Carbon Sequestration in Californian Forests;

Two Case Studies in Managed Watersheds

Report By

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Summary

This study was initiated by Sierra Pacific Industries to understand how various forms of forest management affect carbon sequestration over a 100-year planning period. Timber inventory data from two California watersheds, located within the mixed-conifer forest zone, were analyzed to: 1) quantify the total forest carbon pool within each watershed; 2) account for the carbon stored in the wood products harvested within the watersheds; and 3) track the carbon stored in the forest residue created by management activities.

Four scenarios were modeled to determine how different forest management approaches affect carbon sequestration within each watershed: Custodial; Option C Selection; Intensive; and Regulated timber harvests.

- Custodial harvest removes 1% of the basal area in a watershed per year.
- Option C Selection harvest reduces basal area 25%- 45% of initial stocking at 100 years, down to the minimum California Forest Practice Rules and relies on natural regeneration under California Option C sustained yield regulations[4].
- Intensive even-aged plantation silviculture harvests and reforests 12.5% of the land base per decade meeting California Forest Practice Rules Option A sustained yield regulations[5].
- A theoretical, fully Regulated forest with periodic harvests equal to periodic growth in a stable equilibrium over time.

In addition to examining how forest management relates to carbon storage in a watershed, the impacts of two different forest stand conditions and site quality were examined. The Upper San Antonio watershed (USAW) in Calaveras County is composed of older relatively well stocked stands on high site (trees are ~ 90 feet in height at a breast high age of 50 years). Canyon Creek watershed (CCW) in Shasta County has younger, moderately stocked stands of average site quality (~70 feet in height at a breast high age of 50 years).

Large differences in the forest carbon pool over the 100-year planning period were found between the four management scenarios within both watersheds. Stand age, initial stocking, and site productivity also influenced the overall amount of the forest carbon pool. Initially three

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[4] Option C Selection Management meets the requirements found in 14 CCR § 913.11(c)(2), 933.11(c)(2), 953.11(c)(2).

[5] Option A Even Aged Management meets the requirements found in 14 CCR § 913.11(a), 933.11(a), 953.11(a).

biomass models were used to estimate the forest carbon pool in both watersheds. All three biomass models showed similar patterns but had different levels of forest carbon pool yield over the hundred year planning period. Depending on which biomass model and forest management scenario was used in the analysis, the USAW forest carbon pool ranged from 100 to 165 tons of C/acre, CCW had 83 to 134 tons of C/acre at the end of the 100 year-planning period. Biomass model 2 was used for further data analysis because it was constructed using data from a California forest site whereas the other two models did not. The total forest carbon pool results derived from Live Biomass Model 2 by management scenarios are as follows: 1) the differences in the carbon pool yield curves are relatively the same between watersheds. 2) The Option C Selection management scenario has the lowest yield in the forest carbon pool over the 100-year planning period for both watersheds in the study. 3) Under the Custodial management scenario, the forest carbon pool in the USAW decreases over time and stays level in the CCW. This management scenario also does not appreciably increase forest carbon sequestration over time. 4) The forest carbon pool under the Intensive management scenario rises consistently throughout the entire planning period for both watersheds and is equal to the regulated management level in the last 2 decades.

Both watersheds show higher amounts of carbon sequestered when combining the forest carbon pool with carbon stored in wood products harvested within each watershed and carbon stored in harvest residue resulting from timber management activities. The total carbon pool yield is much higher when wood products and harvest residue are included as components of the total carbon pool. In the USAW the difference between the total carbon pool and the forest carbon pool is approximately 35 tons of C/acre for both the Custodial and Option C Selection management scenarios. The difference increases to 90 tons C/acre for the Intensive Management scenario and to over 150 tons C/acre for the Regulated Management scenario. In the CCW the difference between the total carbon pool and the forest carbon pool is about 15 tons C/acre for both the Custodial and Option C Selection management scenarios, and over 60 tons C/acre for the Intensive Management scenario. The difference is over 100 tons C/acre for the Regulated Management scenario. Intensively managed and regulated forests show substantial increases in the forest carbon pool and total carbon pool yield when compared to the other more extensive Option C Selection and Custodial management approaches.

The State of California’s Air Resources Board adopted California Climate Action Registry protocols (CCAR) in October 2007, establishing methods to calculate carbon credits for forestland owners. Current CCAR forest protocols require project carbon credits be calculated as *Additions* to the Option C Selection management baseline scenario. However, *only specified components of forest carbon pools* are used to calculate carbon credits: live biomass above ground, snags, and downed woody material.

To be consistent with the CCAR protocols, carbon *Additions* were calculated from the Intensive and Custodial management regimes relative to the baseline Option C Selection Management scenario, based on both the forest carbon pool and the total carbon pools at the end of the last decade of the planning period. The results are shown in Table S.1. When wood products and harvest residue are added to the forest carbon pool, the total carbon pool increases 166% in the USAW and 127% in the CCW. Clearly, not accounting for wood products and harvest residues when estimating carbon credits significantly under reports the amount of sequestered carbon.

Table S.1 *Additions* to carbon credits compared with Option C Selection management (CCAR baseline) by forest and total carbon pool basis at the end of the 10th decade.

Watershed	Management Scenario	Forest Carbon Pool based (Tons C/acre)	Total Carbon Pool based (Tons C/acre)	Percent Change from Forest to Total carbon pool basis
USAW	Intensive	35	95	+166%
USAW	Custodial	22	23	+5%
CCW	Intensive	33	75	+127%
CCW	Custodial	26	23	-7%

The results from this study demonstrate how forest management method, stand age, site quality, and including carbon stored in wood products and harvest residues can significantly increase estimates of the amount of carbon sequestered over a hundred-year planning period in California forests. This study details how the forest carbon pool, forest inventory, and biomass models used for carbon modeling were selected, and how the carbon stored in wood products and harvest residues were evaluated and tracked over time. Possible difficulties that may arise in analysis when quantifying carbon sequestration in California forests are also described.

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List of Abbreviations Used

BA	Basal Area
CCR	California Code of Regulations
CCAR	California Climate Action Registry
CCW	Canyon Creek Watershed, Shasta County, California
CFPR’s	California Forest Practice Rules
CVST	Cubic Stem Wood Volume – Includes stump and tree tops
CVT	Cubic Stem Wood Volume from stump to tree top
DBH	Diameter at Breast Height
LBM	Total Live Tree Biomass (weight)
LBMV	Total Live Tree Biomass (volume)
LTW	Long Term Wood
SPI	Sierra Pacific Industries
STEM	Total Stem Biomass
USAW	Upper San Antonio Creek Watershed, Calaveras County, California
WLPZ	Watercourse and Lake Protection Zone, CFPR’s 895.1

1. Introduction

In September 2004, the State of California published draft guidelines for the California Climate Action Registry (CCAR), a complex program designed to inventory and report carbon pools and emissions at the "entity" or participant level (California Health and Safety Code § 42800-42870). In October 2007, the California Air Resources Board adopted greenhouse gas accounting protocols for forest entities based on CCAR forest protocols. Although it is well known that forests play an important role in global carbon sequestration, it is not well known how different forest management strategies affect carbon pools and carbon sequestration rates across California's forest landscape. As a forestland owner with extensive information on the volume and growth of its forests, Sierra Pacific Industries (SPI) can provide meaningful data and analysis on carbon cycling and sequestration.

SPI is the largest private forest landowner in California, with 1.6 million acres of forestland and 16 manufacturing facilities. These forestlands provide high quality water, functional habitats for fisheries and wildlife resources, and recreational opportunities. This is accomplished in conjunction with the primary goal of growing high quality wood products on a sustainable basis. Figure 1.1 below shows SPI's forestland ownership and mill locations in California.

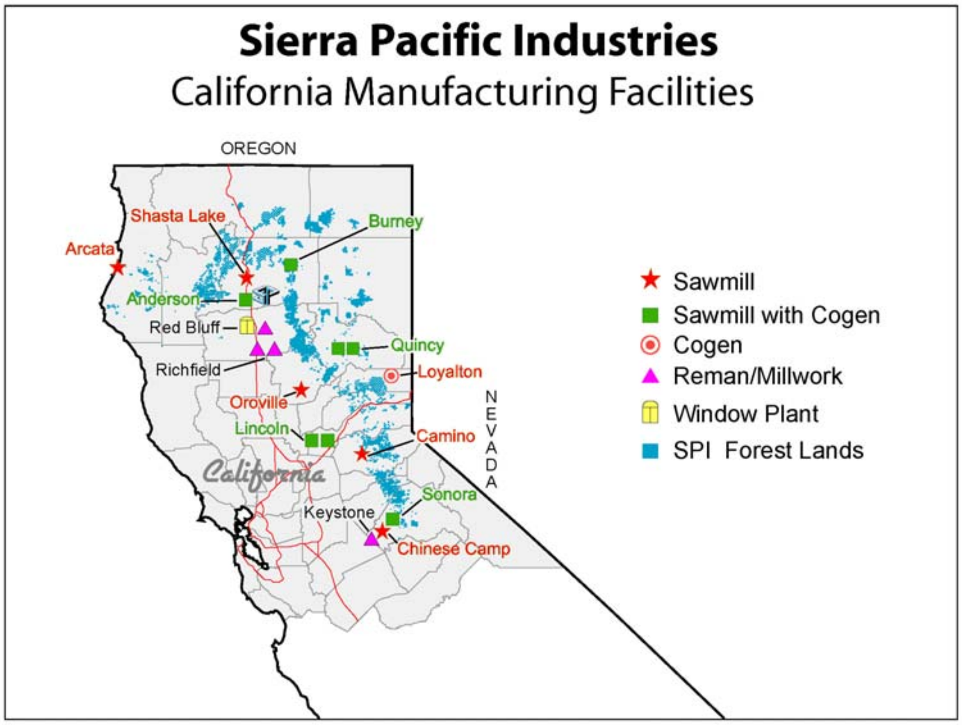


Figure 1.1 SPI's Forestland Ownership and Mill Locations within California

The objective of this study is to determine the best methods to quantify watershed scale carbon budgets over a 100-year sustained yield planning horizon for different management scenarios. This paper documents how carbon appraisals and budgets were determined, how carbon quantities change over a 100-year planning horizon, how different forest management practices influence rates of carbon sequestration and how to account for forest product removals and logging residues in order to create a more accurate assessment of forest carbon dynamics.

Results from this study provide information to regulators, forest landowners, and the public on forest management impacts to both the long-term and short-term forest carbon pools, the carbon stored in wood products manufactured from logs milled from California forests, and the decomposition rates of wood products in landfills. Information from this report also allows for assessment of the guidelines in the Air Resources Board's California Climate Action Registry with actual field-based forest carbon sequestration estimates.

The carbon sequestration case studies in this report use data from two forested watersheds in California: Upper San Antonio Creek and Canyon Creek. The first study area, Upper San Antonio Creek Watershed (USAW), is located in the central Sierra Nevada in Calaveras County. The second study area, Canyon Creek Watershed (CCW), is located in the southern Cascade Mountains in Shasta County. Both study areas contain private and public ownership and provide realistic examples of the differences in carbon sequestration based on four different forest management regimes within a relatively high and relatively lower productivity forest.

Actual forest inventory and manufacturing data were available for modeling efforts to track carbon sequestration over a 100-year planning horizon. Stand inventory data sets supplied by Sierra Pacific Industries were used to run forest growth simulation models to predict stand growth, yields, and harvests. Forest inventory data sets specific to the watershed allowed for better comparison than studies using regional or national averages to quantify carbon sequestration (Brown 2004b). We also analyze different amounts of carbon sequestration and timing of that sequestration as a result of different forest management scenarios on the same project area.

This study was designed to answer to the following questions:

- How many tons of carbon per acre will be present in the forest carbon pool in two different California watersheds over a 100-year planning horizon?
- How do total carbon pools compare for four different forest management scenarios on two California watersheds over a 100-year planning horizon?
- How much carbon remains sequestered in manufactured lumber products once timber is harvested from the forest?
- What are the relative contributions of forest carbon pool components, wood products, and residue from forest management activities on the total forest carbon pool?

- What are issues in using conventional forest growth and yield models to construct carbon budgets in California?

2. Carbon Budgets and Modeling Approaches

The primary analytical objective in the ensuing sections is to develop 10 successive 10-year carbon quantities (decadal state change in carbon sequestered) for the selected watersheds and management scenarios. A basic carbon budget modeling approach is formulated as a set of recursive decadal state change models that, in the most basic form, can be represented as

$$YC_{t+1} = YC_t + GC_t - EC_t$$

where t = decade, YC = **carbon** stocks (yields), GC = net decadal additions or **growth**, and EC = decadal losses or **emissions**.

