Using FORSEE and Continuous Forest Inventory Information to Evaluate Implementation of Uneven-aged Management in Santa Cruz County Coast Redwood Forests[1]

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Abstract

Swanton Pacific Ranch in northern Santa Cruz County has been owned and managed by California Polytechnic State University (Cal Poly) Foundation since 1987. The California Forest Practice Rules specific to Santa Cruz County limit harvest rate and opening size. Cal Poly forest managers are implementing uneven-aged forest management on 1,182 acres of 80 to 110 year old, second-growth coast redwood forests using a modified BDq approach. The Lockheed Fire spread into most of the managed forest area during the summer of 2009 causing significant mortality in lower diameter classes.

Little information is available on implementation of uneven-aged forest management for coast redwood stands in Santa Cruz County especially regarding the influence of fire. This McIntire Stennis funded, observational research study used the Forest and Stand Evaluation Environment (FORSEE) program and a 22 year Continuous Forest Inventory (CFI) record to evaluate changes in past and current stand structure using trees per acre, basal area per acre, and volume per acre. Stand structural changes associated with uneven-aged management and disturbance were detected using FORSEE analysis of the CFI records. FORSEE is a useful inventory, growth and yield model that will become better with local calibration.

Key words: *Sequoia sempervirens*, coast redwood, multi-aged, BDq, FORSEE, growth and yield model, fire effects, monitoring, Santa Cruz County

Introduction

Forest management at California Polytechnic State University's Swanton Pacific Ranch and School Forest began in 1986 when owner Mr. Al Smith, requested Cal Poly assistance with management of his agricultural and forested properties which he bequeathed to Cal Poly in 1993. Mr. Smith's long-term vision focused on Swanton

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[1] This paper is dedicated to Mr. Smith who bequeathed Swanton Pacific Ranch to Cal Poly so that we could have a place for students, faculty, and staff to learn by doing.

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Pacific Ranch being sustainably managed as a working ranch and forest with many interdisciplinary learn-by-doing activities and projects involving students, staff and faculty.

Swanton Pacific Ranch is located in the southern sub-district of the Coast District (Cal Fire 2011). Very strict forest practice rules have been developed for this district due to citizen concerns about the extensive clearcut logging that occurred in the early 1900s to help rebuild San Francisco after the 1907 earthquake. These current, sub-district California Forest Practice Rules specify tree removal limits by diameter class, maximum permitted opening size, and Water Lake Protection Zone requirements.

In consultation with Big Creek Lumber Company and other forest managers, sustainable management of the working forest areas was approached through implementation of uneven-aged, modified BDq forest management practices as discussed in the 1991 forest management plan (Alexander and Edminster 1977, Baker et al. 1996, Big Creek and Cal Poly 1991, de Liocourt 1898, Guldin 1991, Leak and Gottsacker 1985, Marquis et al. 1992, Meyer 1943, Meyer 1952, O'Hara and Gersonde 2004). Two presentations at earlier Redwood Symposiums focused on initiation of forest management practices at Swanton Pacific Ranch (Piirto et al. 1996b, Piirto et al. 2007). Further, a paper on approaches to managing tanoak at the Cal Poly's Swanton Pacific Ranch was presented at the 1996 California Oak Symposium (Piirto et al. 1996a). Current forest management at Swanton Pacific Ranch is guided by the 2008 Non-Industrial Timber Management Plan (Big Creek and Cal Poly 2008).

Forest managers must consider human and ecological legacy as they develop management plans for a specific forested area. Fire, windstorms, landslides, and flooding are several examples of ecological disturbance processes that affect coast redwood forests. Fire has been reported as being a low to moderate disturbance factor that can ultimately lead to multi-aged coast redwood stands (Lorimer et al. 2009). The ecological role of fire in Santa Cruz Mountain coast redwood forests has been and continues to be the subject of a number of recent studies (Brown and Swetnam 1994, Greenlee and Langeheim 1990, Lorimer et al. 2009, Ramage et al. 2010, Stephens and Fry 2005, Stephens et al. 2004). A study by Hyytiainen and Haight (2010) reported that fire had differing effects in even-age stands (decreased optimal rotation lengths and planting densities) as contrasted to uneven-aged managed stands (reduced optimal diameter limits). The occurrence of the Lockheed Fire at Swanton Pacific Ranch in 2009 provided an opportunity to study the impact of fire on a forest under uneven-aged forest management.

