

Restoration of Coast Redwood (*Sequoia sempervirens*) Forests through Natural Recovery

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The management of second-growth *Sequoia sempervirens* (coast redwood) forests for the purpose of restoration and ecological conservation is a growing trend. However, little is known about the long-term regenerative potential of this forest type in the absence of post-harvest management techniques such as thinning and planting. Data on forest composition and structure were collected on a chronosequence (80 - 160 years) of mature recovering stands in the southern coast redwood range using a replicated, randomized, plot design. Results indicated that many stand characteristics including tree density, canopy cover, redwood dominance, species richness, herbaceous cover, and shrub cover reached levels statistically equivalent with old-growth reference sites in recovering stands within the time frame of this chronosequence. The recovery of individual herbaceous understory species was inconsistent however. While the cover of redwood-associated species (*Oxalis oregana*, *Tridentalis latifolia*, and *Disporum hookeri*) reached levels statistically equivalent to old-growth reference sites, others (*Trillium ovatum* and *Viola sempervirens*) did not. Total basal area and species evenness also trended toward, but did not reach, old-growth conditions. The arboreal aspects of coast redwood forests appear to be remarkably resilient following a single logging event, and recover rapidly in the absence of active restoration techniques. The protracted recovery of certain redwood associated herbaceous understory species will require further study.

Keywords: Coast Redwood; *Sequoia sempervirens*; Restoration; Timber Harvest; Natural Recovery

Introduction

The majority of the original old-growth *Sequoia sempervirens* (coast redwood) forest has been converted into managed timber stands and other land uses (Noss, 2000). Preservation efforts have been successful in protecting most of the remaining old-growth in parks and preserves. However, so little of the original forest remains (<5%) that conservation groups are acquiring previously harvested forestlands to serve as additional preserves and buffers. While management of old-growth forests is mainly limited to preservation, management of previously harvested forests often includes some level of active restoration (O'Hara et al., 2010). Whether the restoration objectives, and the tools required meet those objectives, however, is a matter of debate.

In general terms, restoration is defined as "bringing back to a former position or condition" (Merriam-Webster, 2010). However, defining the "former condition" of a particular forest is a difficult task. Forests, as living systems, are in a constant state of flux. Any specific point in time, or set of forest conditions, is essentially arbitrary. In North America the term "restoration" has sometimes been used to indicate an idealized pre-European condition, based on the unfounded assumption that the pre-European population did not actively manage forests (Litvalis, 2003; Anderson, 2006). Restoration efforts towards idealized conditions taken from historic photographs are equal-

ly subjective, as the photographers' choice of scenic vistas must be considered. Conditions found in currently extant reference sites with minimal anthropogenic disturbance is perhaps the best option for a restoration template (Laughlin et al., 2004; Josefsson et al., 2009), though these stands can vary significantly.

Regardless of the choice of reference, forest restoration (much like commercial timber management) has tended to focus primarily on the rapid production of large trees (Meisel et al., 2009) rather than the development of viable ecological communities. As a result, silvicultural treatments in the form of pre-commercial and commercial thinning have become a common tool leading to an almost synonymous use of the terms "restoration", "thinning", and "fuel reduction" (Korb et al., 2007; O'Hara et al., 2010). Regrettably, the reintroduction of human disturbance to an already damaged system may be counterproductive (Brown et al., 2004). In many forest types, especially coast redwood forests, natural regenerative properties allow the development of old-growth characteristics over time without the need for additional active management.

Coast redwood forests have remarkable regenerative properties. They are resistant to fire, insects, and disease due to a high crown, thick insulating bark, and insect and fungi resistant secondary chemicals that permeate the bark and wood (McBride, 1977; Espinosa-Garcia, & Langenheim, 1991; Veirs, 1996;

Barbour et al., 2001). They are also highly resilient following disturbance due to prolific basal and epicormic sprouting (Sawyer et al., 2000; Douhovnikoff et al., 2004). Sprouting occurs when buds at the base of a tree, and under the bark throughout the bole of a tree, are released following disturbance (Roy, 1966; McBride, 1977; Sawyer et al., 2000; Barbour et al., 2001). This sprouting ability is rare among conifers, although it is present to a lesser extent in *Torreya californica* (California nutmeg), *Pinus sylvestris* (Scots pine), and *Taxus brevifolia* (pacific yew) (Dieguez-Aranda et al., 2005).

