Growth trends of blue oak (*Quercus douglasii*) in California

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Long-term growth trends of blue oak (*Quercus douglasii* Hook. & Arn.) at five sites in California were quantified and interpreted with respect to annual precipitation. Mean annual basal area increment (BAI) at sites with deep soil profiles or high precipitation was twice as great as growth at other sites. In general, BAI increased sharply during approximately the first 40 years of tree growth, then increased gradually or leveled off for the next 100 years. Limited data from older trees suggest that BAI decreases gradually after this point. Growth trends are relatively homogeneous within each site, but vary among sites. Most sites have relatively high correlations with precipitation compared with coniferous species at higher elevations. Interannual variation in soil moisture availability is clearly an important factor affecting annual growth of blue oak in the Mediterranean climate of California. This is the first known dendroecological study of blue oak growth trends.

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L'évolution à long terme de la croissance du chêne de Californie (*Quercus douglasii* Hook. & Arn.) dans cinq stations en Californie a été quantifiée et interprétée en relation avec la précipitation annuelle. L'accroissement annuel moyen en surface terrière dans les stations avec un sol profond ou de fortes précipitations était deux fois plus élevé que dans les autres stations. En général, la croissance a diminué abruptement pendant les 40 premières années pour augmenter ensuite graduellement ou se stabiliser pendant les 100 années suivantes. Le peu de données récoltées sur les plus vieux arbres suggèrent que la croissance diminue progressivement par la suite. L'évolution de la croissance est relativement homogène dans chaque station mais varie entre les stations. Dans la plupart des stations, il y a de fortes corrélations avec la précipitation semblables à celles qu'on observe chez les conifères à plus haute altitude. La variation dans l'humidité du sol d'une année à l'autre est définitivement un facteur important qui affecte la croissance du chêne de Californie sous le climat méditerranéen de la Californie. Ceci est la première étude dendroécologique connue portant sur l'évolution de la croissance du chêne de Californie.

[Traduit par la rédaction]

Introduction

Blue oak (*Quercus douglasii* Hook. & Arn.), a California endemic, is an abundant and widespread hardwood species in the state, covering over 1 million ha (Griffin and Critchfield 1972; Bolsinger 1988). It is a prominent tree species in the blue oak woodland encircling the Central Valley and the lower elevations of the Coast Range (McDonald 1990). It typically grows in open stands with a grass understory, and can be found in association with other tree species such as valley oak (*Quercus lobata* Née) and digger pine (*Pinus sabiniana* Dougl. ex D. Don). Fossil evidence indicates that this woodland assemblage has been present in California since 5×10^6 years BP (Axelrod 1977, 1983).

Previous research on blue oak has focused on the synecology of woodland vegetation (White 1966; Griffin 1977; McClaran 1986*a*,1986*b*) and regeneration modes and patterns (Griffin 1971; Matsuda and McBride 1986; McClaran 1986*a*, 1986*b*; Muick and Bartolome 1986; Borchert et al. 1989; Allen-Diaz and Bartolome 1992). Physiological studies have been limited to water stress and rooting patterns in a small number of stands (Lewis and Burgy 1964; Griffin 1973; Baker et al. 1981). There is some concern over the future of blue oak stands in California because of the possible effect of land management practices (such as grazing by domestic livestock) on natural regeneration, particularly regarding low reproduction in some areas of the state since the early 20th century (White 1966; Griffin 1977; Adams et al. 1986; Bartolome et al. 1986; McClaran 1986*a*, 1986*b*; Bolsinger 1988).

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TABLE 1. Characteristics of blue oak sites

	Site				
	Soeth	Butte	Ione	SLO	Hopland
Elevation (m)	240	170	80	550	490
Slope (%)	70	20	20	60	35
Aspect	NW	N	NW	NE	SW
Density (stems/ha)	518	464	470	485	483
Basal area (m^2/ha)	9	15	12	11	17
Annual precipitation (cm)	55	52	46	55	93
Soil					
Depth (cm)	70	45	100	40	60
Texture	Clay loam	Clay loam	Gravelly loam	Gravelly loam	Silt loam
Series	Sehorn	Auburn	Red Bluff	Millsholm	Laughlin
Subgroup	Entic Chromoxerert	Lithic Xerochrept	Ultic Palexeralf	Lithic Xerochrept	Ultic Haploxeroll

NOTE: Precipitation data are from the nearest U.S. National Oceanic and Atmospheric Administration weather station. Soils information is from U.S. Soil Conservation Service reports for Glenn (Soeth), Butte (Butte), Amador (Ione), San Luis Obispo (SLO), and Mendocino (Hopland) Counties.

