td>
<td>8</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Madrone</td>
<td>64</td>
<td>No change</td>
<td>Increased</td>
<td>0.969440</td>
</tr>
<tr>
<td>Giant chinkapin</td>
<td>18</td>
<td>No change</td>
<td>Increased</td>
<td>0.498032</td>
</tr>
<tr>
<td>Pacific dogwood</td>
<td>5</td>
<td>Not tested</td>
<td>Not tested</td>
<td></td>
</tr>
</tbody>
</table>

*Significant at overall $\alpha = 0.05$. To maintain overall $\alpha$ at 0.05, test results for individual species are considered significant at $\leq 0.05/(\text{number of tests within that group})$ as suggested by Bonferroni (Stevens 1992). Thus, the significant probability of individual species of tolerants is $\leq 0.05/7 = 0.0071429$.

**Wilcoxon signed-rank test for difference in medians.
Six Rivers National Forest Stand Initiation Time Line

<table>
<thead>
<tr>
<th>Year</th>
<th>Age</th>
<th>1870-1920 Large-scale stand-replacing fires (USDA 1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1896</td>
<td>1*</td>
<td>1860-1885 State-wide drought (Fritts and Gordon 1980)</td>
</tr>
<tr>
<td>1796</td>
<td>2*</td>
<td>1755-1825 State-wide drought (Fritts and Gordon 1980)</td>
</tr>
<tr>
<td>1696</td>
<td>3*</td>
<td>1910-present Fire suppression (USDA 1995)</td>
</tr>
</tbody>
</table>

Unit = 10 Example: 1* | 2 represents 120 years

1993-1995 CFI Site Tree Ages

Figure 3. Stem and leaf diagram depicting the age distributions of site trees measured on 161 Continuous Forest Inventory plots established in the Six Rivers National Forest, northwestern California, USA. Ages were established from ring counts in 1993-1995. Corresponding periods of possible stand-replacing events are also depicted.
Figure 4. Histogram of the distribution of stand density index (SDI) values calculated for Continuous Forest Inventory plots remeasured during the period of 1993-1995 in the Six Rivers National Forest, northwestern California, USA.
DISCUSSION

The results of this study clearly quantify significant changes in tree density of stands in undisturbed portions of the Six Rivers National Forest. Specifically, the analyses indicate:

(1) a significant increase in overall stand density;
(2) a significant decrease in the proportion of those stands occupied by shade intolerant species;
(3) a significant increase in the density of shade tolerant species; and
(4) a significant increase in the proportion of those stands occupied by shade tolerant species.

These effects raise certain questions. Why is stand density increasing? Why are shade tolerant species the primary increasers of stand density? Will increasing stand densities adversely affect forest health? Are increased stand densities and increased proportions of tolerants the effect of a disruption of some disturbance interval, the processes of natural succession, an increase in the amount of atmospheric CO₂, the activities of pests or diseases on the intolerants, pollution, or climatic change? Is the effect the result of some combination of those factors? Questions and hypotheses about cause and effect are easier to formulate than to test.

The results of this study do not directly validate the interrupted disturbance interval hypothesis. Ponderosa pine is a species which is classically maintained by periodic fires and is accepted as a primary example of this hypothesis in the inland west. Sugar pine and western white pine are also species which may be positively impacted by periodic low-intensity wildfires. If decreases in the proportions of the stand density of these pines
were due to fire alone, one would expect the proportions of the stand density of each of these pines to decrease by a similar degree. However, while the expected decreases in the proportion of stand density for sugar pine and western white pine were significant at the 0.05 level, the expected decreases in the proportion of stand density contributed by ponderosa pine were not significant at the 0.05 level. The inability to detect a change in ponderosa pine may be due to a relatively small sample size (n=17). Alternately, it may indicate that the reduction in sugar pine and western white pine proportions which were detected may be due more to biotic processes (white pine blister rust) than to fire exclusion alone.