The ability to produce new shoots and roots from undifferentiated tissue is not only a disturbance survival mechanism, but also the primary reproductive strategy for *S. sempervirens* (Barbour et al., 2001; Douhovnikoff et al., 2004). The majority of reproduction takes place asexually resulting in a landscape populated by clonal groups. When a mature redwood is felled, due to natural or human causes, shoots are produced from the remaining stump. The shoots compete, but not in the traditional sense. Because *S. sempervirens* is a coppicing species, with shoots connected to a shared root system, individual shoots compete for apical dominance rather than for the survival of the organism (Kauppi et al., 1987; Burrows, 1990; Laureysens et al., 2003). As one shoot achieves dominance, other shoots begin to senesce (Sach et al., 1993) thinning the stand naturally. While *S. sempervirens* self-thins with facility, other coniferous forests face issues of over-crowding due to competition, which can lead to etiolation for individual trees and significant stand-level mortality due to reduced crown to height ratio and predisposition to insect and fungal attack (Floyd et al., 2009; Lutz & Halpern, 2006). Coast redwood forests are less susceptible to these dangers because regenerating tissue is connected to well established root systems, *S. sempervirens* is highly shade tolerant, and suppressed trees can increase their crown to height ratio when released through epicormic sprouting (Sawyer et al., 2000).

The regenerative properties of *S. sempervirens* have allowed foresters to manage second growth stands with minimal effort for decades (Fritz, 1945). These same properties suggest that a natural regenerative approach to restoration could be successful. However, though much work has been done on the effects of forest thinning in coast redwood forests (Cole, 1983; Chittick & Keyes, 2007; O'Hara et al., 2010), very little is known about the natural processes of recovery in the absence of continued human disturbance. This study was designed to address the question; will regenerating coast redwood forests develop structure and composition comparable to old-growth forest reference sites over time in the absence of post harvest management?

Methods

This analysis was conducted in the central and southern range of the coast redwood forest. Study sites were located in five State Parks in the Santa Cruz Mountains in California: Henry Cowell Redwood State Park, Butano State Park, Castle Rock State Park, Big Basin Redwood State Park, and Portola Redwood State Park. These parks support land use associated with eco-tourism such as camping, hiking, and fishing. Surrounding land uses, outside of the parks, include agriculture, small town residential, commercial development, and logging. The majority of the redwood forests in Santa Cruz county, including the five State Parks listed above, were heavily logged

in the second half of the 19th and early part of the 20th centuries. Within the State Park system these second-growth forests have been protected for the most part, and allowed to regenerate naturally.

Vegetation in the Santa Cruz Mountains consists of forests, chaparral, coastal scrub, and grasslands (Sawyer et al., 2000). In the forests, Douglas-fir (*Pseudotsuga menziesii*) and *S. sempervirens* typically make up the canopy trees and the understory is typically comprised of tan oak (*Notholithocarpus densiflorus*), coast live oak (*Quercus agrifolia*), interior live oak (*Quercus wislizeni*), and California bay (*Umbellularia californica*). The soils of the area are derived from the Franciscan assemblage, consisting mainly of sandstone and marine sediments, ideal conditions for redwood communities, which thrive on young, fertile soils with abundant nutrients and moderate pH levels (Zinke, 1988). Climate in the Santa Cruz Mountains is characterized as Mediterranean because of the predominantly mild, rainy winters and cool, dry summers (Lorimer et al., 2009). The climate of the southern range differs from the central and northern redwood region in precipitation levels which tend to be lower in the south, resulting in a longer dry season (Sawyer et al., 2000). Average annual precipitation in the Santa Cruz Mountains varies from the coast to inland. The coast averages 70 cm a year while the higher elevations receive up to 147 cm of precipitation per year.

Data Collection

Ten sites were selected including five old-growth reference sites and five recovering second-growth redwood sites between 80 and 160 years old, following the initial timber harvest. For inclusion in this study, each site was required to be dominated by *Sequoia sempervirens*, previously clear-cut, large enough for adequate sampling without edge effects (Russell & Jones, 2001), and must not have received post-harvest management such as seeding, thinning, or planting. Sites were selected using detailed timber harvest and land management history maps.