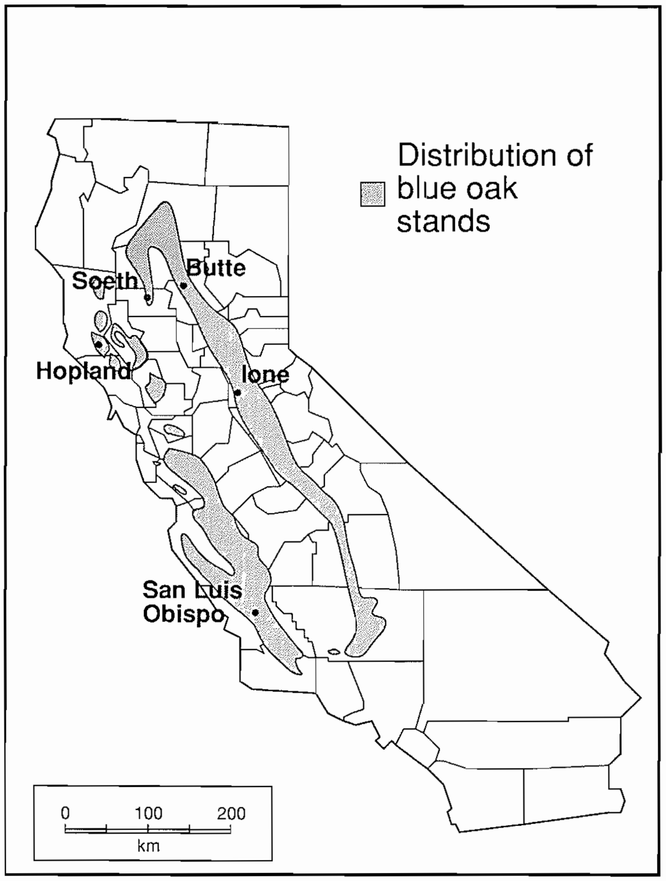

FIG. 1. Distribution of blue oak woodlands (from Griffin and Critchfield 1972), showing study site locations.

Although blue oak is an abundant species in California, there is limited information on temporal growth trends of individuals and stands (McDonald 1990). In fact, detailed analyses of growth trends and growth–climate relationships are rare for most of the California oak species (McDonald 1969). There is currently increasing pressure to convert existing blue oak woodlands to other uses, as urban areas encroach on foothill areas of the state. There is also growing interest in managing blue oak and other California hardwoods for wood production (O'Keefe and Piirto 1986). It has been difficult to develop management and protection strategies for blue oak, because of the lack of basic information on growth rates and their relationship to climate and site factors.

In this study, we used a dendroecological approach to determine long-term growth trends in blue oak. Specific objectives were to: (*i*) quantify growth patterns of blue oak from a range of sites, and (*ii*) evaluate impacts of annual precipitation and general site characteristics on the growth of blue oak woodlands.

Methods

Study sites

Blue oak stands were sampled at five locations in California (Fig. 1): Hopland (Mendocino County), Butte (Butte County), Soeth (Glenn County), Ione (Amador County), and San Luis Obispo (SLO; San Luis Obispo County). Trees were harvested at each location as part of a thinning study (McCreary 1987), allowing us to obtain discs cut at breast height.

All stands are in the blue oak phase of the foothills woodland vegetation type (Griffin 1977). Blue oak is the dominant overstory species (>90% of all trees in each stand), and annual grasses are the dominant understory vegetation. Elevation ranges from 80 to 550 m, and aspect and slope differ among sites (Table 1). Precipitation and soil types vary considerably among sites (Table 1). Over 80% of annual precipitation at all sites falls between November and March. Hopland receives approximately twice as much precipitation as the other sites.