In forest sites, carbon is stored as plant biomass (living and dead) or as soil carbon derived primarily from the decomposition of dead plant biomass. It appears to be generally accepted that the weight of carbon is fifty percent of the plant biomass on a dry weight basis (Smith et al., 2003; Brown et al. 2004b). This constant has been used throughout this study. Consequently, virtually all forest carbon related studies concentrate on measuring and estimating changes in plant biomass.

Table 2.1 shows forest carbon storage components researchers have identified and attempted to quantify in forest biomass and carbon sequestration studies. Actual site-specific amounts will vary by forest type, region, stage of development, management history, and a variety of other factors. The storage components represent all stages in the life and death cycle of trees, from germination to final decomposition/oxidation and return to the atmosphere as CO_2. It is important to note some of the listed gains and losses represent net sequestration and emissions while others represent transfers from one plant biomass source to another.

The 1997 Kyoto Protocols require accounting of greenhouse emissions from all sources. This has been interpreted to mean that total carbon pools originating from forest sources do not end at the forest boundaries. Plant biomass removed from forest sites must also be quantified as carbon in long-term wood products (LTW).

Table 2.1 Forest Carbon Budget Components

Carbon Storage Component	Sources of Additions	Sources of Losses	
Live Biomass			
Stem Wood	Natural growth processes Germination of new trees Planting tree seedlings	Bark sloughing	Tree mortality Harvests
Stem Bark			
Foliage		Dead leaf fall	
Branches		Self pruning	
Roots			
Dead Biomass			
Duff	Litter decomposition	Decomposition	
Litter	Bark sloughing Dead leaf fall Self pruning of snags and live trees Harvest leaves	Decomposition	
Large woody debris	Self pruning of snags and live trees Snag blow-down Harvests	Decomposition	
Snags	Tree mortality	Blowdown Decomposition	
Dead roots	Tree mortality Harvests	Decomposition	
Soil Carbon	Duff and root decomposition	Oxidation	
Off Site Products	Harvests	Decomposition Oxidation Land fill transfers	
Off Site Land Fills	Off site products	Decomposition	

2.1 Study Modeling Approach

This study concentrates on net changes in various carbon pools associated with the watersheds over 10 future decadal planning periods. Table 2.1 provides the conceptual basis for populating a system of accounting equations to create carbon budgets by looking at differences between carbon storage components of live biomass, dead biomass, soil carbon, off site products, and off site land fills. For practical accounting reasons, components were aggregated into groups that could be estimated directly and indirectly from the individual watershed inventories or where we were able to be reasonably estimated from published research. Table 2.2 shows the carbon sources we attempted to quantify and trace through the forest carbon cycle in the ensuing sections. The forest carbon pool is composed of live tree biomass (LBM), sub-tree biomass, dead biomass, and soil carbon, while the off site carbon pool is derived from wood products in service and retired wood products.

Table 2.2 Carbon sources

Carbon Component	Parameter	Description
Forest Carbon Pool		
Live Tree – LBM	STEM	Stem wood from ground to tree tip.
	CROWN	Foliage and branches (wood and bark)
	BARK	Stem bark from ground to tree tip
	ROOTS	Below ground root biomass – includes dead roots
Sub Tree Biomass	SHRUBS	Includes herbaceous plants and woody vegetation not considered to be trees.
Dead Biomass	FLOOR	Duff, leaf litter, and all other forms of dead plant biomass on the forest floor.
	SNAGS	Standing dead trees.
Soil Carbon	SOILC	Organic soil carbon
Harvests	HARV	Merchantable stem wood and bark (1-foot stump to a 6” top dib) removed from the site during logging operations as logs.
	HARVRES	Live biomass harvested but not removed from the site.
Off Site Carbon Pool		
Wood products in service	LTW	Long term wood products manufactured from harvested material into consumer goods.
Retired wood products	LFILL	Long term wood products that end up in land fills.

3. Description of Case Study Areas

SPI holdings are found throughout the forested regions of the Southern Cascade and Sierra Nevada mountain ranges in California, from near the Oregon border down to south central California. Two sample watersheds were chosen within SPI lands to allow for site-specific analysis. These two areas were chosen because SPI’s ownership is reasonably consolidated and is a significant part of each watershed. Both watersheds are comprised of productive forests that have attracted much interest over the years for mining, lumbering, recreation, and recently, vacation home sites. They contain all the elements of commercial forestland ownership at the urban-wildland interface in California. Both watersheds are mixed-conifer forests with ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Psuedotsuga menziesii*) dominating lower elevations and true fir (*Abies sp*.) dominating the higher elevations. Dry, south-facing slopes in the lower elevations may have some live oaks (*Quercus sp*.), while black oak (*Quercus kelloggii*) is the primary hardwood component.

The Upper San Antonio Creek watershed is located in the central Sierra Nevada between the towns of Arnold and Dorrington along Highway 4, northeast of Sonora, California, between 3,500 and 5,500 feet in elevation. Figure 3.1 shows the general location of the USA watershed within Calaveras County and also California. Annual precipitation is 45-55 inches, about half the amount occurring as snow during the winter. Summers are usually dry. USAW is part of the larger South Fork Calaveras River watershed, which is tributary to the San Joaquin River joining it at Stockton, California. The USAW’s 8,743 acres is a small part of southern Calaveras County, occupying only about 1.3 percent of the county land base. Figure 3.2 shows current land ownership in the USA watershed. Approximately 4,430 acres or 51 percent is in SPI ownership. The Stanislaus National Forest includes ~1860 acres or 21 percent of the USAW. Calaveras Big Trees State Park, mostly southeast of the watershed, is a small portion of parkland within the watershed, occupying ~950 acres or 11 percent of the USAW. Various small private landowners hold the remaining land within the watershed (~1,475 acres or 17 percent). The main human population concentrations in and just south of the USAW are the towns of Dorrington (population of 718 in 2000) and Arnold (population of 4,218 in 2000).

The Canyon Creek Watershed is located in the Southern Cascade mountain range between the towns of Shingletown and Manton, east of Redding California, between 2,200 and 8,200 feet in elevation. Annual precipitation ranges from 35-75 inches, about half the amount occurring as snow during the winter. Summer months are usually dry. The Canyon Creek Watershed is part of the larger Battle Creek Watershed, which is a tributary to the Sacramento River near Red Bluff, California. Figure 3.3 shows the general location of the Canyon Creek Watershed within Shasta County and California. The Canyon Creek Watershed occupies about 0.62% of Shasta County land base. Figure 3.4 shows current land ownership in the CCW. Approximately 10,340 acres or 67% is in SPI ownership, the Lassen National Forest includes about 3,325 acres or 22% and 11% is privately owned. This watershed is very remote and is located between State Highways 44 and 36.

Figure 3.1 General location of the USAW watershed within Calaveras County, California.

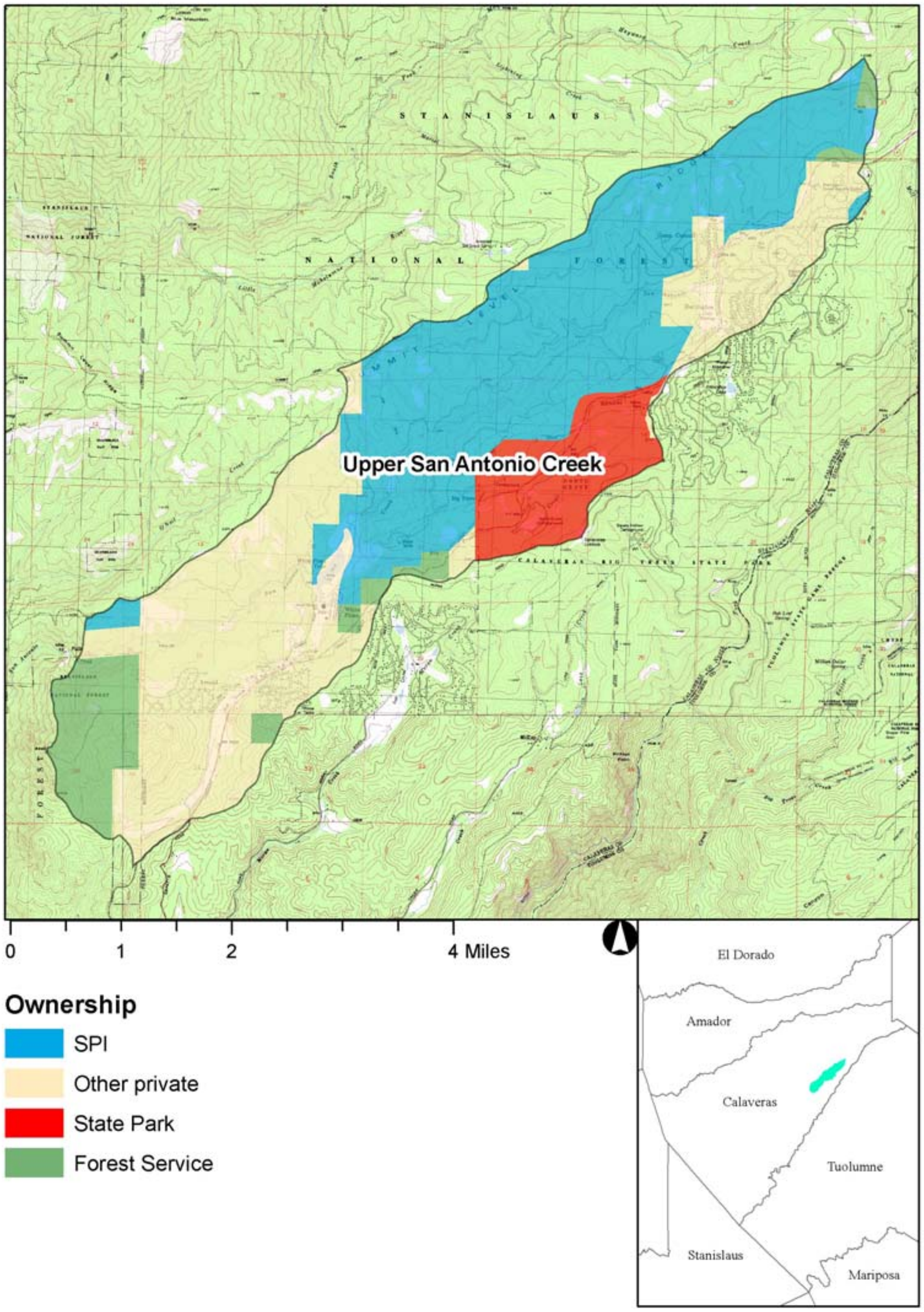


Figure 3.2 Current Land Ownership in the USAW

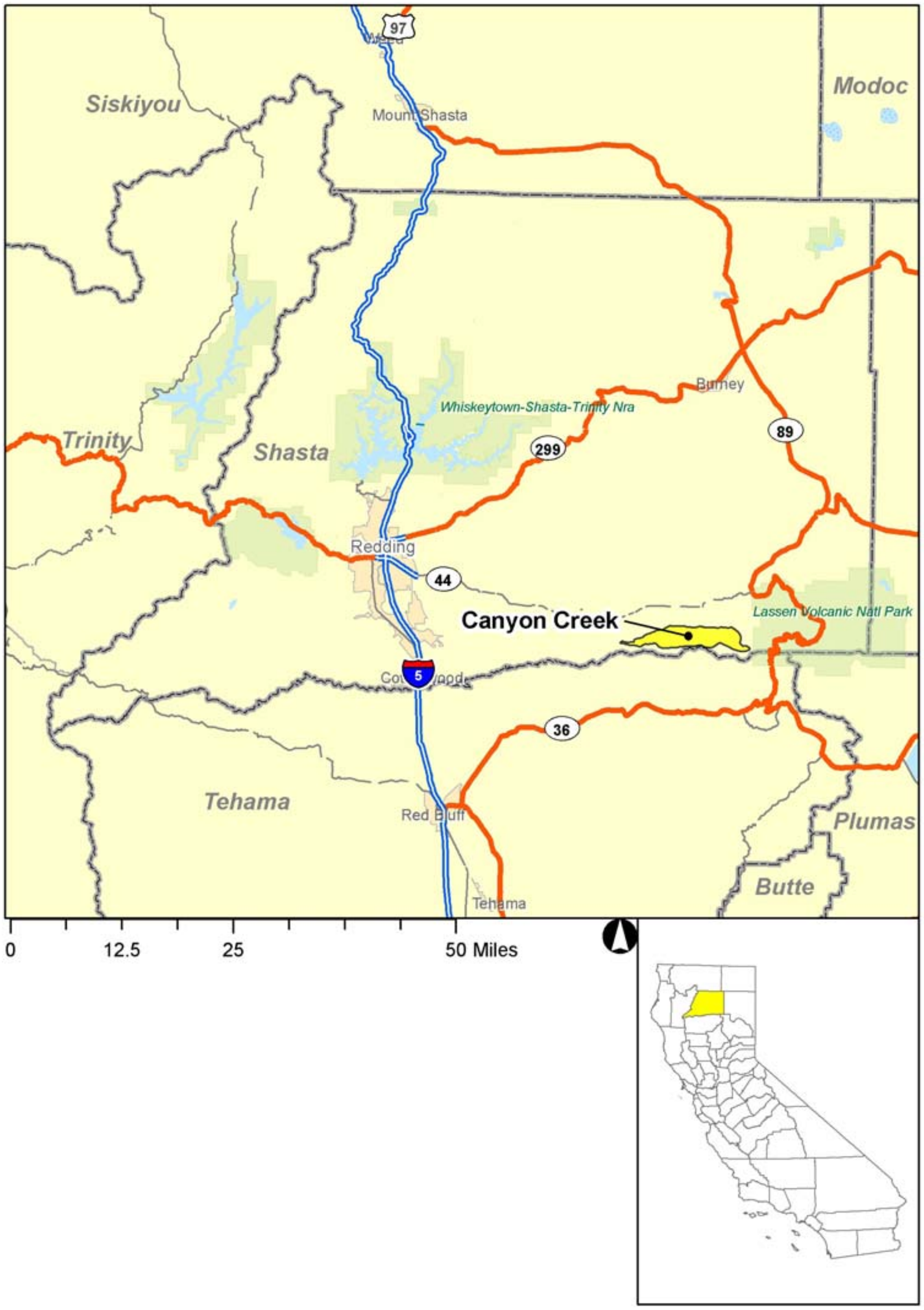


Figure 3.3 General location of the CCW watershed within Shasta County, California.