Measuring key ecosystem attributes is fundamental to successful forest management. The application of ecosystem management principles requires understanding of past and present conditions (i.e., reference conditions) as desired future conditions are defined and adaptive forest management occurs (Manley et al. 1995, Piirto and Rogers 2002). Given these considerations, are we succeeding with implementation of uneven-aged forest management at Swanton Pacific Ranch? The objectives of this observational study were to:

1. Consolidate and standardize the 1989 initial forest inventory, the 1997, 2008, and 2010 (post-fire) Continuous Forest Inventory (CFI) data (*fig. 1*) into one database for use in FORSEE.
2. Utilize the inventory data and the FORSEE model to test two hypotheses:

a. Stand structural changes can be detected using a CFI System and a FORSEE Analysis Tool; and
b. Major disturbance events quantifiably influence establishment and survival of young age-classes in uneven-aged managed stands.

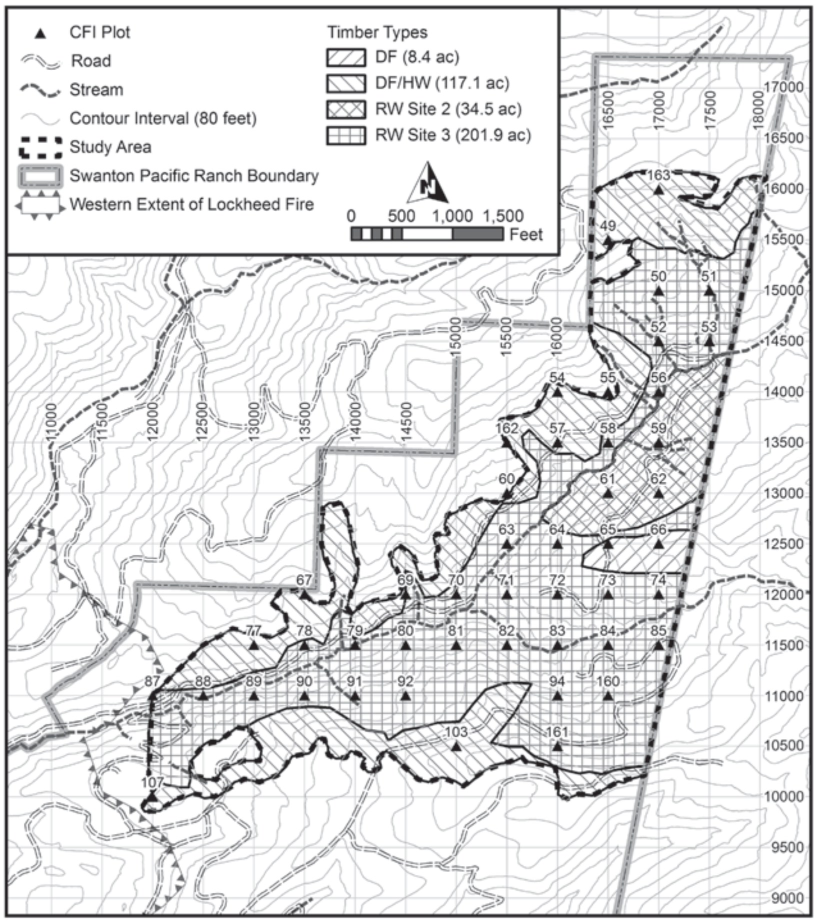

Figure 1—Swanton Pacific Ranch CFI plots and vegetation types in study area.

Methods

The process used to implement forest management, delineate the project area and map development, 1989 forest inventory methods, CFI methods (1997, 2008, 2010), data compilation, data auditing, data analysis, FORSEE calibration, and assumptions are described below.