Study sites varied in size from 1.2 to 2.0 ha. One hundred ninety-two trees >8 and <40 cm DBH were selected according to a random number table and cut at each site in 1987 (McCreary 1987). Sections at breast height from these trees were therefore available for the present study. There is only limited information on stand history and management activities in these stands. There is no evidence of prior tree cutting or recent fires, although a few of the older trees at some sites had small scars. Historical information from the sites indicates that they have been grazed by domestic livestock since at least the 1950s.

Growth measurements and analysis

It was determined that 25 discs per site would be an adequate sample size for statistical analysis based on previous work with tree-ring measurements (Peterson et al. 1989). The adequacy of this sample size was confirmed by initially analyzing the variance properties of annual ring measurements of 25 blue oak discs from one of the

TABLE 2. Mean (±1 SD) and range of DBH, height, and age to pith of sample trees

	DBH (cm)			Height (m)			Age to pith (years)		
Site	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Soeth	15.5 (4.3)	8.6	25.6	6.6 (1.1)	4.1	8.6	133 (42)	72	240
Butte	17.0 (4.0)	10.4	24.4	8.4 (1.3)	6.6	11.2	72 (14)	52	100
Ione	14.3 (3.1)	5.1	23.4	8.2 (1.9)	1.8	11.3	56 (11)	41	98
SLO	14.4 (3.1)	7.9	19.9	8.8 (1.3)	5.8	12.0	88 (18)	37	114
Hopland	21.6 (5.4)	9.4	32.0	11.5 (2.2)	5.5	15.9	116 (10)	93	128

NOTE: Sample size is 25 for Butte and Hopland, 24 for all other sites.

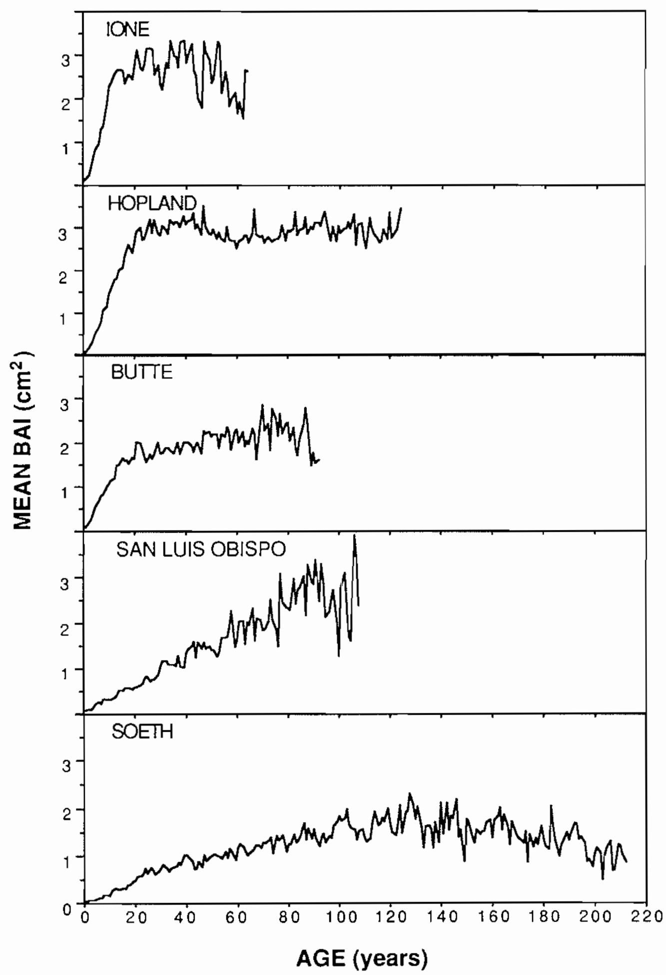

FIG. 2. Mean annual basal area increment (BAI) curves for the five study sites. BAI was calculated on the basis of age rather than calendar year. Sample size decreases with increasing age, and variance of BAI therefore increases with increasing age; curves are truncated at the age at which $n = 3$.

sites in this study. Discs from single-stemmed trees were used, when possible, to decrease variance associated with the growth of stems originating as sprouts. Multiple-stemmed discs were used in a few cases in which there were <25 single-stemmed discs available. Discs were sanded with successively finer grades of sandpaper until cell structure was clearly visible with the use of a microscope.