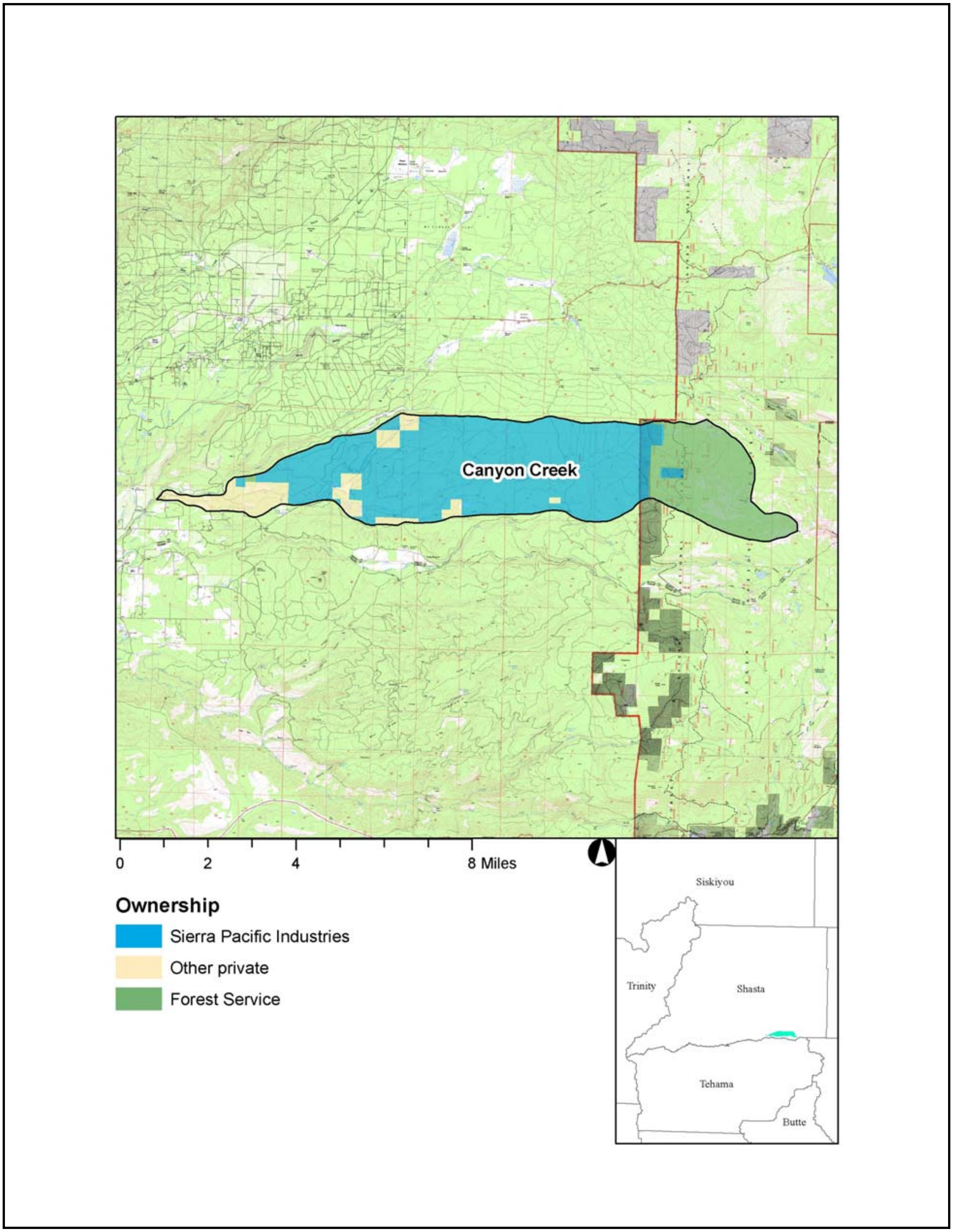


Figure 3.4 Current land ownership in the CCW.

4. Description of Data

4.1 Watershed Inventories

SPI maintains an intensive resource database of ground-based field plot measurements. This database is used for a variety of management analyses and was used in this study to produce initial inventory estimates and the starting basis for growth and yield forecasts.

SPI uses a grid-based sample design with a sample intensity of one ground plot every four acres. Ground plots are point samples with basal area factors of either 20 or 40 depending on the density of live trees. While a wide variety of information is collected at each point, we used primarily live tree and snag measurements. All live trees and snags over one in inch diameter outside bark 4.5 feet above the ground (DBH) were measured. Tree measurements included DBH, total height, live crown percent, species, and crown class (dominant, co-dominant, intermediate, and suppressed). Snag measurements included DBH, total height, and top diameter. In addition, suitable conifer site trees were sampled at a rate of approximately one tree bored per every two ground plots for breast-high age and subsequent site index determination. Both the USAW and CCW watersheds were last measured during the 1998 and 1999 field seasons. For clarity in presentation these measurement dates are both displayed as the year 2000.

Cubic volume of each live tree was computed using appropriate total height/DBH volume equations (Wensel and Olson, 1995). These equations predict stem wood volume from a one-foot stump to the tree tip (CVT). Adjustments to CVT for stump volume to get total stem wood volume (CVST) are described later. Snags were scaled as conic frustrums for cubic volume estimation

Plot data were stratified into ‘stands’ on the basis of basal area density, average breast-high age, and site index (Appendix I.). Stands are the primary units for subsequent growth and yield forecasting. Table 4.1 shows the species composition of the initial live tree and snag inventories in terms of basal area stocking (average outside bark cross sectional area of tree boles measured at 4.5 feet off the ground). Hardwoods are virtually all black oak (*Quercus kelloggii*)

Table 4.1 Initial watershed basal area stocking by live tree species and snags

Live Tree Species	**USAW (Basal Area %)**	**CCW (Basal Area %)**
White Fir	18	21
Ponderosa Pine	21	20
Sugar Pine	12	12
Incense-cedar	39	12
Douglas-fir	3	21
Hardwoods	7	14
Snags[1]	2	6

1/ Snag stocking is expressed as a percent of live tree stocking

Average stocking figures and related statistics are shown in table 4.2. Note that stocking figures are derived from stocked plots only.

Table 4.2 Average forest parameter estimates and related statistics by watershed

Parameter	Watershed	
	CCW	**USAW**
Total Inventory plots	1963	623
Acres Represented	7850	2495
Cubic feet (CVT)/acre of live trees	2526	4200
Cubic feet (CVT)/acre of Snags	119	320
Basal area (sq. feet)/acre	90	172
Average breast-high age of dominant and co-dominant trees	59	75
Average Site index (estimated total height at a breast-high age of 50 years)	71	89
Stocking percent[1]	79	91

1/ proportion of plots with one or more live tree

4.2 Growth and Yield

Carbon budget methods adopted in this study use cubic foot stem wood volume from a one-foot stump to tree tip (CVT) and basal area (BA) as base variables to predict subsequent carbon stocks and storage/emission dynamics. Initially, two tree list based growth models, CACTOS (Wensel et. al, 1986) and the Western Sierra Nevada variant of the United States Forest Service's Forest Vegetation Simulator (Ritchie, 1999), were used to predict future development of existing stands. These mixed-conifer models accept inventory data directly and were considered to be the most site-specific projection basis available. However, we concluded the yield scenarios adopted in following sections required projections substantially outside of the range of data used to construct the component prediction equations of the individual models. Neither of these models performed well. Consequently, we developed whole stand based models from raw data to be applied to existing stands and used SPI's plantation yield tables for regenerated stands. Details of the growth and yield analysis are provided in Appendix I. The primary stand variables derived from growth and yield forecasts and used as the basis for subsequent biomass forecasts are CVT and BA.

5. Management Scenarios

Both the CCW and USAW are being managed under an “Option A” Sustained Yield Plan allowed by the California Forest Practice Rules. Initially, we proposed to use the actual plans as a basis for developing carbon budgets. Numerous types of silvicultural treatments were prescribed for stands in these watersheds providing a range of options that could be used to evaluate the impacts of management on carbon sequestration. Subsequent evaluation indicated this plan of analysis would introduce additional levels of complexity that would detract from the central focus of this study and be difficult to quantify. Chief among them were a) site and initial stand stocking levels were significantly different by proposed management, b) selection management regimes were governed largely by regulatory considerations (WLPZ zones) and proximity to urban structures rather than silvicultural considerations, and c) numerous prescriptions were applied that could be considered sub-optimal in terms of growth maximization due to company imposed flow constraints and regulatory long term sustained yield considerations.

To eliminate these complexities from our analysis we decided the best solution was to group together the approximately 70% of the land base in both watersheds that were targeted for intensive management. Areas in buffer zones or with complex regulatory or biological restrictions on harvesting were excluded from further analysis. Although we recognize the land base we excluded for analysis contributes to forest carbon storage, we felt that the limitations of current growth and yield models prohibited us from adequately projecting future carbon yields for those areas. We subsequently developed four management scenarios that would each be applied uniformly to this land base during the 100-year plan period. These management scenarios are:

Custodial Management: Implement light selection harvests designed to maintain current stocking levels. A 20-year cutting cycle was used with half of the forest being harvested each decade. This amounted to a 20-25% basal area reduction at each harvest entry. This scenario is similar to the current USFS management approach where approximately 1% of the project area is harvested per year.

Option C Selection Management: Use selection harvests to reduce basal area stocking levels to the minimum allowed under the Option C maximum sustained production requirement of the California Forest Practice rules. This is the management option specified in the current California Climate Action Registry (CCAR) protocols to be used as a baseline. A 20-year cutting cycle was used for this option with half of the forest being harvested each decade. This option resulted in reducing basal area at the end of the plan period by 25% - 45% of initial stocking.

Intensive Management: Convert 12.5% of the land base to plantations each decade. This management scenario is based on an 80-year plantation rotation age. This is the age at which board foot mean annual increment is expected to culminate in SPI’s plantations. No harvesting operations of any kind (a ‘let grow’ front end) are applied to existing stands until they are converted to plantations.

Regulated Management: This hypothetical management scenario was created to track carbon over time in a regulated forest plantation. (one with equal areas of each age class). It assumes we have 8 different age-class plantations (ages 0-10, 10-20, … 70-80) currently occupying the forest. SPI's plantation yield tables were used to model this option.

6. Volume to Biomass Conversions

The live plant biomass modeling methods adopted in this study are based largely on estimates and forecasts of total stem biomass (STEM), which is the weight of the woody stem from ground level to the tree tip. Inventory statistics and forecasts of harvests, growth, and yield (See Appendix I) provide per acre estimates of stem wood cubic volume from a nominal one-foot stump to the tree tip (CVT) and basal area (BA). In this section, the necessary empirical relationships to estimate harvest and yield biomass from CVT and BA are developed.