Twenty, 20 m diameter (0.031 ha), circular sample plots were randomly selected within each of the 10 study sites. Each sample plot was placed a minimum of 20 m from adjacent plots, 10 m from special habitats such as riparian areas and rock outcroppings, and 200 m from adjacent age class boundaries and main access roads. Plot size and sampling intensity were determined through a pilot study using the species-area curve method (Cain, 1938) and are consistent with previous research conducted in this forest type (Russell & Jones, 2001; Loya & Jules, 2007).

Data were collected on each plot to describe the composition and structure of the existing stand. Canopy cover (measured at waist height with a spherical crown densiometer), the occurrence and abundance of each tree species, the dbh (diameter at breast height) of all individuals greater than one meter in height, and the percent cover for all understory species, were recorded for each 20 m plot. Understory perennial and herbaceous species were sampled in three 2 m diameter sub-plots within each of the 160 tree plots (Figure 1).

Data Analysis

Linear regression analyses were conducted using SPSS for analysis of correlation with stand age. Second-growth characteristics that were significantly correlated to age the linear regres-

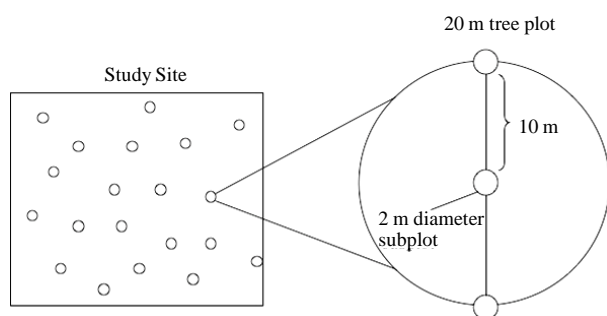


Figure 1. Sample plot configuration with 20 m diameter tree plot, and 2 m diameter nested understory sub-plots.

sion were graphed and compared to the old-growth average in order to determine the age at which the second-growth characteristic began trending towards or reached statistical equivalence with the old-growth reference average. T-tests were used to compare differences between age groups. The Levene's test was used to check the homogeneity of variances and the K-S test was conducted to check for normality of the data.

Results

Tree Density and Dominance

Regression analysis indicated that the combined density of trees was negatively correlated with stand-age ($R^2 = 0.113$, $p = 0.038$) suggesting a decline in the total stems/ha over time. In addition, the individual densities of several species were statistically equivalent between second-growth and old-growth reference sites (Table 1), including *Sequoia sempervirens* (coast redwood), *Aesculus californica* (California buckeye), *Corylus cornuta var. californica* (California hazelnut), and *Acer macrophyllum* (big leaf maple). In contrast, *Pseudotsuga menziesii* (Douglas fir), *Notholithocarpus densiflorus* (tanoak), and *Umbellularia californica* (California bay laurel) all had significantly higher densities in old-growth stands compared to second-growth, and *Quercus wislizenii* (interior oak), *Arbutus menziesii* (madrone) both exhibited lower densities in old-growth stands.

Sequoia sempervirens exhibited the highest relative dominance of all species in both second (87%) and old-growth (82%) stands, with marginally higher measures in the second-growth ($p = 0.002$) (Figure 2). However, average combined basal area in old-growth stands was significantly greater than in second-growth stands ($p < 0.001$). This pattern was repeated for individual species including *Sequoia sempervirens*, *Pseudotsuga menziesii*, and *Notholithocarpus densiflorus* ($p = 0.000$; $p = 0.000$; $p = 0.000$) suggesting that while the ratio of species within stands reached statistical equivalence with old-growth within the time frame of the chronosequence, total basal area did not.

Canopy and Understory Cover

Tree canopy cover exhibited a positive linear correlation ($p = 0.002$) with stand age and reached statistical equivalence with old-growth reference sites at 140 years (Figure 3). A high degree of variation between samples (52% - 91% in second-growth and 50% - 89% in old-growth) resulted in fairly low

Table 1.

The density of trees per ha in second-growth and old-growth coast redwood stands, including means and standard errors for nine tree species.