Implementation of forest management

A modified, specified residual basal area in square feet (B), maximum retained diameter class (D), and negative exponential constant between diameter classes (q) (de Liocourt 1898, Guldin 1991, Leak and Gottsacker 1985, Meyer 1952) approach was employed to implement uneven-aged forest management at Swanton Pacific Ranch consistent with current California Forest Practice laws and associated regulations (Cal Fire 2011). Detailed prescription reports were developed for each of the stands in the Little Creek area of Swanton Pacific Ranch (Haupt and Piirto 2006, Piirto and Cross 1996 [revised 1999], Piirto and Piper 1990). Tree removal was guided by the tree marking rules with BDq adjustments made for specific stands.

Residual stand density basal area (B) target was set at 180 to 220 square feet per acre. This residual largely conifer stand density target was initially established as a percentage reduction of normal stocking as shown in Lindquist and Palley (1963) and Piirto et al. (1996b) consistent with expected growth for the next 10-year growing cycle. This basal area target range thus results in retaining 42 to 51 percent of full stocking if we assume that: 1) a Lindquist and Palley (1963) normal stand with a site index of 130 (site class III, base age 100 years) has 431 square feet and 2) that this Lindquist and Palley (1963) normal basal area value is a reasonable estimate of complete site occupancy for a 100 year old coast redwood stand. Recent work by Berrill and O’Hara (2009) and Oliver et al. (1992) discuss stocking control in multi-aged coast redwood stands.

The largest tree retained in the stand varied between 30 and 38 inches DBH in relation to individual stand objectives. Stand F (The Tranquility Stand), for example, was a favorite spot for Al Smith. He requested that we work to retain some of the larger second-growth trees in Stand F as part of the uneven-aged forest management objectives. As such, the maximum tree size in Stand F was set at 38 inches with retention of a few larger trees consistent with Mr. Smith’s direction. A maximum DBH tree size of 34 inches for uneven-aged managed stands provides good yield and a sizeable individual tree heartwood core which is important to lumber grades and associated value (Piirto and others 1996b).

The negative exponential constant (i.e., in 2 inch DBH classes) was set between 1.2 and 1.3 consistent with advice received from managers at Jackson Demonstration State Forest, Guldin (1991), and as described in Long and Daniels (1990). Further research by Berrill and O’Hara (2009) utilized growth and yield (CRYPTOS) and stocking assessment (redwood MASAM) models to simulate the effects of multi-aged coast redwood management regimes and harvesting scenarios. The timber harvest projects administered by Cal Poly and Big Creek Lumber Company since 1990 are shown in *table 1* (harvest/stand area maps are available upon request).

Study area delineation

The area delineated for this study was determined using the following criteria: 1) inventoried at least twice and preferably three separate times; 2) affected by at least one timber harvest activity since 1990; and 3) affected by the 2009 Lockheed Fire. The total area within the defined study area was 361 acres. Four forest vegetation types occur within the project area: Redwood Site Class III–202 acres; Redwood Site Class II–34 acres; Douglas-fir–8 acres; and Douglas-fir-Hardwood–117 acres. The project area, vegetation types, 1989 initial inventory plots, and 1997/2008/2010 CFI plots are illustrated in *fig. 1*.

Table 1—*Swanton Pacific Ranch Little Creek timber harvest projects (1990 to 2011).*

THP No. and Date	Location	Acreage	Logging system	Gross volume			Net volume			Defect (%)	
				Redwood	Douglas-fir	Total	Redwood	Douglas-fir	Total	Redwood	Douglas-fir
THP 1-89-539 SCR											
1990	South Fork	59	T	285,810	391,260	677,070	215,530	281,930	497,460	24	28
THP 1-94-071 SCR	North Fork	120									
1994			T, C	615,790	326,830	942,620	547,790	253,000	800,790	11	22
1995			T, C	578,810	274,490	853,300	500,240	207,330	707,570	14	24
Emergency Salvage											
1998	Little Creek	10	C	4,760	7,740	12,500	4,290	6,490	10,780	10	16
THP 1-04-053 SCR	Lower Little										
2004	Creek	102	T	588,350	82,280	670,630	495,290	57,320	552,610	16	30
1-07 NTMP-020 SCR											
2008 (NTO#1)	North Fork	143	T, C	847,480	22,620	870,100	742,990	13,950	756,940	12	38
2011 (NTO#2)	South Fork	65	H	652,110	46,510	698,620	548,419	32,093	580,512	16	38
Emergency Salvage											
1-10EM-006	Lockheed										
2010	Fire Area	148	H	838,440	20	838,460	700,010	20	700,030	17	0
			Totals	4,411,550	1,151,750	5,563,300	3,754,559	852,133	4,606,692		