6.1 Estimates of Stump Volume

Stump wood volume (cubic feet of wood volume from ground level to 1 foot above the ground) ranges from over 30% of CVT in small trees (1-2 inches DBH) to less than 2 - 3% in large trees. Wensel and Olson (1995) provide species specific models that can be used to estimate stump diameters from DBH measurements. With some manipulation, these models can be used to express stump volumes as a function of basal area. Weighted estimates based on the basal area proportions in Table 4.1 were developed. For both watersheds, we found that cubic foot wood volume in stumps could be expressed as 1.06 * BA. This value was used for all existing stands. For ponderosa pine singularly, the value was 1.03 * BA and was used for plantations.

6.2 Small Tree Harvest Components

Custodial partial harvests, clear-felling of existing stands, and pre-commercial thinning of plantations all involve removals of trees less than a nominal 'merchantable' size of 8 inches DBH. For this study we assumed all of the volume of pre-commercial plantation thinning is in tree sizes less than 8 inches DBH. We called this 'non-merchantable' and classified it as harvest residue. Commercial thinning and clear-felling of plantations are assumed to be in trees larger than 8 inches DBH.

Based on the current watershed inventories, stem wood volume in trees less than 8 inches DBH (CVTS8) were estimated to be 2.5% and 4% of the CVT for the USAW and CCW respectively.

6.3 Tree Tops

Logging removes tree boles from a one-foot stump to a nominal 6 inches top inside bark that forms the basis for the HARV biomass component. Using the original inventory data and tip estimators from Wensel and Olson (1995), we estimated the volume in tips of trees greater than or equal to 8 inches DBH to be 3.5% of CVT for both watersheds.

6.4 Bark Volume

SPI maintains a database of mixed-conifer stem analysis trees, all of which were used in the construction of the tree volume equations applied in this study (Wensel and Olson, 1995). This database contains measurements of inside and outside bark bole diameters taken at systematic intervals on tree stems. Both bark and stem wood volumes were determined for 2247 mixed-conifer trees. We excluded trees where the outside bark measurements were taken with diameter tapes to avoid counting 'air space' in trees with corrugated bark. Ratio estimators were developed for each mixed conifer species expressing bark volume as a proportion of stem volume (CVT). These estimators were weighted by the species proportions of CVT in both watershed inventories. For both inventories and ponderosa pine separately, a weighted result of bark volume = 0.2 * CVT was obtained. We note that this is almost the same factor presented by Jenkins et.al (2003), 0.185, as a national softwood composite.

6.5 Wood Density

Overall watershed wood densities (lbs/ft^3) were estimated by weighting individual species wood densities (Jenkins et. al. 2003) by CVT proportions of the initial inventories. We obtained values of 23.3 and 24.1 lbs/ft^3 for the USAW and CCW watersheds respectively. Ponderosa pine values were 23.7 lbs/ft^3. We note that Birdsey (1992) suggests a value of 26.5 lbs/ft^3 for western forest types and SPI mill accounting uses a factor of 23.6 lbs/ft^3 for stem wood and bark combined. We also note that the density of roots, bark, and branches tends to be slightly higher than that of stem wood bark because plant cells get crushed in the growth process and branches have higher lignin to cellulose proportions. Foliage is somewhat less from the lack of lignin. Due to a lack of definitive and complete results, we use a value of 24 lbs/ft^3 for all biomass components whenever volume-to-weight conversions are necessary in subsequent carbon budgeting.

7. Forest Carbon Pool Modeling

In this section, component estimates of forest carbon pool storage were used in developing carbon budgets. All carbon estimates are expressed in terms of tons (2000 lbs) of carbon/acre.

7.1 Soil Carbon (SOILC)

Although there are no direct measurements on soil carbon for either watershed, a value was obtained from previous work. Brown et al. (2004b) estimated soil carbon in a mixed conifer forest and found values in the approximate range of 20 – 100 tons/acre. Possible differences due to stand ages and management activity were not found to be substantial. Birdsey (1992) suggests a soil carbon value of about 43 tons/acre in relatively undisturbed secondary forests on the Pacific Coast. In lieu of more definitive results, this figure was used as a constant stock value for all management scenarios.

7.2 Snags (SNAGS)

Snag volume (CVTS + BARK) was estimated to be 125 and 375 ft^3/acre for CCW and USAW respectively based on the current inventory. Virtually no correlation was found with stand age, density, or volume. A factor of 1.2 was used to account for some branch and root retention and bark loss. Wood density was reduced to 75% of the nominal 24 lbs/ft^3 to account for decay. Resulting per acre-adjusted values were multiplied by 0.5 to produce carbon yields. This produced snag carbon yield estimates of 0.75 and 2 tons C/acre for the respective watersheds. These are small compared to other forest carbon pool components. Historically, snags were systematically clear-felled in harvest operations due to fire risk. In the last few decades, snags have been left standing for the values they provide wildlife. For this analysis we assumed stasis in snag carbon component contributions and the above amounts were added as constant stock values to all management scenarios.

7.3 Forest Floor Biomass (FLOOR)

No direct sampling of dead biomass other than snags was available to this study. Forest wide, we expected these values to be fairly stable. Birdsey (1992) suggests an equivalent value of 11 tons C/acre value for all forms of dead material (above and below ground) except standing snags for Pacific Coast forests. Powers et al (2005) reported forest floor biomass estimates for six older mixed conifer soil productivity installations in California ranging in age from 65 to 230 years. Assuming 50% of the floor biomass is carbon, their results would indicate a range of 13.5 tons C/acre for the youngest stands and 25 tons C/acre for the oldest. Brown et al. (2004b) modeled floor components as a function of stand age and produced results that indicated minor forest floor contributions to carbon storage in very young stands and values of 20-40 tons C/acre in undisturbed 100- to 200 year-old stands. In lieu of more definitive and site specific information, we assumed a constant forest wide value of 11.5 tons C/acre for carbon stored in dead biomass for all management scenarios and plan periods. Decomposition and accumulation are assumed to be in equilibrium.

Past forest management practices cleared all forms of biomass from the site prior to planting new plantations. Cleared biomass was usually burned. Current practices are to leave more if not all floor biomass in place due to fire risks of burning and the recognition that dead biomass is a source of nitrogen. Young plantations may not contribute enough to this source so it was assumed that all pre-commercial thinning biomass would contribute to the forest floor biomass source and not be counted in harvest residue pools when the stand were harvested decades later.

7.4 Shrubs (SHRUBS)

There are no direct sampling data on shrub biomass components. Aerial photography indicates no significant component of either watershed land base is in brush fields. Birdsey (1992) indicates biomass components due to this source are < 1 - 2% of forest totals. In the absence of catastrophic events, they typically are in some form of annual stasis. Therefore this component was effectively assumed to be zero for the rest of the analysis.

7.5 Live Tree Biomass (LBM)

Inventory data and growth and yield forecasts of stem wood volume (CVTS) are used to estimate total tree biomass (LBM). As adopted in this study, total tree volume (LBMV) can be converted to LBM by the factor of 24 lbs/ft^3. All tree biomass components are assumed to have the same density so LBM and LBMV components differ by a fixed proportion.

With no other variables than CVTS and BA to estimate biomass components, an extensive review of the literature indicates we have three possible and reasonable methods of estimating LBM and subsequent carbon yields:

1. Develop suitable estimates of proportionate biomass yields for all of the live tree biomass components listed in Table 2.2. The inverse of the stem proportion (Q) can be used to estimate total LBM. Suitable algebraic operations can be used to estimate all other tree biomass components if needed.
2. Estimate LBM for each tree as an allometric function of DBH ($LBM = a_0DBH^{a1}$). Sum the results to get plot and stand LBM. This metric is useful where such equations exist and tree list modeling is used consistently throughout a study. Stand based growth and yield models using basal area, age, and site index for existing stands preclude this possibility.
3. Apply estimates obtained in suitable inventories from method 2 above and develop second stage estimators of the form: LBM = f(CVST).

Three live tree biomass models were developed based on available published research, which are referred to thereafter as models 1, 2, and 3.

Model 1. Jenkins et al. (2003) produced 'national' softwood composites of the proportion of LBM that could be attributable to the LBM components adopted in this study. These proportions were presented as functions of tree DBH. For small diameter trees, these proportions varied considerably, however they stabilized at diameters around 10 inches DBH and these were the proportions that were used.

Model 2. This model uses Powers et al. (2007) estimates of CROWN and total bole (STEM + BARK) for a representative mixed-conifer site, bark volume ratios developed in section 6.4 (above), and root proportions supplied by Jenkins et al. (2003).

Model 3. In this model, we used equations supplied by Smith et. al. (2005) that predict stand LBM as a function of growing stock volume. We used the Pacific Southwest regions Other Conifer Equation and suitably modified it to be compatible with the measurement unit basis used in this study. Model 1 proportions were used to allocate LBM to various stand components when necessary as the equations are a derivative of the data used by Jenkins.

Biomass proportions of Models 1 and 2 are shown in Table 7.1. It was noted that differences in Q values range from 1.85 to 2.77 between Models 1 to 2. This is substantial. Corresponding Q values for Model 3 range from about 1.8 at low stocking levels to 2.7 at higher stocking levels across the range of CVTS densities encountered in this study.

Table 7.1 Live tree biomass component proportions by model

Model	STEM	BARK	CROWN	ROOTS
1	.54	.10	.18	.18
2	.36	.07	.39	.18

7.6 LBM Estimation Evaluation

It was not possible to directly verify which of the above models (1 through 3) provide the most accurate biomass assessments for the watersheds in this study over the entire planning horizon.

Model 1 is based on a composite of several nation-wide softwood studies and apparently includes a wide variety of species, size and density classes. However, none of the sampling locations (with the possible exception of a pinyon-juniper study) were from California.

Model 2 is based on a limited number of mixed conifer sites in California and overall, appears to represent stand conditions that are denser and larger than both watersheds at the start of the study.

Both models 1 and 2 assume that CROWN components are constants. Tree crown ratios are frequently in the 80 – 90% range in young stands. Stands managed at light densities can maintain deep crowns well into their rotation. Conversely, natural stands or stands targeted for ‘let grow’ management may experience crown ratios in the 20-40% range. Thus, the influence of management on foliar dynamics and subsequent affect on overall stand biomass is ignored in the application of both models.

Model 3, while being easy to apply, has the same biomass allocation problems as models 1 and 2. In addition, problems arise from several other sources: 1) the stands used as the basis for the equations had few, if any California mixed-conifer components; 2) the tree volume equations used to summarize stand volumes (the independent variable in the equation) were not the same as the ones used in this study; and 3) estimation of LBM (the dependent variable in the equation) was based on Jenkins et al. (2003) allometric tree biomass equations.

Jenkins et. al. (2003) produced four hardwood and five softwood allometric biomass equations of the form

$$\mathrm{LBMa} = a_0 \mathrm{DBH}^{a1}.$$

Where LBMa denotes live biomass above ground. This was a ‘meta-study’ synthesizing a large collection of national studies mainly restricted to the lower 48 states. None were apparently from California. They were intended to be used in national scale biomass assessment. CCAR has adopted these equations as part of their forest carbon assessment protocols.

Jenkins indicated over 10 possible issues (interpreted as sources of bias) that one might consider before applying these allometric estimators to specific stands and locations. Chief among the concerns listed was the assumption that the ‘application’ project has the same height, crown, and root composition as the sample over the analytical lifetime. Allometric relationships have a long history in forest inventory of the form CVT = f(DBH) and such relationships are typically derived for each stand and for one point in time. They are commonly called ‘local’ volume equations. We compared the ‘standard’ total height/DBH volume estimators (CVT) used in inventory and growth and yield processing with ‘local’ volume equations based on a California sample of 387 trees in 9 locations. These trees were not included in the construction of the Wensel and Olson (1995) tree volume equations. This comparison was for the ponderosa pine component of our initial inventory only. Here we can evaluate one component of the LBM matrix. Coefficient of variation for the Wensel and Olson total height/DBH volume equations was about 7% while corresponding value for our local volume equation was about 30%. If such variation is concentrated within stands/assessment areas, there is no cause for bias concern. But, if aggregate differences between stands are found (indicating biases), then questions of applicability arise. We estimated the aggregate difference between the both sources of volume estimation and found that application of the local volume equation produced CVT estimates that were 5% high for CCW and 14% low for the USAW. The difference for individual stands ranged from a low of 26% to a high of 78%. As we are comparing models, these differences are only indicative of bias rather than assessments of actual bias. We suspect that with using national scale models (i.e., Jenkins pine equation uses red pine studies from the northeast, loblolly pine from Texas, and ponderosa pine from Arizona), differences may be much greater when applied to individual stands.

In summary, the above three models are what we could reasonably extract from published literature about stand biomass estimation applicable to mixed-conifer stands in California. None are perfect and it would appear that live biomass estimation methods currently available in California are the most limiting in terms of precision when estimating total carbon stored in forest stands.