Tree Species	Second-growth		Old-growth		t-test $p =$
	Mean (stems/ha)	Std. error	Mean (stems/ha)	Std. error	
<i>Acer macrophyllum</i>	0.00	0.00	2.39	2.02	0.240
<i>Aesculus californica</i>	3.58	2.65	0.00	0.00	0.179
<i>Arbutus menziesii</i>	14.71	3.48	1.19	0.68	0.000
<i>Corylus cornuta var. californica</i>	3.58	1.96	0.80	0.56	0.174
<i>Notholithocarpus densiflorus</i>	197.16	33.67	674.56	73.10	0.000
<i>Pseudotsuga menziesii</i>	13.52	4.03	69.96	18.12	0.003
<i>Quercus wislizenii</i>	52.07	12.45	6.36	1.99	0.000
<i>Sequoia sempervirens</i>	674.56	44.51	515.16	85.63	0.101
<i>Umbellularia californica</i>	12.72	5.14	37.37	10.07	0.031

predictive power for the regression ($R^2 = 0.113$). However, this variation was consistent between old-growth and second-growth sites and appeared to be an indicator of natural stand complexity rather than an artifact of human management. The average cover of perennial shrubs was statistically equivalent between second-growth ($14\% \pm 1.346\%$ std. error) and old-growth ($16\% \pm 1.98\%$ std. error) stands ($p = 0.893$). The average cover of herbaceous species was also found to be statistically equivalent between second-growth ($5\% \pm 1.06\%$ std. error) and old-growth (7.88 ± 1.45 std. error) ($p = 0.963$) (Figure 4). Individually, the recovery of specific understory species was mixed. The recovery of *Trillium ovatum* (western wake robin), a perennial associated with old-growth forests, was incomplete with significantly lower cover found in second-growth compared to old-growth stands (Table 2). This was also true for *Viola sempervirens* (redwood violet), a shade tolerant herbaceous species closely associated with coast redwood forests. In contrast, three other species closely associated with coast redwood forests—*Oxalis oregana* (redwood sorrel), *Trientalis latifolia* (pacific starflower), and *Disporum hookeri* (Hooker's fairy bells)—reached levels of cover statistically equivalent to old-growth reference sites within recovering stands.

Total species richness was positively correlated with stand age in second-growth ($p = 0.000$, $R^2 = 0.43$), reaching old-growth equivalence at 100 years. However, there was greater variation in richness in second-growth stands (15.36 species/plot, 0.64 std. error) than in old-growth stands (10.33 species/plot, 0.46 std. error). Total understory species richness was also significantly correlated with stand age ($p = 0.000$) ($R^2 = 0.44$). Combined second-growth understory richness (11.78 species/plot, 0.57 std. error) was significantly higher than old-growth understory richness (7.36 species/plot, 0.45 std. error) ($p = 0.000$).

Shannon-Weaver diversity (evenness) was positively correlated with stand age ($p = 0.000$, $R^2 = 0.50$), indicating a trend toward old-growth conditions. The index did not reach old-growth equivalence however, and combined evenness was significantly higher in second-growth stands (1.63, 0.61 std. error) than old-growth stands (0.97, 0.57 = std. error).

