

Modeling Coast Redwood Variable Retention Management Regimes¹

John-Pascal Berrill² and Kevin O'Hara³

Abstract

Variable retention is a flexible silvicultural system that provides forest managers with an alternative to clearcutting. While much of the standing volume is removed in one harvesting operation, residual stems are retained to provide structural complexity and wildlife habitat functions, or to accrue volume before removal during subsequent stand entries. The residual overstory trees and the new understory cohort will have different growth rates, and should therefore be modeled as distinct stand components. We used the redwood MASAM (multiaged stocking assessment model) to predict the growth of overstory and understory cohorts within pure coast redwood (*Sequoia sempervirens*) stands managed under dispersed variable retention management regimes. A range of overstory densities were simulated, and compared with an even-aged stand in terms of stand growth, and the growth and yield of each stand component. Results showed that overstory density had a minor influence on stand volume production, and a major influence on volume increment within overstory and understory cohorts. As overstory density increased, less growing space was available to the understory cohort. Too few data were available to model a combination of redwood and Douglas-fir. The redwood MASAM does not consider the spatial arrangement of stems, preventing comparison of aggregated and dispersed variable retention.

Key words: coast redwood, growth and yield, leaf area, variable retention

Introduction

The variable retention harvest system is a flexible silvicultural method that offers some continuity of forest ecosystem processes and structural diversity. It may represent a viable alternative to clearcutting in young coast redwood forests of north coastal California. The objective of this study was to predict coast redwood stand growth and yield under variable retention management. The redwood MASAM (multiaged stocking assessment model) was used to demonstrate the influence of density, one of the major variables that define a variable retention harvest system, on growth and yield.

The variable retention harvest system has been defined as “an approach to harvesting based on the retention of structural elements or biological legacies (trees, snags, logs, and so forth) from the harvested stand for integration into the new stand

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² Division of Ecosystem Sciences, Dept. of Environmental Science, Policy and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, (510) 643-2025. email: pberrill@nature.berkeley.edu

³ Division of Ecosystem Sciences, Dept. of Environmental Science, Policy and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, (510) 642-2127. email: ohara@nature.berkeley.edu

to achieve various ecological objectives...the major variables in the variable retention harvest system are types, densities, and spatial arrangement of retained structures; aggregated retention is the retention of structures or biological legacies as (typically) small, intact forest patches within the harvest unit; dispersed retention is the retention of structures or biological legacies in a dispersed or uniform pattern” (Helms 1998). The residual overstory trees and the new understory cohort initiated by the partial harvest treatment will occupy different amounts of growing space, grow at different rates, and should therefore be modeled as distinct stand components.

The multiaged stocking assessment model for coast redwood stands (redwood MASAM) was developed with data collected from young coast redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirbel) Franco) trees on Jackson Demonstration State Forest, Mendocino County, north coastal California (Berrill 2003). The model was developed with breast-height increment core data consisting of age (20 to 100 years), diameter growth and sapwood area data. Tree leaf area, the key explanatory variable, was predicted from sapwood area, and regressed against tree volume increment and basal area data (Berrill 2003).

The redwood MASAM model predicts volume increment and tree size of distinct stand components (species within canopy strata) in multiaged stands. Growth and yield is predicted over one even-aged rotation or one cutting cycle under multiaged management. The model user must define the density of each species within each canopy strata, and the growing space (as represented by projected leaf area) allocated to, or occupied by each stand component at harvest. All or part of each stand component is harvested at the end of the cutting cycle (the time between partial harvests under multiaged management), when stand leaf area index (LAI) returns to the user-defined maximum. Volume increment is predicted from average tree leaf area in each cohort, which is assumed to increase linearly over the cutting cycle (*fig. 1*).

