To Manage or Not to Manage: The Role of Silviculture in Sequestering Carbon in the Specter of Climate Change

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Abstract—Forests and the soils beneath them are a major sink for atmospheric CO_2 and play a significant role in offsetting CO_2 emissions by converting CO_2 into wood through photosynthesis and storing it for an extended period. However, forest fires counter carbon sequestration because pyrolysis converts organic C to CO and CO_2, releasing decades or centuries of bound C to the atmosphere as a pulse, exacerbating the greenhouse gas effect. With global warming, the probability of fire has increased. Silviculture is an important tool for reducing wildfire risk and enhancing long-term carbon sequestration and—through this—mitigating the effect of climate change. Using the data collected from three studies over the last several decades, we compared treatment effects (density manipulation, fertilization, vegetation control, and interactions among some of them) on tree growth and subsequently carbon accumulation, fire risks predicted with fire behavior simulations, and responses of stand to future climate changes modeled by a process-based model (3-PG). With these case studies, we found that (1) intensive management (vegetation control and fertilization) increased C sequestration 400 percent and decreased fire caused tree mortality 50 percent compared to control at age 21 (Whitmore Garden of Eden study). (2) Density manipulation and vegetation control increased C sequestration 30 percent and decreased fire caused tree mortality 50 percent compared to control at age 40 (Challenge Initial Spacing study). (3) Density manipulation increased C sequestration 9 percent and decreased fire caused tree mortality 40 percent compared to control at age 55 (Elliot Ranch LOGS study). In addition, bark beetles killed significantly more trees in the control (high density plots) than in the lower density plots. (4) The 3-PG model predicts that global warming impacts carbon sequestration more in unmanaged than managed stands. These findings suggest that if carbon sequestration and storage are goals, our forests should be managed more aggressively in the future.

Introduction

Global climate is changing at an unprecedented rate. The latest assessment from the Intergovernmental Panel on Climate Change (IPCC 2007) states that the global average surface temperature has increased 0.74 °C from 1906 to 2005. By 2100, increases of 1.1-6.4 °C are projected over the 1990 level using different models with various scenarios. Warming trends are believed to be due to the anthropogenic increase of greenhouse gases (GHG), with an increase of 70 percent between 1970 and 2004. Carbon dioxide (CO_2) is one of the most important anthropogenic GHGs. Annual emissions grew by about 80 percent between 1970 and 2004. Not only have CO_2 and GHG concentration increased greatly since 1750, but the rate of increase far exceeds pre-industrial values determined from ice cores spanning many thousands of years (IPCC 2007).

Forests play a significant role in offsetting CO_2 emissions by converting CO_2 into organic C through photosynthesis. Much of the product of photosynthesis

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is stored in the forest for decades or centuries. Despite uncertainties, annual carbon sequestration is estimated to vary between 149 and 330 million tonnes C by forests in the United States (Woodbury and others 2007), which offsets about 10 percent of US CO_2 emissions. Wildland fires have annually affected about 1.7 million ha of forests across the United States in recent decades with the area increasing in the last 10 years, thereby releasing vast pulses of ecosystem carbon back to the atmosphere.

Fire was historically an integral ecosystem process in the forests, especially forests in the Interior West. Prior to Euro-American settlement, forests of the region were more open, containing fewer trees and wider crown spacing than today (Agee 1993; Cooper 1960; Covington and Moore 1994; Skinner and Taylor 2006). Fires historically burned every 4-25 years (Graham and others 2004), thinning forest stands of small trees but also creating bare mineral soil environments favored by seedlings of some tree species, such as light-demanding pines. Starting in the late 19th and early 20th century, logging, livestock overgrazing, and fire suppression created conditions more suitable for tree regeneration and survival. Today, fire suppression and a lack of density management in both young and old stands have resulted in forests dominated by dense thickets of saplings and pole-sized trees, often with a higher proportion of shade-tolerant species. Furthermore, long intervals between fire events have led to heavy accumulations of litter, duff, and woody fuels in many areas. Therefore, today's forests are more susceptible to stand-replacing crown fires (Agee and Skinner 2005).

Managing these forests has become a great challenge to forest managers. In recent decades, Federal land management agencies and private land owners have treated millions of acres of hazardous fuels using mechanical thinning, prescribed fires, and other means. These treatments are absolutely necessary because forest structure and function would not be restored without them (Agee 2007). However, there is limited information on how these treatments affect carbon sequestration and storage and how treated stands are likely to respond to future climate. On one hand, fuel treatment may remove carbon by harvesting small-size trees and shrubs and by disturbing soils that may stimulate soil respiration. On the other, treatment may increase the vigor of remaining trees that will sequester more carbon. At the stand level, we would reallocate more carbon to residual living trees.

Manipulating stand density through thinning is not new. Since the birth of silviculture, thinning has been a major means for controlling stand density, structure, and composition (Smith and others 1996). Standing fuel reduction is merely a modern extension of density manipulation. The results from growth and yield studies established across the US in the past century can be interpreted to answer some of today's questions such as effect of density and competing vegetation control on carbon sequestration and storage, as well as fuel accumulations.

In this paper, we present three case studies that were conducted over several decades by the PSW Redding Silviculture Laboratory demonstrating how forest vegetation management has affected the fate of carbon and how silviculture may help mitigate climate change effects on our forests (table 1). These long-term permanent installations are the (1) Whitmore "Garden of Eden" study of the effects of understory vegetation control and fertilization on stand dynamics, established by the second author; (2) Challenge Initial Spacing study of the effects of stand density and understory vegetation control on stand growth; and (3) Elliot Ranch Levels-of-Growing Stock study of the effect of density on stand growth. Both established by retired Research Silviculturist William W. Oliver. These plantations represent 21, 40, and 55 years of development respectively and include a range of silvicultural treatments.