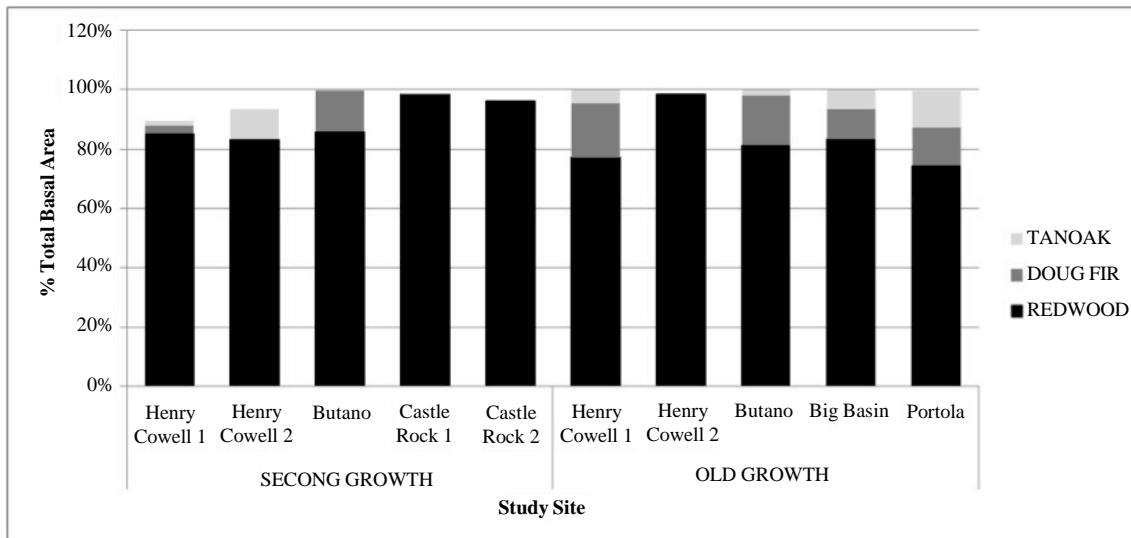


Figure 2. Relative dominance of the three most common tree species—*Sequoia sempervirens* (Coast Redwood), *Pseudotsuga menziesii* (Douglas-fir), and *Notholithocarpus densiflorus* (tanoak)—on ten sites in the Santa Cruz mountains.

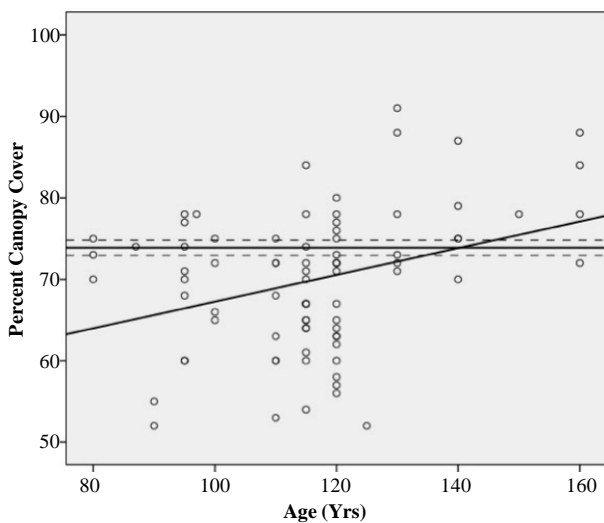


Figure 3. Linear Regression of percent canopy cover on a chronosequence of second-growth stands with old-growth percent canopy cover mean reference line and standard error confidence band.

Conclusion

The results of this study indicate that natural recovery is an effective technique for the restoration of coast redwood forests. The overall density of trees declined over time in recovering stands reaching statistical equivalence with old-growth reference sites for most tree species. The dominance of *S. sempervirens* also reached statistical equivalence with old-growth, as did canopy cover, understory cover, and species richness. Associated herbaceous species also trended toward recovery, though the cover of some species (*Trillium ovatum* and *Viola sempervirens*) did not reach statistical equivalence with old-growth reference sites in the time frame of this chronosequence. Active management tools such as stand thinning are counter indicated as they are generally employed as a restoration technique to

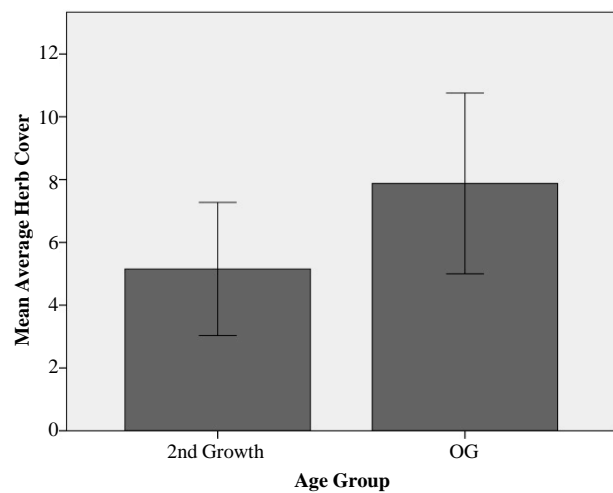


Figure 4. Mean averaged herb cover in coast redwood second-growth and old-growth stands with 95% confidence intervals.

reduce tree density in overstocked stands and to promote the dominance of desired species. Additionally, the added disturbance of mechanical thinning is likely to impact sensitive understory herbaceous species that are dependent on the moist shady environment provided by a mature forest canopy.

Discussion

Forest structure and composition on the chronosequence analyzed exhibited significant trends toward old-growth conditions for stand density, the relative dominance of *Sequoia sempervirens*, tree canopy cover, shrub cover, species richness, and total herbaceous cover. However, results were mixed for the shade-adapted understory species that are common in healthy coast redwood stands, with some recovering fully while others did not. This finding was concerning, though not unexpected. Previous research on a chronosequence in the central part of the

Table 2.