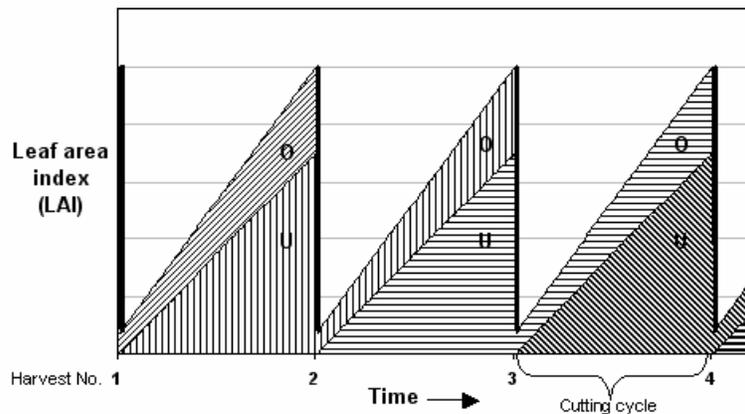


Figure 1—Schematic diagram of stand dynamics under variable retention management, showing theoretical overstory (O) and understory (U) leaf area index (LAI) over time between successive partial harvests. Harvesting involves removal of all overstory stems, and understory stems not needed to replace overstory. Each cohort has unique shading, showing that some understory stems are retained during partial harvesting at the end of each cutting cycle, becoming overstory stems over the next cutting cycle. This example depicts approximately 10 percent retention. Note: LAI increase assumed linear over the cutting cycle, however tree size and volume growth may not be linear.

O’Hara and others (2003) used the ponderosa pine MASAM to model multiaged ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stand growth, including management for pre-settlement structures with numerous large overstory trees and sparse regeneration. The main advantages of the MASAM approach are that (a) growth of each stand component is predicted separately in accordance with the different growth rates and growing space availability of each component, and that (b) growth projections are constrained within the biologically realistic limits of maximum stand LAI.

The redwood MASAM does not consider the spatial arrangement of stems, preventing comparison of aggregated and dispersed variable retention. In this study, the redwood MASAM was used to evaluate the influence of overstory density on growth and yield under dispersed variable retention management, using tree size, leaf area and LAI data from Jackson Demonstration State Forest as user-defined model inputs.

Methods

Growth and yield under the variable retention harvest system was simulated using the redwood MASAM and data from sample plots on JDSF. Partial cutting in a pure even-aged redwood stand leaving up to 40 trees per acre (tpa) was simulated. A schematic diagram depicts the even-aged redwood stand before partial harvest, and early and late in the cutting cycle under variable retention management (*fig. 2*). Clearcutting at age 50 was also simulated for comparison. These simulations demonstrated the influence of overstory density under variable retention management on a 50-year even-aged rotation or variable retention cutting cycle. Diameter and age data from overstory trees in 46 sample plots on JDSF gave indicative estimates of dominant redwood tree size and age for each simulation.

The influence of overstory density was demonstrated by simulating a range of overstory densities while holding constant the harvest age and amount of growing space allocated to overstory and understory cohorts. This test assumed that trees would grow at the same rate when allocated the same amount of growing space, as represented by leaf area at the end of the cutting cycle.

The MASAM model was used to allocate growing space to emergent overstory trees at each density level tested (0, 5, 10, 20, 30, 40 tpa). The overstory trees were allocated enough growing space (represented by leaf area) at the end of the cutting cycle to attain 44 inches dbh. The remaining growing space was allocated to the understory cohort. The density of this cohort was adjusted until MASAM predictions showed that an average diameter of 24 inches could be attained once the allocated growing space was completely occupied at the end of the 50-year cutting cycle. Stand density index (SDI) was calculated as the sum of cohort SDIs obtained from MASAM predictions of average tree size at the end of the cutting cycle and the user-defined cohort density. Cohort SDI (SDI_C) was calculated for cohort i such that $SDI_{Ci} = D_{Ci} (Q_{Ci}/10)^{1.6}$ where D_{Ci} was the density and Q_{Ci} the quadratic mean diameter for cohort i (O’Hara and Valappil 1999).

The MASAM model predicted average cohort and stand volume increment over the cutting cycle at each level of overstory density tested. Harvest volume was calculated from harvested density and average stem volume at harvest for each cohort. Stem volume was predicted from a one-foot stump height to a five-inch

diameter top using a volume equation for young redwood (Wensel and Krumland 1983) and coefficients for JDSF (Griffen 1986) assuming a 100 ft site index (50 year base age; Wensel and Krumland 1986).