8. Harvest Utilization and Efficiency

When trees are harvested, carbon is removed from the live biomass forest carbon pool and a) transferred to the harvest residue pool, b) taken off site in the form of logs (stem wood plus bark) to be converted to products, or c) converted on site to hog fuel for transfer to co-regeneration facilities. Discussions with SPI forest managers indicate that the proportions will vary with site characteristics, logging methods, and market conditions. Broadcast burning in the forest has largely been phased out over the last decade. Where possible, mechanized harvesters are used to harvest trees up to about 26 inches DBH. These trees are skidded whole to landings, limbed and bucked, and logs are taken to the mill. If markets are favorable, tops and branches are chipped for hog fuel otherwise they are scattered on site or the piles of landing slash are burned. Larger trees are felled conventionally by a human with a chain saw and only logs are removed. On some sites, all trees are felled conventionally.

Rather than attempt to derive suitable proportions for various possibilities, we have attempted to bracket the range of outcomes in terms of effects on overall carbon budgets. Two scenarios are developed. The common denominator is that merchantable tree boles (stem wood plus bark from a one-foot stump to a merchantable top diameter of 6 inches) are removed from the site and shipped to manufacturing facilities.

- In scenario 1, we assume that all tree biomass less merchantable boles contribute to maintaining the stasis of the dead forest biomass/carbon (FLOOR) pool.

- In scenario 2, we assume that all tree biomass less merchantable boles are transferred to the harvest residue pool. This is assumed to be separate from (or additive to) the ‘naturally’ occurring FLOOR biomass/carbon pool. This was done to assess the differences in decomposition rates from each approach due to modeling dead forest biomass vs. harvest residue.

8.1 Harvest Residue Pool Dynamics

Harmon (1987) estimates decomposition rates of harvest residue to be about 5% a year. This rate was used here and we applied it to branches and foliage, stumps, bole tops, broken logs, and bark (lost from tree boles during logging operations). This 5% value produces a half-life of harvest residue of about 15 years. Silver and Miya (2001) estimate decomposition rates of all sizes of softwood roots to be about 15% a year (with a half-life of 5 years). Both of these decomposition rates may be excessive for application to the harvest residue components especially when stumps and root crowns are considered. But we used them since they are the best available information.

8.2 Merchantable Biomass

In determining harvest biomass/carbon, the removals in terms of volume (Hv) were first estimated. Density factors and carbon proportions were then used to estimate removals of carbon by weight. The following methods were used:

1. CVST was reduced by watershed specific factors given in section 6.2 to account for trees less than 8” DBH for clear-felling of existing stands and custodial harvests. No reductions for this component were applied to plantation commercial thinnings and clear-fellings.
2. Pre-commercial thinnings were ignored in terms of harvest residue /removals. These values, estimated to be less than 1 ton of carbon/acre, were assumed to contribute to the FLOOR biomass stasis.
3. CVST was reduced by stump factors described in section 6.1 to produce stem wood volumes from stump to tree tip: CVT
4. Merchantable bole volumes (CV) were estimated from CVT by applying merchantable tip adjustment factors described in sections 6.2
5. Based on roundtable discussions with SPI foresters, CV was reduced by 5% to account for breakage and defect to produce a net volume (CVn). The 5% waste volume was left in the woods.
6. Based on foresters and log scaler’s estimates, total biomass bark proportions (Table 7.1) were reduced by 15% to account for bark sloughing resulting from timber falling and skidding. We denote this adjusted proportion as pb.
7. With biomass stem wood proportions denoted as ps, harvest volumes were computed as:

$$Hv = CVn * (ps + pb)/ps$$

8. Density factors and carbon proportions can be used to convert Hv to biomass and carbon weights.

8.3 Removals as Percentages of BIOMASS and Carbon

Application of the harvest accounting methods to the initial inventories indicated similar results for both watersheds. For biomass Model 1, merchantable stem wood and bark volume removals were about 54% of the total live biomass pool. For Model 2, a value of 36% was estimated. In the cases examined here, stem wood reductions due to stumps, tops, and decay/breakage are offset by additions due to stem bark suggesting stem wood proportions are a reasonable 'rule – of – thumb' estimate of net harvest removals.

9. Mill Utilization and Efficiency

A proportion of the forest carbon pool is transferred to the long-term wood (LTW) product carbon pool when trees are harvested, logs are trucked to mills, and processed by these facilities. Not all of the biomass is transferred to solid wood products during this manufacturing process. A significant amount is processed into residual by-products and sold into various markets or burned in cogeneration facilities as market conditions dictate.

These residual by-products usually consist of bark, sawdust, pulp chips, planer shavings, and what is known locally as hog fuel. The bark is bagged and sold for landscape uses. Sawdust is sold as a soil amendment or to the medium density fiberboard (MDF) plant. Pulp chips are shipped to pulp mills to make paper and kraft/box products. Planer shavings (derived when rough sawn boards are planed into smooth lumber) are sold to the MDF plant or into the market for animal bedding. Hog fuel is the term used for the chunks and slabs of waste wood derived in the process of sawing lumber. It is chipped, "hogged", and usually burned in the boiler of the cogeneration plant.

As market conditions and raw material availability change during a year, the allocation of the products into the various markets described above also changes. In a typical year the SPI mills involved in this study will sell these by-products into markets where they are sequestered in some form- not burned for energy production- about 70% of the time. The exception is hog fuel, which is almost always burned in the cogeneration plant. Many factors affect these allocations, particularly the availability of alternative fuel for the power plant such as orchard prunings and recycled urban wood waste. When alternative fuels are not available due to pricing issues or seasonal restrictions, a portion of the by-products described will be diverted into the cogeneration plant and burned.

These shifting allocations and the myriad options they portray are complex and difficult to model over time. This study assumed for simplicity that 30-32% of the residual by-products were burned in the cogeneration plant (Table 9.1) While this somewhat underestimates the amount of carbon sequestered in products in a typical year of operation, it did not materially affect the focus of the study -- a comparison of alternative forest management prescriptions and their effect on carbon sequestration estimates. The burning of biomass for energy production also offsets some fossil fuel consumption, but again this was not a focus of the study.

Table 9.1 SPI mill utilization

Wood Product Source	**Percent Weight**	
	Small Log Mill	**Large Log Mill**
Sawn Lumber	42%	50%
Chips for Products	6%	0%
Chips for Pulp/Paper	22%	18%
Utilization Sub Total	**70%**	**68%**
Chips for fuel	20%	9%
Hog fuel	10%	23%
Waste Sub Total	**30%**	**32%**

Sawn lumber is tracked by volume directly in accordance with American Forest and Paper Association (AF&PA) guidelines. Cubic foot lumber volume is converting to weight by the factor of 23.6 lbs/ft^3. All other product sources are tracked by dry weight directly.

10. Long Term Wood Product Carbon Pool

Carbon sequestration originating in the forest persists in the form of wood products used in houses, furniture, and a variety of other consumer goods. These products have a lifetime before they are oxidized and return to atmospheric carbon. As deliberate burning of wood products is currently prohibited, wood products taken out of service appear to have these major fates:

1. In place decomposition or incineration due to accidental fires.
2. Hog fuel for co-regeneration plants.
3. Recycled back to new products.
4. Terminal landfills.

Disposition of all these items vary regionally within California and the U.S. at large and are subject to market shifts due to supply and demand factors. Items 1 and 2 represent emissions while recycling and landfills represent further storage.

The following method was used to account for carbon storage in the long-term wood product carbon pool.

1) 25% of long-term wood products are assumed to go to landfills when they are taken out of service. Recent studies (Ximenes et.al., 2005) indicate that the decomposition of wood products in landfills is insignificant so we assume wood carbon in landfills is permanently sequestered.

2) An additional 10% of wood products are assumed to be immediately taken out of service in the year of manufacture to account for additional remanufacturing and construction waste with 25% of this amount going to landfills.

3) Wood products are subsequently taken out of service at an annual rate of 1% of year (Winjnn et. al. 1998).

11. Simulating Carbon Budgets.

Growth and yield was estimated for each stand on an annual basis over the 100-year plan. All management activities (harvests and regeneration) were assumed to occur in the midpoint of each decade. The various conversions necessary to estimate biomass and carbon from primary stand variables, volume (CVT) and basal area per acre, were then applied to estimate net carbon yields. Additions and decomposition of long-term wood product and landfill carbon pools were maintained annually as were harvest residue carbon pools. Weighted per acre stand values for each management scenario were estimated and average decadal carbon stocks and average annual changes were subsequently derived and form the basis for summary results.

For each management scenario, we produced estimates of average decadal stocking and annual change in carbon pools (Table 11.1).

Table 11.1 Summary Carbon Pools

Carbon Pool	**Carbon Components**
Forest Carbon Pool (FCP)	FLOOR, SOILC, SNAGS, LBM
Product Carbon Pool (PCP)	LTW, LFILL
Harvest Residue Carbon Pool (HRCP)	HARVEST

Three summary pools were used in the presentation of results:

1. FCP
2. FCP + PCP
3. FCP + PCP + HRCP

12. Results

12.1 Forest Carbon Pool Overview by Management Scenario and Biomass Model

Figure 12.1 provides a graphical overview of the differences in the forest carbon pool due to watershed, biomass model, and management scenario. Note that the forest biomass pool in all instances contains about 55 tons C/acre in the form of soil carbon and forest floor carbon. Several general items can be immediately noted:

- Biomass Model 2 is consistently associated with greater carbon yields than Model 1 due to a higher Q value. Model 3 is intermediate in all cases. It does not maintain the same relative position compared to the other two models as the functional form of Model 3's equation is non-linear.

- Generally, USAW shows higher carbon yields than CCW. Such differences are most pronounced in the early decades and are due to higher site quality and stocking in the USAW than those found in the CCW.

- Results of the Intensive Management scenario show a steady climb in the forest carbon pool throughout the entire 100-year planning horizon for both the USAW and CCW. Values ranged from 100 to 165 tons of carbon per acre for the USAW and from 82 to 134 tons of carbon per acre for the CCW for all three models.

- The Custodial Management scenario indicates a gradual increase-stable-declining pattern for USAW in the forest carbon pool for all models. In USAW, the forest carbon pool ranged from 104 to 142 tons of carbon per acre over the 100-year period for all three models. For the first five decades the carbon pool rose up to 15 tons per acre more in the USAW and then had a corresponding slow steady decline of up to 15 tons per acre in the last five decades for each model. The forest carbon pool for each model in the CCW exhibits an increasing-stable pattern. The forest carbon pool in the CCW ranges from 83 to 127 tons of carbon per acre over the 100-year planning horizon for all models. The different forest carbon pool results between the two watersheds are largely due to interactions between the harvest prescription (~1% of the stocking/year) and declining growth rates predicted by the stand model as the stands in each watershed get older.

- Under Option C Forest Management, the CCW shows a slight increase in the forest carbon pool: up to 5 tons of carbon per acre over the 100-year planning horizon. The USAW total forest carbon pool declined up to 15 tons per acre over the 100-year planning period for all three models used. Trends in the USAW and CCW forest carbon pool are different in the first five decades, but similar patterns were found in the last five decades. At the end of the planning period both watersheds contain approximately the same carbon yield levels with USAW at 108 tons of carbon per acre and CCW at 101 tons of carbon per acre. The USAW forest carbon pool yield is slightly higher due to higher residual Board of Forestry stocking regulations associated with higher site classes.

- Results in both watersheds for the regulated management scenario show stable levels of forest carbon sequestration throughout the entire 100-year planning period. The forest carbon yield was highest in Model 2. USAW was found to have 165 tons of carbon per acre and the CCW 134 tons of carbon per acre under a regulated flow management method. By definition, harvests, stocking, and growth are constant in a regulated forest management condition. Differences in the regulated forest carbon pool between watersheds are primarily a reflection of site quality differences.

Upper San Antonio Creek Watershed　　　　Canyon Creek Watershed

Figure 12.1 Forest Carbon Pools by Model and Management Scenario

12.2 Comparison of Forest Carbon Pool by Management Scenarios Using Live Biomass Model 2

The total forest carbon pool results derived from Live Biomass Model 2 will be discussed from this point on to compare the difference in carbon sequestration due to the four management scenarios used in this study. Figure 12.2 contrasts change in the forest carbon pool yield due to management scenarios for each watershed using biomass Model 2. We arbitrarily used Model 2 as a comparative basis since model differences are largely proportional and can be inferred from the data in Figure 12.1. We have included floor and soil carbon results so the relative contributions of all sources of forest carbon can be put into perspective. Several general items can be immediately noted:

- The differences in carbon pool dynamics are relatively the same between watersheds.

- The Option C Selection management scenario has the lowest yield in the forest carbon pool over the 100-year planning period for both watersheds in this study.