Logging system: T = Tractor; C = Cable; H = Helicopter

1989 forest inventory

The forest resources of Cal Poly's Swanton Pacific Ranch were inventoried for the first time in 1989 to support development of a Forest Management Plan (Big Creek and Cal Poly 1991, Piper and others 1989). A 500 foot grid system was established in relation to a baseline and benchmark on Swanton Road at the Little Creek Bridge. Fifty-two circular 1/5th acre plots (radius 52.7 feet) were installed using a systematic approach at the intersecting points of the grid (Piper 1989, Todd 1988). Thirty-one of these plots in the upper Little Creek drainage affected both by timber harvesting and the Lockheed Fire were used for this study. This initial 1989 forest inventory was never intended to be a permanent CFI system even though it was set up on the 500 foot grid system.

1997, 2008, 2010 continuous forest inventories

A CFI system with permanently located plots on a 500 foot grid system was developed under the direction of Cal Poly faculty and staff in 1997. One-fifth acre circular plots have been established. Witness trees were selected and where possible GPS coordinates were established to assure proper follow-up measurement of all CFI plots. A report describing the specific protocol was developed by Sarah Cross (1997). The CFI system was installed in 1997 after the first timber harvest project in Little Creek. The results of the 1997 CFI plot measurements are discussed in a separate report (Bonner 1998). The CFI plots were re-measured in 2008 just after the second timber harvest project for the North Fork area had occurred. The CFI plots were subsequently evaluated 2 years later in 2010 after the 2009 Lockheed Fire to determine the extent of mortality that occurred. The 2008 CFI measurements are discussed in the 2008 Swanton Pacific Ranch Non-Industrial Timber Management Plan (Big Creek and Cal Poly 2008). The South Fork area was harvested for a second time in 2011.

Data compilation, data auditing, and data analysis

All inventory entries were converted into one spreadsheet template with consistent species designations, fields, notation and formats. Data were sorted by each field and verified with the original field notes where possible (Ali and Cody

2011). All edits and assumptions were annotated and are nested within the master spreadsheet. Tree, stand, and site data went through an integrated auditing process as it was imported into Access and uploaded to FORSEE.

FORSEE processing

The inventory data were compiled and analyzed using the FORest and Stand Evaluation Environment (FORSEE) computer program (CAGYM 2011). The CRYPTOS growth model option within FORSEE was used to model forest growth, as this model is appropriate for the coast redwood forest type (Wensel et al. 1987). All suitable site trees within the project area (dominant/co-dominant trees with no observable abnormalities and greater than 30 percent crown ratio) for both the 1997 and 2008 measurements were utilized to establish the initial site index value for the delineated project area (Cross 1997). The FORSEE calculated coast redwood site index (base age 50) came out to be 100 for this study (Krumland and Eng 2005) with a standard deviation of 10 which is considered to be an acceptable estimate. Estimates of site index (base age 100) based on Lindquist and Palley (1961, 1963) have ranged as low as 80 to a high of 200 with an average around 130 (Big Creek and Cal Poly 2008). Both of these average site index estimates fall into a Redwood Site Class III and are consistent with documented values (Big Creek and Cal Poly 2008).

The 1989 initial inventory, 1997, 2008, and 2009 post fire CFI inventories were processed and analyzed to evaluate stand attributes for: 1) all vegetation types (ALLTREES) over the entire 361 acres; 2) redwood vegetation types on site II (RW2) and site III (RW3) on 236.4 acres; and 3) Douglas-fir and hardwood vegetation types (DFHW). The Douglas-fir/hardwood timber type did not receive full evaluation due to high variability, significantly diminished sample size, and tendency for most forest management activities to occur in more productive vegetation types.