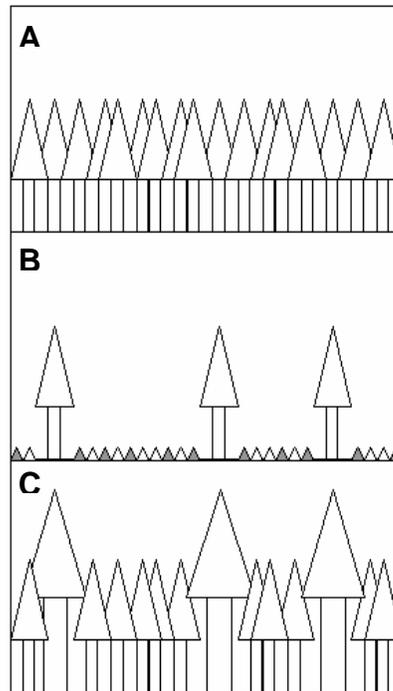


Figure 2—Schematic diagrams of even-aged stand (A) converted to multiaged stand managed under variable retention, early (B) and late (C) in the cutting cycle. Shading denotes removal of unwanted regeneration during pre-commercial thinning (PCT) of new understory cohort initiated after partial harvest removed most overstory stems (B). Crowns expand between successive partial harvests to re-occupy available growing space (C). Stems retained during partial harvesting have more leaf area and thus occupy more growing space per stem over the cutting cycle than trees in the understory cohort.

Results

The linear regression fitted to maximum tree diameter data indicated that widely-spaced emergent redwood trees could attain an average diameter of approximately 44 inches by age 100 years (*fig. 3*). The data suggested that a second cohort growing beneath the emergent overstory trees could attain approximately 24 inches diameter by age 50, provided that these trees were thinned (for example, *fig. 2b*) to give each tree adequate growing space to maintain dominance or codominance within the cohort until harvest (*fig. 3*).

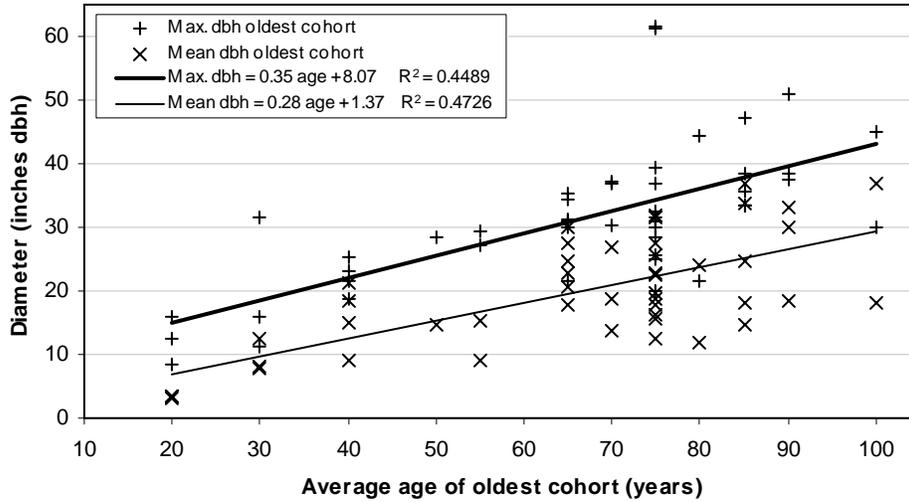


Figure 3—Average and maximum diameter (inches dbh), and average breast-height age (years) of the oldest cohort in 46 sample plots on JDSF. Note: density of oldest cohort ranged from 100-2600 tpa (age 20 to 40 yrs) and 18 to 600 tpa (age 50 to 100 yrs).

When more overstory trees were retained during partial harvesting of the even-aged redwood stand at age 50, less growing space was available to the understory cohort initiated by harvesting. Across the range of overstory densities tested, precommercial thinning in the understory cohort reduced density to leave the same amount of growing space for each stem, in other words, higher overstory densities resulted in lower densities in the understory cohort, while stand-level SDI remained approximately equal (*table 1*).

Table 1—Component and stand-level density and predicted stand density index (SDI) for variable retention management regimes with a 50-year cutting cycle. Stand harvested at end of cutting cycle (ECC) once LAI attained 14 ft²/ft², yielding overstory stems with average 44-inch dbh and 7600 ft²/tree leaf area, and 24-inch dbh stems in understory cohort with 2750 ft²/tree leaf area at harvest. Dominant heights of 150 ft and 100 ft at harvest for overstory stems and understory cohort respectively assuming 100-ft site index (dominant height at breast-height age 50 years).