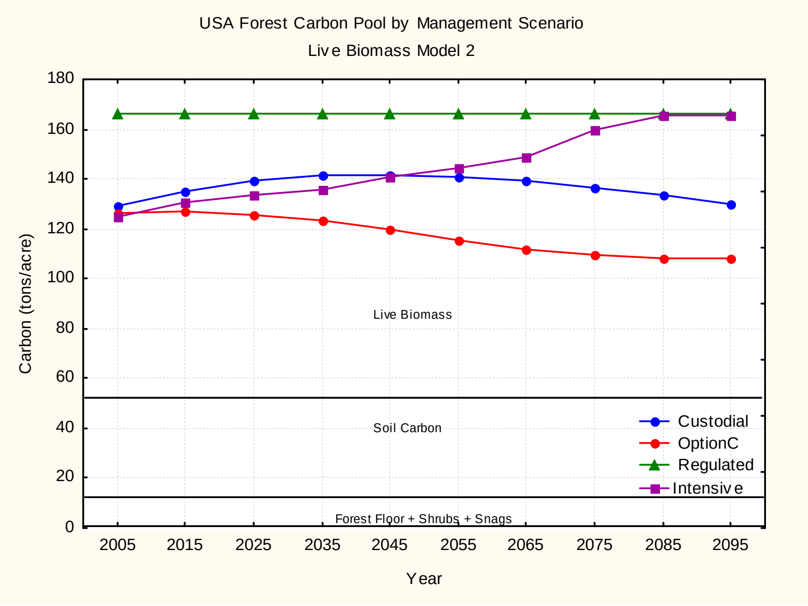
- In the first eight decades, the Regulated management scenario has the highest yield in the forest carbon pool. For the last two decades both the Regulated and Intensive Forest Management have the same high yield level in both watersheds.

- For the USAW under Option C Selection management there is a slow steady decline of carbon over time, in the Custodial management scenario there is a slight rise and then a corresponding drop in carbon over time. In the Intensive Management scenario there is a steady increase in the first eight decades and then the last two decades show a stable level in the forest carbon pool that is equal to that of the regulated management scenario which sequesters the highest values of forest carbon for any decade and management method.

- Note that there is little difference in the early decades between the custodial and intensive scenarios for USAW. Custodial growth is slightly more than harvest during these periods and there is little difference between harvesting 10% of the forest-wide growing stock each decade versus clear cutting 12.5% of the land base in the intensive scenario. As growth slows relative to custodial harvest prescriptions, a loss up to 15 tons per acre in the forest carbon pool results. The cumulative effect of introducing new fast growing plantations each decade begins to be noticeable within the forest carbon pool yield under intensive management by the sixth decade and by the last two decades equals that of the Regulated Management level of 165 tons of carbon per acre.

- In contrast to the USAW, the Custodial management scenario increases tons of carbon per acre consistently over time in the CCW. Under the Intensive management scenario the forest carbon pool rises steadily throughout 7 decades in the CCW, and then in the eighth decade the forest carbon pool exceeds that of the Custodial Management, and reaches the same level as the Regulated Management level of 134 tons of carbon for the last two decades. This occurs because growth is greater than custodial harvests for the CCW watershed until about the seventh decade and new plantation growth is slower than the USAW due to lower site quality. Thus in the CCW, it takes about 30 years more than the USAW before the intensive scenario carbon pool surpasses the custodial management carbon pool.

Upper San Antonio Creek



Canyon Creek

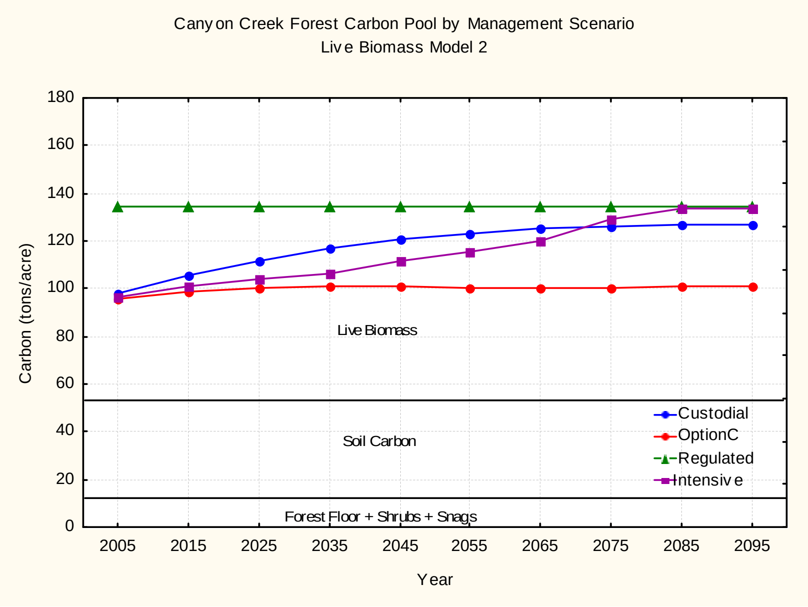


Figure 12.2 Forest Carbon Pools by Management Scenario

12.3 Total Carbon Pool: Accounting for Wood Products and Harvest Residue Carbon Pools

Our next analysis quantifies how the total carbon pool is estimated to change over the planning period for each watershed and management scenario using biomass Model 2. To review, we define the total carbon pool to be the sum of a) the forest carbon pool, b) additional carbon contributions over and above natural processes and pre-commercial thinnings in the form of harvest residue from logging operations, and c) wood products in service and in land fills. Note that the harvest residue and wood product carbon pools are all assumed to be zero at the start of the planning period. We will compare the forest carbon pool yield to the total forest carbon pool.

Figure 12.3 provides a comparative overview of the differences due to watershed and forest management scenarios in accounting for three different summary carbon pools.

1. Forest carbon pool
2. Forest carbon pool + Wood products carbon pool
3. Forest carbon pool + Wood products carbon pool + Harvest Residue carbon pool.

Figure 12.4 displays how the total carbon pools change over time by Forest Management Scenario in each watershed. As noted previously, the total carbon pools for this study are the same as the third case in Figure 12.3.

We note the following:

- In the USAW, the difference between the total carbon pool and the forest carbon pool is about 35 tons carbon per acre at the end of the analysis period for both the Custodial Management and Option C Selection Management scenarios. In contrast, the difference between the total carbon pool and the forest carbon pool is over 90 tons of carbon per acre for the Intensive Management and over 150 tons of carbon per acre for the Regulated Management scenarios.

- In the CCW, the difference between the total carbon pool and the forest carbon pool is about 15 tons of carbon per acre in the terminal decade for both the Custodial Management and Option C Selection Management scenarios. In contrast, the difference between the total carbon pool and the forest carbon pool is over 60 tons of carbon per acre for the Intensive Management and over 100 tons of carbon per acre for the Regulated Management scenarios.

- Clearly, when you account for carbon stored in wood products manufactured from logs milled from California forests and carbon stored in harvest residue that results from timber harvest operations, there is a large increase in the total forest carbon pool. When wood products and harvest residue are included as sources of carbon in the total carbon pool, the yield is much higher.

- Intensively managed forests show substantial increases in the forest carbon pool and the total carbon pool when compared to the other passive forms of forest management scenarios examined in this study.

- The only way to achieve the theoretical Regulated forest management condition that sequesters the most carbon over time is through intensive forest management that converts legacy forests into age classes of equal area over time.

- Current CCAR forest protocols indicate that project carbon credits are to be determined as the additions above an Option C Selection Management baseline scenario. However, only portions of the forest carbon pools are used to calculate carbon credits: live biomass above ground, snags, and downed woody materials. We estimated additions of the Intensive and Custodial management regimes based on both the forest carbon pool and the total carbon pools during the last decade of the planning period and the results are shown below in table 12.1.

Table 12.1 Increases in carbon credits relative to CCAR Option C Selection Management by forest and total carbon pool basis during the 10th decade.

Watershed	Management Scenario	Forest Carbon pool based (tons C/acre)	Total Carbon Pool based (tons C/acre)	Percent Change from Forest to Total carbon pool basis
USAW	Intensive	35	95	+166%
USAW	Custodial	22	23	+5%
CCW	Intensive	33	75	+127%
CCW	Custodial	26	23	-7%

- Differences between the Custodial and Option C Selection Management scenarios are relatively minor for both watersheds regardless of the carbon pool basis. Dramatic increases however are evident for stands managed under the Intensive Management scenario. We note that both the carbon stored in harvest residue and wood products contribute substantially to this increase. Examination of the Regulated management scenarios (stable harvests) indicates that harvest residue carbon pools stabilize after about 30 years. We examined how the wood product carbon budget would change by extending the forest projection length for over 200 years. Even at the 200-year mark, two complete planning periods, the carbon stored in wood products does not begin to level off. Rather the wood products carbon pool continues to increase and indicates a long-term persistence in carbon sequestration for intensely managed forests.

Upper San Antonio Creek

Canyon Creek

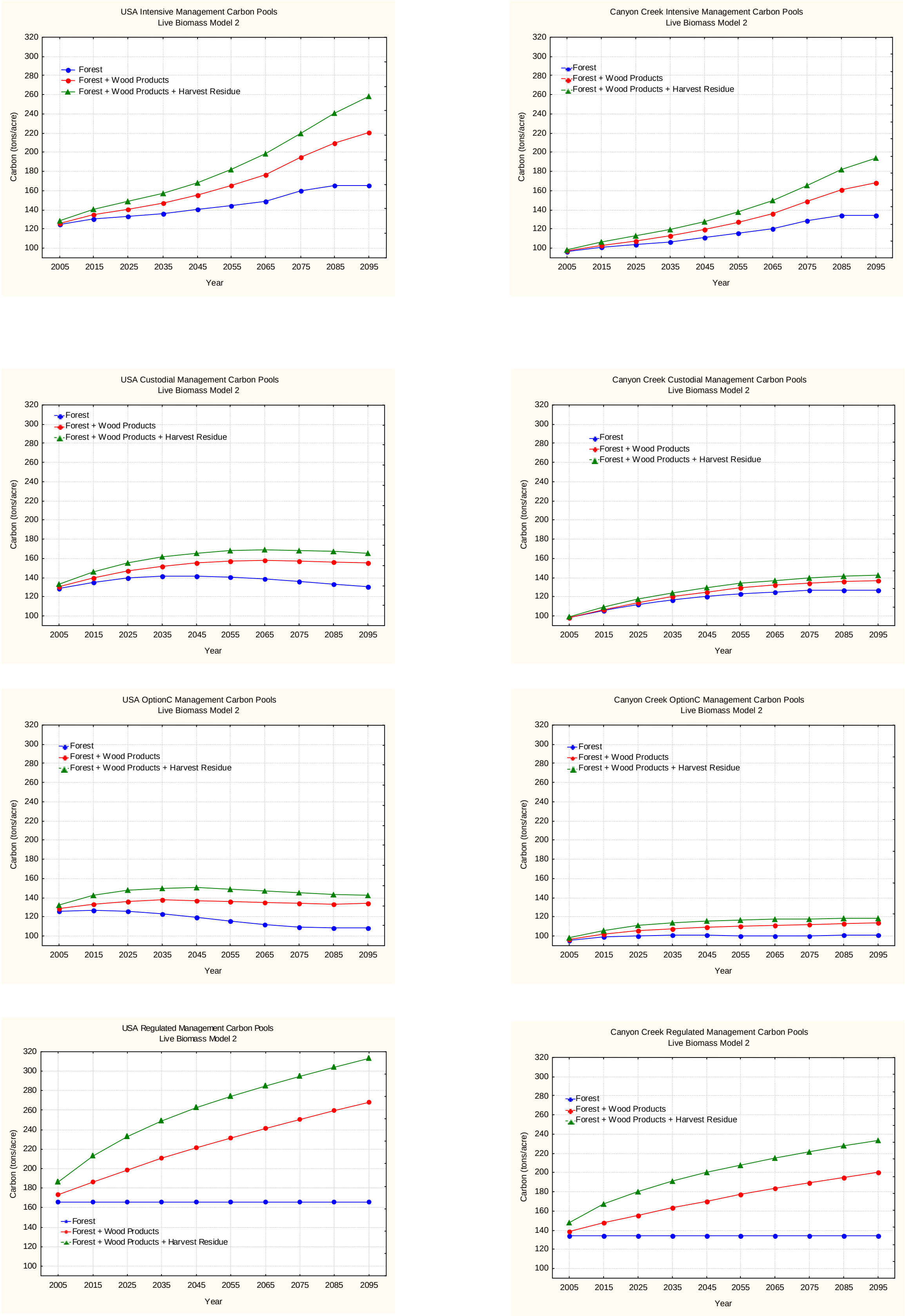
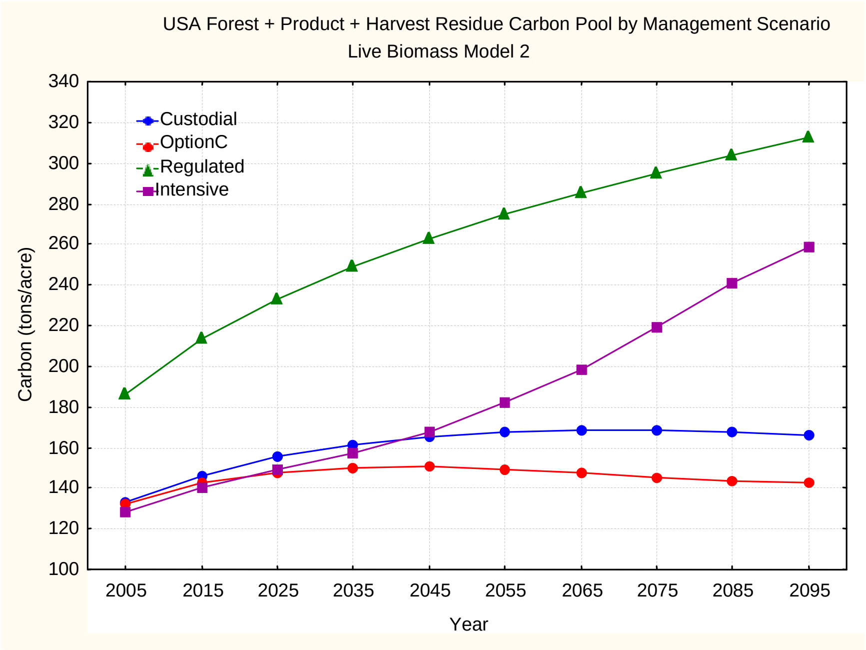