Nonetheless, the combination of the evidence of increasing stand densities presented in this paper, and Adams and Sawyer's (1980) tree ring analysis in the Six Rivers National Forest strengthens the case for the hypothesis that stand density is increasing due to an interrupted disturbance interval. Additional strength could be added to this hypothesis if the ages of ingrowth tolerant trees contributing to increased stand densities could be shown to coincide with the cessation the fire interval. The 16.5 year fire-free interval detected by Adams and Sawyer (1980) was derived from analysis of stumps in clearcuts. The evidence for increasing stand densities reported by this study was developed from analysis of undisturbed stands. The inferences from this study and that of Adams and Sawyer may not overlap. The fire-free interval may be appropriate for stands which had successfully progressed to later successional stages and thus were suitable for harvest because of size and density, but not for stands which did not meet those criteria. The topographic position and the proximity of stands to existing roads may have been factors in the selection of areas to be clear-cut which are not applicable to the undisturbed forest in general. Species selected for clearcutting may not be representative of the species mixture in the undisturbed forest. Nonetheless, the results of both studies suggest
that further investigation, with careful attention to the population of inference, could be fruitful.

The hypothesis of increased stand density due to an interrupted disturbance interval may be more appropriate for the forests of the inland west than for the Six Rivers National Forest. Recurring stand-replacing wildfires may have been the primary regenerating disturbance in the Six Rivers National Forest even prior to the policy of fire suppression; natural succession may be the primary factor contributing to current community ecology changes. If the site trees measured on the plots considered in this study represent the stand initiation cohort, the ages of the site trees suggest that most of the stands are relatively young and that increasing stand density is consistent with early successional stages (Figure 2). Data presented in Figure 3 illustrate a possible correlation between the stand ages and three large-scale natural events pre-dating fire suppression. These events may have precipitated stand replacement due to subsequent events including mortality from stress, insects, disease and pests, windthrow, and fire. It may be that the forest is not so much responding primarily to a disruption of frequent low-intensity disturbances as it is to infrequent high-intensity stand-replacing disturbances which preceded the fire suppression era. Analysis of SDI data grouped by stand age may reveal that these test results were driven by a high proportion of younger stands. Conversely, if the older stands are found to be increasing in density, analysis of mortality data incorporated into this database may yield evidence that older stands had entered the understory re-initiation stage prior to 1910 and have since reverted back to the stem exclusion stage due to the ingrowth of tolerants. Increasing densities of those stands would be consistent with the disruption of fire disturbance interval hypothesis.

The increase in stand density suggests that most stands are still in the stem exclusion stage. This corresponds to the situation in the inland west, which now has
"...an excess of closed forests (especially the 'stem exclusion' stage), thus setting the stage for widespread, catastrophic fires" (Oliver et al. 1994). Historically, few stands in what is now the Six Rivers National Forest may have reached the old growth stage, perhaps due to susceptibility to lightning fires during long, dry summers. This database could be used in testing correlations between older, late-successional stands and topographic position. If stands occupying topographic positions which are highly susceptible to lightning fires are expected to progress to later successional stages to maintain Historic Range of Variability (HRV) objectives by the USDA Forest Service, then continued fire suppression in those stands may be necessary.

Reineke (1933) found the maximum SDI for California mixed conifer to be approximately 760. Over 96 percent of the plots remeasured during the period of 1993-1995 had SDIs below that level (Figure 4). If Reineke's SDI_{max} is appropriate for the Six Rivers National Forest, the current densities should not pose unusual forest health problems. The question of whether or not continued increasing stand densities will lead to catastrophic health problems and/or stand replacing fires remains unanswered.

The question of how close these stands are to maximum densities may warrant further study. Sterba and Monserud (1993) discuss methods of predicting maximum stand densities in uneven-aged mixed species stands. Sterba's modified Competition Density Rule adds habitat types to the parameters of stem number, dominant height, quadratic mean diameter, and maximum basal area, which are estimated from non-linear regression analyses. Predictions are complicated by changes in the skewness of the DBH^{1.5} distribution and the effect of site on yield. Their results demonstrated that maximum basal area (therefore SDI_{max}) is higher for even-aged stands than for uneven-aged stands.