Results

The summarized information for the 1989 inventory and 1997, 2008, and 2010 CFI inventories are shown in *table 2*, and *figs. 2* and *3*. For the ALLTREES scenario, there was an overall reduction in quadratic mean diameter (QMD) from 16.09 inches in 1989 to 14.87 inches in 2008 with a subsequent increase following the 2009 Lockheed Fire to 18.91 inches. Trees per acre (TPA) increased from 154.84 in 1989 to 246.52 in 2008. Following the Lockheed Fire, TPA decreased by approximately 45 percent down to 136.83 with significant mortality occurring in trees 12 inches in diameter and smaller. Volume and basal area averages increased from 1989 to 2008. The percent standard errors for these per acre estimates are also shown in *table 2*.

Table 2—*Swanton Pacific Ranch FORSEE current status by inventory period for all vegetation types combined (361 acres).*

Inventory	Acres	Species Group	Plot Number	TPA	BA	QMD	BF/AC	CF/AC	% SE TPA	% SE BA	% SE BF/AC	% SE CF/AC
1989	361	Conifers	31	73.87	161.68	20.03	31,295	5,262	11	12	16	14
1989	361	Hardwoods	31	80.97	56.03	11.26	7,404	1,597	16	17	44	31
1989	361	Totals	31	154.84	217.72	16.06	38,699	6,859	9	9	14	12
1997	361	Conifers	33	122.12	191.63	16.96	42,930	6,927	9	8	12	11
1997	361	Hardwoods	33	106.82	67.90	10.80	10,387	2,268	22	16	26	21
1997	361	Totals	33	228.94	259.53	14.42	53,316	9,195	11	6	10	8
2008	361	Conifers	33	139.85	231.15	17.41	54,907	8,600	9	7	11	10
2008	361	Hardwoods	33	106.67	66.22	10.67	8,777	2,020	20	16	22	19
2008	361	Totals	33	246.52	297.37	14.87	63,683	10,620	10	6	9	7
2010	361	Conifers	30	81.50	209.60	21.71	51,789	8,044	12	9	13	11
2010	361	Hardwoods	30	55.33	57.32	13.78	8,545	1,930	16	16	22	20
2010	361	Totals	30	136.83	266.92	18.91	60,333	9,974	9	7	10	9

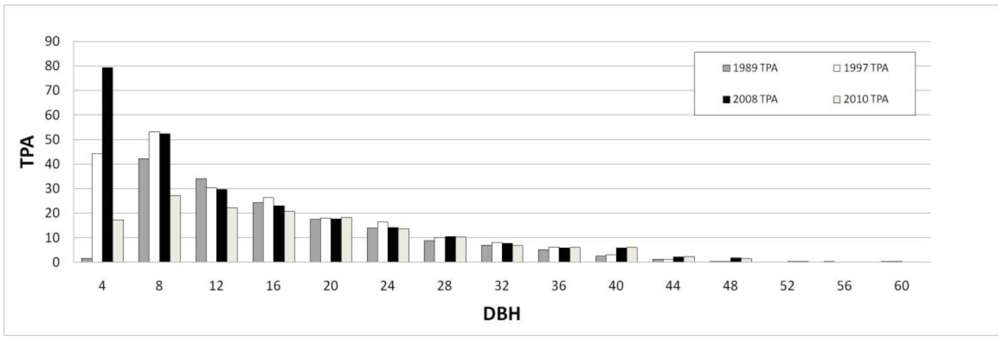

Figure 2—Stand structure for combined redwood site II and III vegetation types (includes hardwoods and conifers on 236.36 acres).

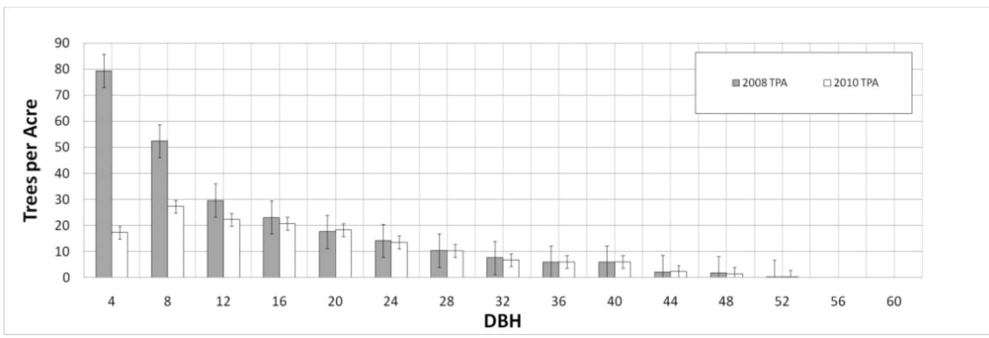

Figure 3—Stand structure for combined redwood site II and III vegetation types (236.36 acres). One standard error is illustrated.