Figure 12.3 Total carbon pools by watershed and management scenario

Upper San Antonio Creek Watershed Total Carbon Pool



Canyon Creek Watershed Total Carbon Pool

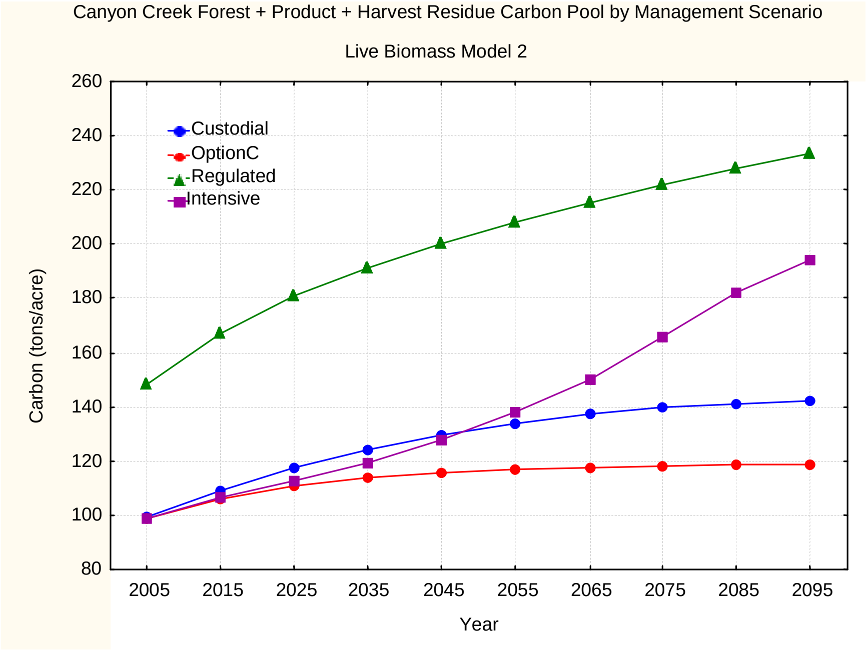


Figure 12.4 Total Carbon Pool by Management Scenario using Live Biomass Model 2 (Forest carbon pool + Wood Products carbon pool + Harvest Residue carbon pool)

13. Discussion and Recommendations

13.1 Discussion

In this study three different biomass modeling approaches, four management scenarios, three broad definitions of forest carbon pools, and two forested watersheds were compared to determine carbon sequestered over a 100-year planning horizon. The study also quantified a total carbon pool consisting of the forest carbon pool, wood products removed from the site, and harvest residue from operations. Substantial absolute differences were found in carbon sequestration rates due to the biomass modeling approach. However, these differences appeared to impact other items in a fairly stable proportionate manner. An examination of the forest carbon pool indicated the Option C Selection, Sustained Yield scenario under the California Forest Practice Rules consistently yielded the least amount of carbon over the entire planning horizon. This is largely the result of prescribing stocking standards that are the minimum allowed by regulations. In contrast, when examining the total carbon pool resulting from forest management, the intensively managed scenario clearly shows a substantial increase in carbon accumulation, particularly in the later decades of the planning period as new, vigorous plantations begin to dominate the watersheds. When comparing the forest carbon pool with the total carbon pool under the Option C Selection and Intensive management scenarios, total carbon pool increases 166% in the USAW and 127% in the CCW. Omitting the carbon stored in wood products and harvest residues in the carbon pool significantly reduces the amount of sequestered carbon that is reported and available for carbon credits under the adopted CCAR protocols.

13.2 Recommendations for Future Research; Technical Problems Identified in the Construction of Carbon Budgets in California Forests.

This study initially used growth and yield models currently available and widely used in California, but they are limited in their ability to predict total biomass. It is also difficult to determine if existing biomass models were appropriate for use in California forests. Therefore, the study concluded the two main problems in providing an accurate forest carbon appraisal system in California that could be applied at the project level under the CCAR protocols were a) imprecise biomass modeling systems and b) shortcomings of publicly available forest growth models.

Accurate tree species biomass models that can be applied to statewide carbon appraisals minimally need to account for tree DBH, total height, and crown size to adequately take into account the existing variability and impacts on biomass that result from different types of management and stages of tree development. Desirable systems would provide biomass estimates of primary tree components (stem, bark, crown, etc.) in addition to total tree biomass. Such an effort would involve substantial research and coordination to become a reality. However, the alternative is to have carbon credits potentially being bought and sold based on highly imprecise and, in the context of specific forest projects, biased appraisal methods. Initial work to construct biomass models based on California forest types could be reasonably accomplished by a committee of informed research scientists. The first task would be to assimilate all relevant data and studies specific to California and possibly other western states. Reasonable inference based on data could partially populate the system. A consensus based on informed judgment and comparative processes could provide an interim basis for what is current lacking in available biomass models.

Existing California tree-list based forest growth models were largely developed with data from young-growth stands at density levels likely to be found under active management. Projecting beyond the bounds of data used in model construction led to highly unrealistic volume and subsequent biomass estimates. Clearly, tree-list models that incorporate biomass subsystem components as well as being able to accurately simulate stand growth through conditions required by long-term carbon studies would be highly desirable for accurate and precise carbon appraisals.

General world-wide awareness about global warming and recently enacted national and state regulations indicate that concerns about the role forests play in carbon sequestration will be with us for some time to come. This study found that managed California forest watersheds sequester substantial yields of carbon over a100-year planning cycle. This study has also identified further work needed to improve the technical methods used to estimate carbon sequestration for California forests.

Appendix I. Growth And Yield Forecasting

Accurate forecasts of forest growth, yields, and harvest in the form of stem wood volume and basal area are the basic elements needed to develop precise carbon budgets. This study requires two basic modeling frameworks: a) one for existing stands to form the basis for the Option C Selection and Custodial Management scenarios, and the 'front end' of the Intensive Management scenario up to the time of the initial clear – felling;, and b) one for Intensively Managed plantations once they are regenerated. The latter framework is also the basis for the Regulated Forest Management scenario.

Yields of Existing Stands

Both CACTOS (Wensel et. al., 1986) and U.S. Forest Service's FVS (Ritchie, 1999) models were used initially to project growth and harvests for existing stands. These models are based on individual tree lists (DBH, total height, crown ratio, species, and per acre expansion factors) and are directly applicable to both watershed's inventory data. These models however performed poorly within our analysis specifications. CACTOS performed well for the first 2-4 decades. Thereafter, growth appeared excessive showing basal area stocking levels reaching in excess of 600 square feet/acre by the eighth and ninth decade. This is largely due to extrapolating the model to size/density ranges well outside the data bounds used in CACTOS construction. FVS immediately 'killed' about 15% of the smaller trees in the USA watershed causing substantially reduced first decade growth compared to CACTOS. In the third and fourth decades, growth began to fluctuate excessively (>300%) between decades. We suspect these problems are due to threshold/bounding functions incorporated in the model.

We concluded that neither of these models provided realistic yield predictions for the watersheds considered here. We subsequently adopted an empirical whole stand modeling approach designed to model yields for the management scenarios and whole stand characteristics of both the USA and CC watersheds. This was a two-stage equation system designed to:

1. Predict basal area/acre at any breast high stand age as a function of site index, initial basal area, and initial breast high age.

2. Predict cubic foot stem wood volume/acre from stump to the tree tip (CVT) as a function of basal area, breast high age, and site index.

I.1 Modeling Data

SPI maintains a growth plot database system for mixed conifer stands in California. These plots were measured 4-6 times between 1980 and the present. This database contains many of the growth plots used to construct the CACTOS growth model. We removed all plantation plots and plots not from the west slope of the Sierra Nevada or the Southern Cascade Mountains from consideration. The remainder of the dataset was from stands of naturally regenerated forestland. Virtually all had experienced some form of prior harvesting activity. We classified all these plots by forest type and removed all plots that had over 15% hardwood basal area stocking or had more than 70% of the basal area stocking in a single mixed conifer species. All true fir (red fir and white fir combined) forest type plots were excluded. We then extracted the longest measurement interval

possible where there were no harvests, fires, or other catastrophic effects between measurements. This produced 298 plots with usable growth series. 116 additional plots meeting the same criteria were extracted from the USFS FIA program's 1980 and 1990 private forest inventories in California.

For each plot, we determined 50-year breast high age site index (S) based on all site tree measurements (total height and breast high age on suitable dominant and co-dominant conifers). Base-age invariant mixed conifer site index models from Krumland and Eng (2005) were used for this purpose. Numbers of site tree measurements ranged from 3 to 22 for each plot.

For each plot on each of the two measurement occasions, we developed the following per acre values:

- Basal area per (BA1 and BA1). Based on all live trees over one inch DBH at the time of measurement.
- Stem wood volume (CVT1 and CVT2). Same criteria as basal area. The same species-specific tree volume equations applied in the base watershed inventories (Wensel and Olson, 1995) were used for plot summaries.
- Breast – high age (A1 and A2). Average age of corresponding site trees. We note that site trees were limited to ponderosa pine, sugar pine, white fir, and Douglas fir. Incense cedar was not considered as it typically has a site index about 30% less than other mixed conifer species.
- Average overstory height (H1 and H2). Average total heights of corresponding site trees.

We note that growth estimates (BA2 – BA1 and CVT2 – CVT1) represent net increments: growth of survivors + ingrowth – mortality.

I.2 Basal Area Prediction Model

We adopted a model to predict basal area at occasion 2 (BA2 and A2) from estimates of site index and initial conditions (BA1 and A1). The generalized algebraic difference approach (GADA) as described by Cieszewski and Bailey (2000) was used to transform a base equation (BA = f(A)) into a site index dependent variable density basal area prediction model. We summarize the steps involved as follows:

Postulate a base yield equation: BA = f(A)

We tried several yield equation forms and found a modified version of Schumacher's (1939) growth equation to fit best. The form we used as a starting point was

$$BA = \exp(M + dA^{d3}) \qquad (I.1)$$

Where BA is basal area at age A, exp(M) is an asymptotic value, and d and d3 are parameters that control the shape and rate the basal area reaches M. Schumacher's initial model assumed d3 was –1. However, experimentation indicated that allowing this parameter to vary significantly increased precision in subsequent statistical estimation.

Introduce Site Index effects

Here we define

$$M = d1 + d2*\log(S) \tag{I.2}$$

Where d1 and d2 are additional model parameters.