Density (trees per acre)			Harvest SDI (ECC)		
Overstory	Understory	Stand	Overstory	Understory	Stand
0	225	225	0	910	910
5	210	215	53	853	906
10	200	210	107	798	905
20	170	190	213	683	897
30	140	170	320	569	889
40	110	150	427	454	881

Predictions of cohort volume increment over the cutting cycle showed that higher overstory densities resulted in marginally greater stand volume increments, higher overstory cohort increment and lower volume increment in the understory cohort. The same trends were more pronounced when harvest volumes were

calculated for each cohort across the range of densities tested (*fig. 4*). Overstory cohort harvest volume increased relatively more than volume increment because among fewer stems present in the understory, more were retained as overstory trees. At the end of the 50-year cutting cycle, the large overstory tree crowns occupied approximately three times as much growing space (in terms of leaf area) as individual crowns of understory trees.

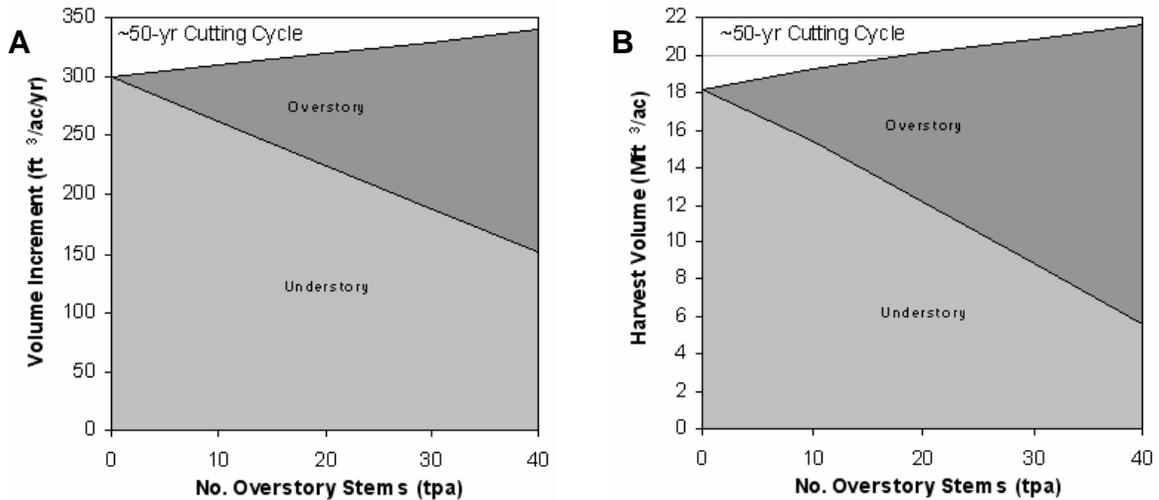


Figure 4—Redwood stand component (overstory and understory cohorts) (A) average annual volume increment in cubic feet per acre and (B) approximate harvest volume (ft³/acre÷1000) under variable retention management on a 50-year cutting cycle. Site index = 100ft. Maximum stand LAI = 14 ft²/ft². Average tree dimensions at end of cutting cycle, for (i) overstory trees: 44-inch dbh, 150ft height, projected leaf area = 7600 ft²/tree; and (ii) understory trees: 24-inch dbh, 100ft height, leaf area = 2750 ft²/tree.

The emergent tree volume increment model in MASAM predicted lower growth efficiency (volume increment per unit of leaf area) than the main canopy model used to predict the volume increment of the understory cohort with smaller branches and crowns. However, overstory volume increment over the cutting cycle was still greater per unit of occupied growing space at the end of the cutting cycle because the overstory trees had considerable leaf area (and thus produced considerable volume) at the beginning of the cutting cycle. Conversely, the new understory cohort initiated by harvesting was assumed to have no leaf area at the beginning of the cutting cycle, and was therefore predicted to produce little volume early in the cutting cycle.

Discussion

Coast redwood tree and stand volume growth were positively correlated with tree leaf area and stand LAI respectively on Jackson Demonstration State Forest (Berrill 2003). The relationship between leaf area and volume production explains greater productivity predicted at higher overstory densities in coast redwood stands under variable retention management. By retaining trees (and therefore leaf area) at the end of the cutting cycle, some level of volume production is sustained continuously over successive cutting cycles (*fig. 1*). By contrast, even-aged stand

volume production ceases when all leaf area is removed during clearcutting and resumes slowly during the next rotation as stand leaf area develops. This difference explains the lower stand volume production predicted under even-aged management than under variable retention, where the productivity advantage of maintaining some continuity of growing space occupancy and canopy cover increases as more trees are retained at harvest.