The FORSEE current status analysis for the combined RW2 and RW3 (236.4 acres within the 361 acre project area) areas indicate a similar reduction in QMD from 17.35 to 15.28 inches from 1989 to 2008, and a subsequent increase to 19.05 inches following the Lockheed Fire (*table 3*). Trees per acre (TPA) for the combined

Table 3—*Swanton Pacific Ranch FORSEE current status for redwood vegetation types.*

Inventory	Acres	Species Group	Plot Number	TPA	BA	QMD	BF/AC	CF/AC	% SE TPA	% SE BA	% SE BF/AC	% SE CF/AC
1989	236.36	Conifers	20	87.50	213.05	21.13	45,301	7,467	11	9	13	12
1989	236.36	Hardwoods	20	71.25	47.71	11.08	4,158	1,105	19	23	32	31
1989	236.36	Totals	20	158.75	260.76	17.35	49,459	8,571	10	8	11	10
1997	236.36	Conifers	23	128.26	222.25	17.82	52,091	8,379	10	6	11	10
1997	236.36	Hardwoods	23	88.70	52.00	10.37	6,137	1,502	30	22	27	26
1997	236.36	Totals	23	216.96	274.25	15.22	58,228	9,880	13	5	9	8
2008	236.36	Conifers	23	154.57	263.02	17.66	65,587	10,215	9	6	9	8
2008	236.36	Hardwoods	23	95.43	55.28	10.31	6,945	1,641	26	23	30	28
2008	236.36	Totals	23	250.00	318.30	15.28	72,532	11,856	11	5	8	7
2010	236.36	Conifers	20	105.50	253.27	20.98	64,446	10,019	11	6	10	9
2010	236.36	Hardwoods	20	46.75	48.19	13.75	6,775	1,573	21	24	28	27
2010	236.36	Totals	20	152.25	301.46	19.05	71,221	11,592	9	5	8	7

RW2 and RW3 vegetation type showed a similar increase as the ALLTREES scenario going from 158.75 in 1989 to 250 trees in 2008 with a subsequent decrease in 2010 following the Lockheed Fire to 152.25. Increases in basal area and volume also occurred similar to the ALLTREES scenario from 1989 to 2008 with some reduction occurring after the Lockheed Fire. The percent standard errors for these per acre estimates are also shown in *table 3*.

The 1989 even-age stand structure prior to initiation of Cal Poly forest management is shown in *figs. 2* and *3*. Significant development of understory trees in the 2, 4, 6, 8, and 10 inch diameter classes leading to a reverse J shaped curve representation occurred after implementation of uneven-management which began in 1991. A subsequent reduction in the smaller diameter classes occurred after the Lockheed Fire *(tables 2* and *3*; *figs. 2* and *3*).

Discussion

A number of good lessons were learned as a result of this 25 year effort to initiate uneven-aged forest management at Cal Poly's Swanton Pacific Ranch in the truest sense of our motto of learn-by-doing. First, we did not have 1989 inventory and 1997, 2008, and 2010 CFI in one database. The four Swanton Pacific inventories were completed by different individuals and analyzed per procedures established for that inventory with a subsequent written or electronic report for each. Using FORSEE to evaluate and to predict how our stands were likely to change over time required that we: 1) put all data into one database in a consistent manner; 2) fully consider the appropriate volume equations for standing trees; 3) establish and adhere strictly to plot measurement and site tree selection protocols; and 4) delineate a project area in relation to the objectives of the study. All previously collected inventory information is now in one database for future studies.