Means, standard errors, and *p*-values (paired t-test) of the percent cover of redwood associated understory species in second-growth and old-growth coast redwood stands.

	Second-growth		Old-growth		t-test <i>p</i> =
	Mean (% cover)	Std. error	Mean (% cover)	Std. error	
<i>Disporum hookeri</i>	0.14	0.06	0.06	0.02	0.217
<i>Oxalis oregana</i>	4.91	1.42	5.86	1.30	0.622
<i>Smilacina stellata</i> var. <i>sessifolia</i>	0.04	0.02	0.01	0.01	0.145
<i>Stachys bullata</i>	0.13	0.05	0.10	0.08	0.773
<i>Trientalis latifolia</i>	0.20	0.07	0.09	0.03	0.207
<i>Trillium ovatum</i>	0.27	0.05	0.56	0.35	0.008
<i>Viola sempervirens</i>	0.35	0.14	0.02	0.01	0.021
<i>Polystichum munitum</i>	2.80	0.50	2.25	0.50	0.416
<i>Pteridium aquilinum</i> var. <i>pubescens</i>	1.80	0.30	1.64	0.41	0.757
<i>Lonicera hispidula</i>	2.08	0.31	0.50	0.10	0.000

coast redwood range offered similar results (Russell & Michels, 2010). Overall, the arboreal features of the forest appeared to be quite resilient to human disturbance, while shade loving herbaceous species were not. With this in mind, implementation of mechanical restoration techniques, such as stand thinning, are counter indicated.

Mechanical disturbance in the form of stand thinning has been presented as an effective restoration technique for many forest types as a means of quickly returning stands to old-growth density levels (Boe, 1965; Bosch, 1971; Oliver et al., 1994; Brown et al., 2004; Lindquist, 2004; Smith et al., 2005; North et al., 2007). Such treatments can also increase the growth rate of selected trees through the removal of competing individuals thereby promoting the growth of large individual trees (Cole, 1983; Oliver et al., 1994; Lindquist, 2004; O'Hara et al., 2007).

In coast redwood forests, however, this model is not well applied, as regenerative clonal sprouts do not compete in the traditional sense. In addition, mechanical thinning can have unintended consequences. Removal of trees exposes the forest floor to increased levels of solar radiation (Kjeldsen-Ederer & Rivas, 1998; Russell & Jones, 2001) allowing opportunistic non-native species to colonize disturbed areas, and can alter soil conditions through compaction and reduction of nitrogen levels (Corns, 1988; Ebrecht & Schmidt, 2003; Jussy et al., 2004). Thinning has been shown to decrease epicormic sprouting response of coast redwood (Powers & Wiant, 1970; Cole, 1983) and allows for non-native shade intolerant species to persist in the community. In addition, stand density often increases in coast redwood stands a few years following thinning as a response to increased solar radiation (Russell & Jones, 2001), thus the effects of mechanical thinning are temporary.

The purpose of stand thinning as a restoration tool is to speed forest development in order to produce certain old-growth characteristics more quickly. However, the development of a forest with a dominant species, such as *Sequoia sempervirens*, that commonly persists for 1500 to 2000 years is a lengthy process. And though the temptation to manipulate a regenerating forest

so that management goals can be reached in a human time scale is compelling, the ecological costs of continued disturbance, particularly when using the same tools that caused the original damage, must be considered. The reason why some associated understory species reached old-growth equivalence, and others did not, is not clear. However, the answer likely relates to soil conditions and the relationships between plant roots and communities of soil microorganisms. Therefore, the protection of the soil from further human disturbance is essential so that natural soil development processes can occur. In addition, allowing natural processes to restore a system allows for stochastic factors to create stand complexity, while eliminating the simplifying influence of subjective human management.

Busing and Fujimori (2002; 2005) determined that small-scale natural disturbances and unmanaged processes of community development were sufficient for the regeneration of coast redwood forests. The results of this study support Busing and Fujimori's conclusions by providing quantitative data on the development of coast redwood stands over a significant period of time. For maximum effectiveness, the focus of restoration should shift from arboreal canopy species to the recovery of old-growth associated understory species, such as *Trillium ovatum*, that have been shown to be severely impacted through logging (Jules & Rathcke, 1999).

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