Introduce initial conditions

For an initial stocking level, say BA1 at age A1, we can solve I.1 for t;he parameter d in terms initial stocking giving

$$d = (\log(BA1) - M)/A1^{d3} \tag{I.3}$$

Produce the variable density basal area yield equation

We can now combine I.1 – 1.3, collect terms for the sake of mathematical tractability, and produce a site index dependent basal area yield equation that can predict BA2 at age A2 given initial conditions BA1 and A1:

$$BA2 = \exp((d1 \ +d2*\log(S)) * (1 - (A2/A1)^{d3)} + \log(BA1) * (A2/A1)^{d3}) \tag{I.4}$$

We note the following characteristics of the model:

- BA2 is undefined for ‘non-stocked’ stands (BA1=0).
- When A2 = A1, predicted BA2 = BA1 so consistency is maintained
- The model can be used to predict in both forward (A2 > A1) and backward (A2 < A1) directions.
- The model can be used recursively (iterations of say 5 years, with BA2, A2 substituted for BA1 and A2 to seed the next iteration) or cumulatively (predict the terminal values of BA2 directly from BA1 and A2) with results being numerically identical.

I.3 Basal Area Model Parameter Estimation

Model I.4 could be fit by non-linear parameter estimation in numerous ways: a) BA1 and A1 could be used as initial conditions with BA2 being the dependent variable (forward differences), b) BA2 and A2 could be used as initial conditions with BA1 being the dependent variable (backward differences), c) as suggested by Borders et.al (1988) a combined data set based on observations from both data orderings could be used in an ‘all combinations’ approach. d) recognizing that basal area appears as both an independent and dependent variable and is somewhat at odds with the normal assumptions of statistical estimation, a variety of unbiased estimation procedures could be employed (Cieszewski et. al, 2000). These methods are quite tedious and were not considered here.

We have tried methods a–c and found negligible differences between them. Method c), which split whatever marginal differences existed between methods a and b were used as the parameter estimation method.

I.4 Basal Area Model Results

Table I.1 shows parameter estimates and a statistical summary from fitting equation I.4 to the data. The mean difference in breast-high age between occasion 1 and 2 measurements was 11.3 years. The mean difference between BA2 and BA1 was 33.2 square feet.

Table I.1 Basal area prediction model statistical summary

Parameter Estimates			**R2**	**RMSE**
d1	**d2**	**d3**		
5.47	.23	.94	.92	15.2

I.5 Stand Volume Estimation Models

The second stage of yield prediction is to estimate stand cubic volume (CVT). A traditional model used in estimating stand volume from stand basal area and upper canopy height (H) is

$$CVT = a1 * BA * H \qquad \text{I.5}$$

Equation I.5 is usually used in the context of a single stand. We used the growth plots summaries at both occasions to estimate the parameter ‘a1’ in I.5 and found that there were significant trends in the residuals with both basal area and height. We then extended the model by adding the parameters a2 and a3 as follows:

$$CVT = a1 * BA^{a2} * H^{a3} \qquad \text{I.6}$$

The model extensions incorporated in I.6 reduced the residual variance from I.5 by over 25% and eliminated trends in the residuals.

We can thus use I.4 to predict basal area at any desired age, use site index and age to estimate upper canopy height, and derive corresponding cubic foot yields from I.6.

I.6 Forming Watershed Stands from Inventory Plots

Our next task was to partition watershed inventory plots into ‘stands’ that are reasonable and compatible with the existing stand growth projection framework. Inventory plots were systematically laid out on a grid at a sampling intensity of about 1 plot every 4 acres. Site trees were taken at about the rate of one site tree per 2 ground plots. Site indices were determined using the mixed-conifer site index models described above. Geophysical gridding techniques were employed in GIS software so every plot was assigned a site index. All dominant and co-dominant mixed conifer trees were assigned an ‘effective’ breast high age using their total height and plot site index (no incense cedar was used in this process) and inversely solving site index models. Average plot breast-high ages and dominant heights were subsequently computed.

After summarizing the available plot data for both watersheds, plots were initially stratified into groups on the basis of a) site index (20 foot ranges), b) average breast-high age (20 year ranges), and c) basal area classes (~ 100 square feet ranges). Boundaries of classes were adjusted in each watershed case so approximately even numbers of plots were in each class. This process produced 23 'stands' for the USA watershed and 31 for the Canyon Creek watershed. Summary (initial conditions) statistics for each stand were subsequently estimated and included upper canopy average total height and breast-high age, site index, basal area and CVT per acre.

I.7 Adjusting Stand Volume Equations

Application of the original growth plot based parameter estimates of the stand volume equation (I.6) to the watershed 'stands' indicated an overestimate of 13% for Canyon Creek and 21% for USA when compared to the original inventory. We suspect this is due to more ponderosa pine and less incense cedar in the growth plot inventories than the respective watershed inventories. Of all mixed conifer species for a given DBH and total height, ponderosa pine has the most stem volume and incense cedar has the least (Wensel and Olson, 1995). In lieu of these results, we subsequently refitted the stand volume equation I.6 to all initial inventory plots in the Canyon Creek and USA watersheds. A summary of statistical results are shown in table I.2

Table I.2 Stand Volume Model Statistical Summary

WAA	Parameter Estimates			R2	RMSE	Plots
	a1	a2	a3			
USA	.75	.91	.86	.89	716	623
CC	1.64	.77	.86	.93	422	1553

By watershed, we applied the stand volume models to the initial conditions for each of the stratified stands and estimated a total watershed volume. This was compared to the conventional inventory based on plot volume expansions. Differences were in the 1-2% range, which was considered to be acceptable within the context of this study.

1.8 Forecasting harvests and yields

Suitably parameterized, models I.4 and I.6 in conjunction with applicable site index models provide a forest yield projection system that can predict both basal area and volume. Growth can be determined by successive differences. Light harvests can be specified by reducing the basal area and 'reseeding' the model for future forecasts. Interpretations about the form of harvest can be addressed as what happens to A2 when a harvest is conducted. If tree harvests are assumed to be equally applied across the range of species/tree DBH's, then the average height of upper canopy trees (and A2) won't be changed. This form essentially treats stands as even-aged: tree heights of upper canopy trees get progressively taller with time. This is the form we have adopted in this study for the Option C Selection and Custodial management scenarios. Moderate selective harvests, which attempt to maintain the DBH/height stand distributions could be affected by a simultaneous reduction in both B2 and A2. Innovative harvests in the form of creative species/DBH class removals are the domain of tree list models and are not considered to be applicable to this model system.

Intensive Management

The Intensive Management silvicultural regimes used in this study have evolved and are currently in use by SPI as one of several forest management prescriptions. Elements of the Intensive Forest Management Scenario are:

- Clear- felling existing stands. All snags and some large hardwoods are left standing to satisfy regulatory retention requirements and provide wildlife values. Remove all merchantable (small end dib 6"+) logs from the site. Lop and scatter all branches and tree tips.
- Mechanically rip the site to 3 feet to reduce soil compaction resulting from past harvest entries.
- Plant at a 12 x 12 foot spacing (~300 trees/acre) using ponderosa pine seedlings derived (currently) from second round genetic selection tree orchards. In reality SPI plants predominately pine it its lower elevation stands where it is the dominant, naturally adapted tree species. In the mid-elevation, mixed conifer zones a mix of ponderosa pine, sugar pine, and Douglas-fir are planted. For purposes of this study we assumed all planting were ponderosa pine.
- If necessary, apply herbicides to control competing vegetation.
- At year 10, apply a pre-commercial thinning and reduce stocking to ~150 trees per acre. Concentrate on leaving the biggest well-formed trees, spaced to fully allow each tree to grow with a minimum of competition. Effectively, this is a third round genetic selection.
- At year 50, apply a commercial thinning and reduce stocking to ~65 trees per acre. Concentrate on leaving the largest well-formed trees, spaced to fully allow each tree to grow with a minimum of competition.
- At year 80, clear – fell the plantation and start all over. Age 80 is the estimated time of the culmination of board foot mean annual increment.

Ponderosa pine plantation management is in its relative infancy in California and the mensurational database needed to provide a refined and complete modeling basis is not totally available. SPI has developed managed plantation yield tables thought to be applicable to its emerging plantation resource by a variety of means, which include:

- Calibrating the SYSTUM_1 (Ritchie and Powers, 1993) small stand-plantation growth model to be in line with observed early plantation development.

- Calibrating the CACTOS model to be in line with data from the few older (50-70 years) managed pine plantations that exist in California and early results with the Gspace ponderosa pine plantation model developed by Drs. Stone and Cavallaro from U.C. Berkeley.

Site class specific yield tables have subsequently been produced from these models and form the basis of plantation yields used in this study. Particularly note worthy items about estimated plantation yields are:

- Site index classification of actual plantations based on observed dominant heights in the 20-35 year age range indicate increases from the stands they replaced in the range of 20 – 40 ft. For conservative purposes, we have assumed plantations will have a site index 20 feet greater than the stands they replaced.
- Continually checking existing plantations against current plantation yield tables indicates that yield tables are conservative in terms of basal area increment.

Field measurements indicate plantation growth parameters are exceeding growth projections derived from the models discussed above.

Yield Comparisons

For illustrative purposes, graphics are provided of the predicted development of the unharvested 'average stand' of both the USAW and CCW watersheds overlaid with predicted 'average' plantation development. Figure I.1 shows basal area yields and Figure I.2 shows cubic foot (CVT) yields.

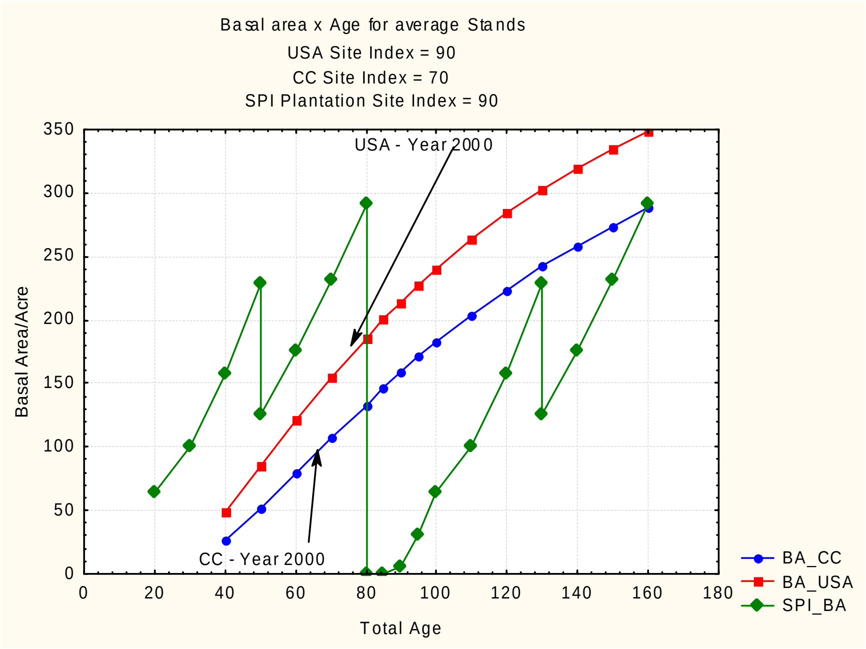


Figure I.1 Basal area yields

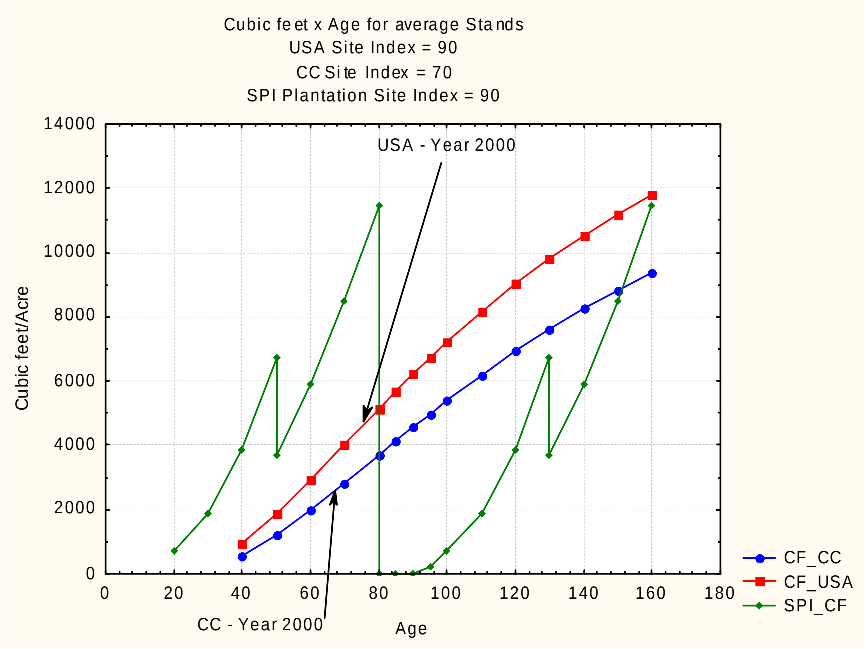


Figure I.2 Cubic Volume Yields

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