Dagley and O’Hara (2003) compiled density data from old growth redwood stands, reporting overstory densities ranging from about 20 to 150 tpa. These large old growth stems in the overstory probably occupied most available growing space. If, for example, 25 trees on one acre of old growth forest collectively carried $15\text{ft}^2/\text{ft}^2$ of leaf area, the average crown would have $26,136\text{ ft}^2$ of projected leaf area. Similarly, if 50 trees collectively carried $15\text{ft}^2/\text{ft}^2$ of leaf area, the average crown would have $13,068\text{ ft}^2$ of projected leaf area, although the larger stems probably have much more. The largest leaf area estimate for second growth trees on JDSF was $12,050\text{ ft}^2$. It follows that around 55 trees of this size would also occupy most available growing space on any given acre if the upper limit of available growing space was assumed to be $15\text{ft}^2/\text{ft}^2$ of leaf area (a stand LAI of 15). When overstory trees occupy most available growing space, the growth of understory cohorts would be restricted. Thus, care must be paid to design structures with adequate end-of-cutting cycle growing space for all cohorts. If harvesting was delayed, or ultimately if residual overstory trees were retained over successive cutting cycles, leaf area in subordinate cohorts would be ceded to the overstory as a result of competition for limited growing space.

The redwood MASAM was formulated to predict growth and yield in pure stands and mixtures of redwood and Douglas-fir. However, the sampling strategy used for MASAM model development did not capture many Douglas-fir trees. Thus, while the regressions within the Douglas-fir component of the model were correctly estimated given the data at hand, there is much uncertainty around the estimates leading to uncertainty in predictions of growth and yield. It must be assigned a high priority for validation and revision once more data are obtained. The results of the simulations presented herein depended largely on accurate estimates of average tree size at harvest (*fig. 3*). Too few data were available to obtain reliable estimates of average Douglas-fir tree size at harvest. MASAM predictions are also sensitive to changes in stand LAI at harvest. In this study, maximum LAI was defined as $14\text{ft}^2/\text{ft}^2$, slightly below the largest estimate ($14.9\text{ft}^2/\text{ft}^2$) obtained in 42 sample plots on Jackson Demonstration State Forest (Berrill 2003). More information on residual overstory tree mortality and maximum LAI within species mixtures is also required before mixed stand development can be simulated with any confidence. The redwood MASAM model could also be improved by adding components for other tree species in coast redwood forests, for example, tanoak (*Lithocarpus densiflorus*).

The redwood MASAM is a stand component-level model that does not explicitly consider the spatial arrangement of stems. The results presented herein assumed a dispersed form of variable retention. Aggregated groups of residual overstory trees should occupy less growing space per stem at harvest, leaving more growing space for the understory cohort. This effect could theoretically be modeled with MASAM by reducing growing space allocation to overstory stems that will be crowded and competing for growing space within aggregated groups, but would have no scientific basis without information on the spatial patterns and growing space occupancy of aggregated groups of trees. More data from groups of residual

overstory stems are needed to quantify this response, which likely differs between interior and edge tree positions, or as a function of proximity to the group edge. In theory, stands managed under aggregated retention should produce less volume from overstory stems and more from the understory cohort than stands managed under dispersed retention, for a given density and cutting cycle length.

The influence of density in the overstory cohort on stand component volume increment and harvest volume will depend on the size, condition and spatial arrangement of the overstory stems. Smaller overstory stems and tree crowns will produce less volume, but occupy less growing space, leaving more growing space for the understory cohort. More data are needed to understand growth efficiency among stump sprouts sharing root systems, within groups of aggregated retention trees, and within species mixtures. The influence of the amount and spatial arrangement of overstory leaf area on growth of trees in the understory cohort must also be assessed over the entire cutting cycle under variable retention management.

Conclusion

The redwood MASAM simulations showed that overstory density was predicted to have a minor influence on stand volume production, and a major influence on volume increment of the overstory and understory cohorts. As overstory density increased, less growing space was available to the understory cohort. Additionally, fewer stems were harvested from the understory cohort since more stems were retained as overstory trees over the next cutting cycle. The flexibility of the MASAM approach allowed simulation of differing levels of growing space occupancy by overstory and understory cohorts under a range of dispersed variable retention management regimes. The user-defined maximum stand LAI constrained model projections within realistic biological limits. More data are required before growth and yield under aggregated variable retention, and within species mixtures can be predicted with any confidence.

Acknowledgements

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