Second, we have been collecting separate stand exam information to support individual stand prescriptions and associated marking rules. Whereas this stand specific data was useful for the prescriptions, it could not be used for monitoring purposes given that the plots were not permanently located. Thus, we decided to utilize 1997, 2008, and 2010 CFI inventory data to evaluate if reliable trends in stand structural changes could be detected from timber harvest and disturbance events such as the Lockheed Fire. We have shown here that our CFI system, when delineated to a defined project area, does provide reliable trend information. Both the stratified, combined (RW2 and RW3) and no vegetation type classifications (ALLTREES) show similar abilities to monitor changes in stand structure when there is a large sample of plots, though this threshold is far from being determined. Smaller stratification layers, such as the DFHW type, tend to exhibit larger variance due to smaller sample sizes. In essence, vegetation stratification needs to ensure statistically viable sample sizes in order to meet variance standards commonly used by the professional forestry community, but this requires a much broader study.

Third, we have defined in this study the significant changes in stand structure that resulted with implementation of uneven-aged forest management. Stand structure (refer *to tables 2* and *3*; *figs. 2* and *3*) in 2008 was approaching a regulated state in relation to the BDq targets discussed in Piirto et al. (1996b). The Lockheed Fire caused a substantial reduction in the recruited trees less than 12 inches. The extent of that mortality is illustrated in *figures 2* and *3*. It is clear that a void in the understory diameter classes less than 12 inches has resulted from the Lockheed Fire which will affect forest regulation. These results point out the difficulties and challenges foresters face as they implement, monitor, and adjust their uneven-aged forest management procedures.

Fourth, FORSEE requires the user to thoroughly and systematically audit potential errors and inconsistencies. Once data are prepared and successfully imported, the user can generate custom inventory reports and forecast growth and yield under different harvest scenarios. There is concern among some Swanton Pacific Ranch field foresters that results generated from FORSEE are overestimating current volume per acre from what is actually observed (Big Creek and Cal Poly 2008). This could be related to CFI sample size, plot location, the need for local calibration of volume equations or other factors. FORSEE must be validated for southern coast redwood stands. Additional fall-and-buck studies would validate or provide local coefficients for volume equations. CFI data could be used to validate growth model projections once more repeat measurements are collected. Further research is required.

Conclusions and management implications

Success of uneven-aged forest management in coast redwood stands is dependent on a number of factors in addition to land owner objectives and forest practice regulations. Uneven-aged forest management is as much an art as it is a science in determining the correct residual basal area (B), maximum retained diameter class (D), negative exponential constant between diameter classes (q), and cutting cycle length. Implementing stand management prescriptions via marking rules is complicated by coast redwood’s clumpy spatial distribution which results from coppice sprouting. In that context, we offer the following suggestions based on our 25 years of working and monitoring selection forestry.

Frequency and/or intensity of harvesting can profoundly affect success of coppice development (O’Hara and Gersonde 2004). Maintaining a continuous forest cover in terms of residual basal area stocking therefore must be tempered with site conditions, growing space considerations, harvesting impacts, risk of catastrophic fire, and landowner needs for recurring income. The highly varied nature of Santa Cruz Mountain redwood stands suggests a silvicultural prescription and associated marking rules that adaptively responds to these conditions. Knowing that deficits exist in lower DBH size classes should be considered in relation to leaving a few larger trees to cover that deficit on subsequent entries (modified BDq approach). Long-term success of uneven-aged forest management in coast redwood stands requires development of a documented prescription that describes 1) implementation of individual tree and/or group selection regeneration methods; 2) tree marking rules; 3) follow-up reforestation; 4) timber stand improvement treatments (for example, fuels treatment, site preparation, tanoak control); and 5) resource concerns.

There are a large number of complexities associated with implementing uneven-aged management in coast redwood stands. Much remains to be determined as to the "correct" approach for Santa Cruz County coast redwood stands. We suggest more research to: 1) regionalize FORSEE particularly with regard to southern coast redwood forests; 2) include biomass and carbon quantification as a component of FORSEE; 3) examine how uneven-aged managed coast redwood stands respond after a damaging fire to filling deficit diameter classes; and 4) examine how multi-aged coast redwood stands respond to various stand manipulation approaches.

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