Mean radius of each disc was calculated on the basis of the circumference of each disc, assuming the discs were round with the pith located at the center (most discs have low eccentricity of ring growth). Rings were measured at two locations where the radius equaled the mean, on the opposite sides of the disc when possible. Additional radii were measured on a subsample of discs, but the additional data had little impact on the accuracy or variance of radial growth measurement. Ring widths were measured to the nearest 0.01 mm with an incremental measuring machine equipped with television camera and monitor. This machine is linked with a digital encoder interfaced with a microcomputer that uses software to store ring-width measurements by year for each disc (Robinson and Evans 1980).

The rings of each disc were accurately associated with a specific year through the process of cross dating (Fritts 1976). The most recent year cross-dated was 1986, because trees were cut during the growing season of 1987. Discs were cross-dated visually by indicating dates directly on the disc (Stokes and Smiley 1968; Swetnam et al. 1985). All rings were measured and recorded. Cross dating was verified following ring measurement, with the program COFECHA (Holmes 1983), which calculates correlation coefficients between a single series and a master series. Discs were included in the database only if they could be confidently cross-dated. Only three discs were eliminated because of inadequate cross dating.

Ring-width measurements were initially used to calculate basal area increments (BAI) for each disc, based on a mean of the two measured radii. BAI values were plotted as a function of time in order to examine general growth trends.

Discs were also obtained from the base and breast height of 12 trees from both the SLO and Hopland sites to examine vertical growth patterns. Discs were processed as mentioned above, with ages determined for each disc of each pair. Number of years from base to breast height was calculated for the two sites. This analysis was used to get a general idea of how many years of growth are missed by using discs removed at breast height; however, age and growth data from discs at breast height were not adjusted for data analysis.

Detrending of radial-growth time series was performed for each tree using exponential and spline functions (program ARSTAN; Cook and Holmes 1985). Remaining persistence in the individual series was removed by fitting the series with an appropriate autoregressive model. The residuals were averaged using Tukey's biweight estimator. The resulting time series of mean growth-index values (chronologies) for each site was used in subsequent analyses.

Annual precipitation data (previous October through current September) were obtained from the nearest representative U.S. National Oceanic Atmospheric Administration weather station to each study site. All records date back to at least 1919. Correlation analysis was performed using Pearson product–moment correlations. Correlations between growth-index values and annual precipitation were determined for each site. Statistical analysis, site information, and available historical information were used to interpret growth trends within and among sites.

Results and discussion

Site and sample characteristics

Tree density for the five study sites varied from 464 to 518 trees/ha (Table 1). Multiple-stemmed trees were most common at Ione, where 34% of the 192 trees sampled for the tree thinning project had two or more stems. The remaining sites varied from 9% (Soeth) to 14% (SLO) multiple-stemmed individuals. Basal area ranged from 9 to 17 m^2/ha (Table 1).

TABLE 3. Summary of correlations (r) between growth index and mean annual precipitation for each site

Site	Starting date of a common time series for 20 trees	r
Soeth	1886	0.72
Butte	1935	0.37
Ione	1946	0.49
SLO	1929	0.76
Hopland	1894	0.72

NOTE: The starting date of a common time series of growth for a minimum of 20 trees used in correlation analysis is indicated for each site.

Mean DBH of sample trees ranges from 14.3 to 21.6 cm, and mean height ranges from 6.6 to 11.5 m (Table 2). The relatively low standard deviations of these mean values indicate that diameter and height are fairly uniform within the sample for each site. Mean age of the sample trees varies from 56 to 133 years. Soeth has the widest age range, with 83% of trees from 70 to 160 years old. Hopland has a narrow age span, with 76% of trees 110–130 years old. The relative order of mean tree age is (from youngest to oldest): Ione, Butte, SLO, Hopland, and Soeth (Table 2).