Forest managers need methods to predict maximum densities of uneven-aged mixed species stands which can be based on data from existing cruises or on data which
are readily obtainable. Knowledge of present and predicted maximum stand densities can aid managers in determining the current relative stand density and in predicting the progression of forest components from one successional stage to another. These predictions can aid managers in maintaining the HRV objective. Working approximations of maximum densities may be possible from data referencing only DBH and trees per acre by species. These kinds of data can be rapidly and feasibly obtained.

Perhaps Sterba's modified Competition Density Rule and the following proposed method of predicting maximum SDI and relative stand density can be tested by following the plots of this dataset through future measurement intervals until they reach maximum densities. This proposed method would be independent of age and site, assuming the sites are capable of supporting a closed canopy. By increasing stand densities, shade tolerant tree species appear to be the decisive component in the determination of maximum stand densities in the stem-exclusion stage. Intolerant species become crowded by increased densities which approach the tolerant species' maximums.

Using the methods detailed in this study, it is possible to calculate the overall SDI, the amount of that SDI contributed by each shade tolerant species, and the sum of the contributions of shade tolerant species can be calculated. The ratio of the SDI contributed by each shade tolerant species to the sum of SDI contributed by all shade tolerant species can then be calculated. Although the requirement of prior maximum curves are a disadvantage of this method, maximum SDIs have been calculated for many California tree species (Reineke 1933). The predicted maximum SDI would then be the sum of the products of the ratio and the predicted maximum SDI for each species. Relative stand density would then be the proportion of the current SDI to the predicted maximum SDI. Relative stand density would be the equivalent of Reineke's (1933) "percentage stocking."
So, the equation for maximum SDI for an uneven-aged mixed-species stand is:

\[ \sum \left( \frac{SDI_i \text{ for a tolerant species}}{\sum SDI_i \text{ for tolerant species}} \right) \times SDI_i^{\text{max}} \]

where \( SDI_i^{\text{max}} = \) maximum SDI calculated for that species.

The equation for relative stand density is:

Current SDI/predicted maximum SDI.

For example, in the Mad River Ranger District, CFI plot 00593, which is plot ID 54059 in this database, contained a mixture of Douglas-fir, ponderosa pine, white fir, and California black oak when it was first measured during the 1961-1963 period. The overall SDI for that plot was 387.2, of which 166.1 is attributed to Douglas-fir, 13.3 is attributed to ponderosa pine, 130.2 is attributed to white fir, and 77.6 is attributed to California black oak. Douglas-fir and white fir were the shade tolerant components of the plot.

The amount of SDI attributed to shade tolerant species would then be:

\[ 166.1 + 130.2 = 296.3 \]

Of that sum, \( \frac{166.1}{296.3} = 56 \) percent is attributed to Douglas-fir, and \( \frac{130.2}{296.3} = 44 \) percent is attributed to white fir.

Reineke's (1933) estimated maximum SDI for Douglas-fir is 595, and for white fir is 830.

So, the predicted maximum SDI would be:

\[ (.56 \times 595) + (.44 \times 830) = 698.4, \] and

relative stand density would be:

\[ \frac{387.2}{698.4} = .55 \text{ or } 55 \text{ percent of maximum density.} \]

When the same plot was re-measured in 1993, the ponderosa pine component had dropped out of the plot and the California black oak component had decreased. The overall SDI for that plot had increased to 400.6, of which 163.0 is attributed to Douglas-fir, 211.6 is attributed to white fir, and 26.0 is attributed to California black oak.
Douglas-fir and white fir were still the shade tolerant components of the plot. The amount of SDI attributed to shade tolerant species would then be:

\[ 163.0 + 211.6 = 374.6 \]

Of that sum, \[ \frac{163.0}{374.6} = 43.5 \text{ percent} \] is attributed to Douglas-fir, and \[ \frac{211.6}{374.6} = 56.5 \text{ percent} \] is attributed to white fir.

So, the predicted maximum SDI would be:

\[ (.435 \times 595) + (.565 \times 830) = 727.8, \text{ and} \]

relative stand density would be:

\[ \frac{400.6}{727.8} = .55 \text{ or } 55 \text{ percent of maximum density.} \]

The results of these estimates could be compared with future empirical data from remeasurements of these plots. If predicted maximum SDIs have equivalent slopes with actual maximum SDIs, a local coefficient may be derived to adjust predictions.

Increases in stand densities may also be caused in part by several other factors. First, increases in CO₂ levels may have improved site utilization for all species relatively equally or may have favored some over others. Comparisons of enhanced CO₂ response between intolerants and tolerants may help explain past trends and suggest influences upon the direction of future trends in community ecology. Second, diseases and insects such as white pine blister rust (Cronartium ribicola), western pine beetle (Dendroctonus brevicomis), and madrone canker (Fusicoccum sp.) may have reduced the contribution of the affected species to current densities over the measurement period, decreasing the proportions of stand densities occupied by those species. Analysis of mortality data may quantify this effect. For example, effects of the madrone canker may help explain the finding that, while the densities of madrone increased, their proportion of stand density has declined. Third, while air pollution has been shown to be a significant factor upon tree health in southern California (Miller et al. 1977, 1979), it may not be an influential factor
in the Six Rivers National Forest. Winter air movement from the Pacific Ocean and the forest's location within the least densely populated portion of California may protect these stands of trees from damage caused by air pollutants. Finally, climatic changes in factors such as changes of global mean temperatures or changes in the distribution, intensity or timing of precipitation may be influencing site utilization by changing the competitive advantages of various species or groups of species. This effect would be very difficult to quantify due to lack of controls (non-affected areas).

Further study into the effects of any of these factors may increase our understanding of current forest trends. The observed changes in community ecology may well be an example of multiple determinism influenced primarily by both stand-replacing fires and an interrupted low-intensity fire interval. If the identification of any one of the possible factors affecting the community ecology in the undisturbed portions of the Six Rivers National Forest is problematic, then quantifying multiple causes may remain enigmatic. While this study raises many questions, the hypotheses tested were clearly answered. The combination of Forest Inventory Data, user-friendly relational databases, the concept of stand density index, statistical analysis, and research time and money has yielded solid and statistically powerful analyses that have detected changes in forest community ecology. Continued development of such tools and efforts should lead to new approaches and possible solutions to contemporary issues in data management, forestry and forest ecology.
CONCLUSION

The creation of a relational database proved to be an effective management strategy for organizing complex plot and tree data covering lengthy periods. This organization strategy facilitated the testing of questions currently of concern to forest managers. Comparison of stand density index values proved to be an effective analysis method in detecting changes in forest community ecology. Changes in stand characteristics could be detected at the forest, plot, and species level. This process exemplifies the utility and value of historic datasets and analysis methods in meeting the analysis needs of managers addressing a changing emphasis on forest values.

Forested stands within undisturbed portions of the Six Rivers National Forest have become more dense since 1961-1963. This increase in stand density is the result of increasing densities of shade tolerant species. Specifically, Douglas-fir, white fir, tanoak and madrone have increased densities. Douglas-fir has increased in its proportion of site occupancy relative to other species. Of the shade intolerant species, sugar pine, western white pine and California black oak have decreased in their proportion of site occupancy. The overall stand densities are apparently below theoretical maximum densities and should not be precipitating forest health crises.

Possible causes of these effects include natural succession, the interruption of some disturbance interval, increases in atmospheric CO$_2$, the activities of pests or diseases on the shade intolerants, or climatic change. While these quantified changes in community ecology may lead to further research which may isolate or partition the contribution of specific factors to these effects, it is the effects with which forest managers must cope. To reiterate the advice of Albert Stage (1991) "...one should be looking for effects of causes rather than looking for causes of effects."
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PERSONAL COMMUNICATIONS

APPENDIX A. Cluster plot record. Data collection form for Continuous Forest Inventory plots located in the Six Rivers National Forest, northwestern California, USA.