Because sections were cut at breast height, basal and breast height sections were collected at SLO and Hopland to determine vertical growth to breast height to estimate true age. A few discs from each site were discarded because cross dating was not possible. The mean difference in age from base to breast height at SLO was 19 years (SD = 7.8, n = 9); the mean difference at Hopland was 14 years (SD = 6.6, n = 11). Tree ages discussed here should be considered approximate, because vertical growth varies within and among sites.

Growth trends

Time series of mean annual BAI by tree age vary considerably among sites (Fig. 2). BAI was calculated for each site on the basis of tree age rather than calendar year, allowing for examination of growth trends of trees germinating or sprouting at different times. BAI growth is greater at Hopland and Ione than at other sites and is nearly twice as great as at Soeth (Fig. 2). BAI at Hopland and Ione increases sharply during approximately the first 40 years (including the time needed to reach breast height), then reaches a stationary level faster than at sites with slower growth. Differences in BAI growth may be related at least partially to site quality. Hopland has mollisols that generally have high nutrient availability, as well as the highest annual precipitation of the five sites (Table 1). Ione has alfisols with a deep soil profile compared with other sites. The BAI record at Soeth is at least twice as long as the other four sites. BAI at this site starts to decline after 150 years. Unfortunately, we do not know if this is a typical long term pattern for blue oak growth because of the limited number of older trees at the other sites.

Relationship of growth to precipitation

Correlations of growth index with annual precipitation values were used to determine how much variance in growth could be accounted for by interannual variation in precipitation. Previous dendroecological studies in central California (Peterson et al. 1991) have shown that precipitation (approximately 80% of which falls during October through March) is the dominant climatic variable that affects tree growth. Correlations range from 0.37 to 0.76, indicating that there are relatively large differences among sites in sensitivity to climate (Table 3). Most years with very low annual precipitation are correlated with decreased growth at all sites. Many of these low-growth years (e.g., 1961, 1976, 1977) are the same as those found in conifer tree-ring chronologies at higher elevations in the Sierra Nevada Range (Holmes et al. 1986). The correlation between growth and precipitation is generally higher in blue oaks than in Sierra Nevada conifers (Peterson et al. 1987, 1991; Peterson and Arbaugh 1988), indicating that blue oak growth may be influenced more by precipitation than are neighboring conifers at higher elevations with greater annual precipitation.

Conclusions

This is the first dendroecological study of blue oak in California. Although there is considerable variation among sites, we detected several growth trends and growth–climate relationships. The magnitude of BAI varies greatly among blue oak sites. Site quality, as expressed by soil type, slope, and mean annual precipitation may be related to these differences. The general pattern of BAI growth over time is similar among sites. Growth generally increases sharply during the first 40 years after germination or sprouting, followed by gradually increasing or stationary growth for the next 100 years. BAI growth appears to decrease gradually after this point, although this trend is based on a relatively small sample of old trees from one site.

Growth trends within sites are relatively homogeneous. Correlations with annual precipitation tend to be higher for sites with steep slopes and shallow soils as suggested by dendroclimatic theory (Fritts 1976), although it is difficult to develop broad inferences from such a limited number of sites. Most of California is dominated by a Mediterranean climate with warm, dry summers and cool, wet winters. Because summer storms are infrequent, tree growth depends on winter rainfall to provide sufficient soil moisture throughout the year. The potential for soil moisture to limit growth at foothill locations occupied by blue oak is even greater than for conifers at higher elevations in the Sierra Nevada Range and elsewhere. The correlation between blue oak growth and annual precipitation is relatively high compared to other species in California, and indicates how strongly interannual variation in growth is affected by precipitation.

Variability in growth rate, growth trends, and growth–climate relationships among different sites makes it difficult to develop general management guidelines for blue oak woodlands throughout California. We suggest that management plans for blue oak should be developed on a site by site basis. Information on local soils, climate, and growth patterns are needed in order to optimize rotation ages (for commercial timber or firewood) and use of management practices such as thinning. Analysis of additional blue oak stands and other oak species in California are needed to improve our understanding of long-term growth trends and growth–climate relationships in oak woodlands.

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