Table 1—Study site, silvicultural treatments, and climate change effect (percentage reduction) relative to normal climate on aboveground live tree carbon stock modeled with 3-PG for three plantations by assuming three scenarios (25% precipitation [ppt] reduction, 2 °C increase, and both) since the trees were planted at these sites.

Study site	Spacing/ density	Treatment	–25% ppt	+2 °C	–25% ppt +2 °C
Whitmore	2.4 x 2.4 m	Control (C)	–1.6	–14.5	–15.2
		Fertilizer (F)	–2.6	–9.6	–10.9
		Herbicide (H)	–3.3	–7.2	–9.7
		HF	–2.4	–4.5	–6.9
Challenge	1.8 x 1.8 m	Shrub present	–4.7	–3.4	–6.0
		Shrub absent	–2.3	–1.3	–3.7
	3.7 x 3.7 m	Shrub present	–1.5	–1.9	–3.7
		Shrub absent	–0.4	–1.7	–2.2
	5.5 x 5.5 m	Shrub present	–0.1	–1.8	–1.9
		Shrub absent	0.0	–1.8	–1.8
Elliot Ranch	38 m^2 ha^{-1}	Shrub present	–21.0	–16.0	–18.9
	16 m^2 ha^{-1}	Shrub present	–8.4	–0.3	–6.2

General Procedures

Aboveground Carbon Comparison

Using historical inventory data for each tree at each plot, we calculated and compared aboveground biomass among silvicultural treatments and controls. A diameter-based biomass regression (fig. 1) was established with 36 ponderosa pine (*Pinus ponderosa* C. Lawson) trees harvested at the Whitmore Garden of Eden (5-24 cm DBH) and 40 smaller diameter trees harvested from the Long-Term Soil Productivity Study installations (4-8 cm) in northern California (R.F. Powers, unpublished data). The biomass estimate for trees with DBH smaller than 4 cm must be used with caution. The allometric equation for trees with DBH of 25 cm and above was developed from 110 mature ponderosa pine trees harvested in natural stands prior to the Long-Term Soil Productivity Study installations (15 – 152 cm) at 11 sites in Northern California (fig. 2; R.F. Powers, unpublished data). After plotting predicted values from two equations, we found that both were remarkably similar for trees with DBH smaller than 25 cm (inset of fig. 2). For trees that are larger than 25 cm DBH, the equation extrapolated from small diameter trees (fig. 1) clearly underestimates the aboveground biomass. We concentrated on aboveground biomass because (1) it is more sensitive to disturbance such as wildfires and insect infestation and (2) it is relatively easier to measure the aboveground biomass than the below-ground biomass, which is not available for the larger-diameter trees. The biomass data were converted to carbon stock assuming a carbon content of approximately 50 percent by dry weight.

Fire Effects

Fire Family Plus (FFP) (http://www.fs.fed.us/fire/planning/nist/distribu.htm) software was employed to derive weather variables to use in fire simulations. We used data for Station 040615-Whitmore (http://nwcg.gov/fam-web/) to represent

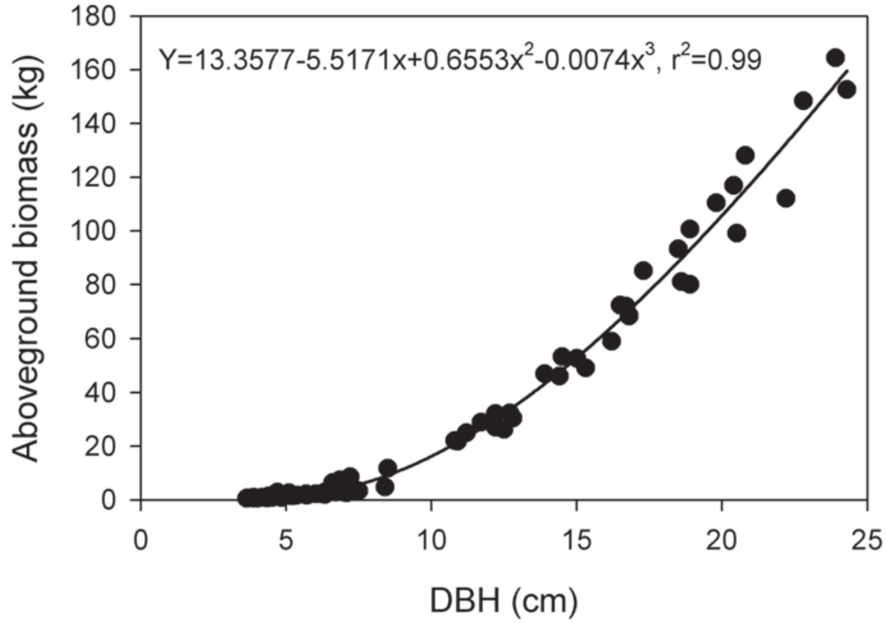

Figure 1—Ponderosa pine diameter-based biomass regression for 21-yr-old trees at Whitmore and some small diameter trees harvested at the Long-Term Soil Productivity installation in northern California. The range of DBH is between 3.6 cm and 24.3 cm.

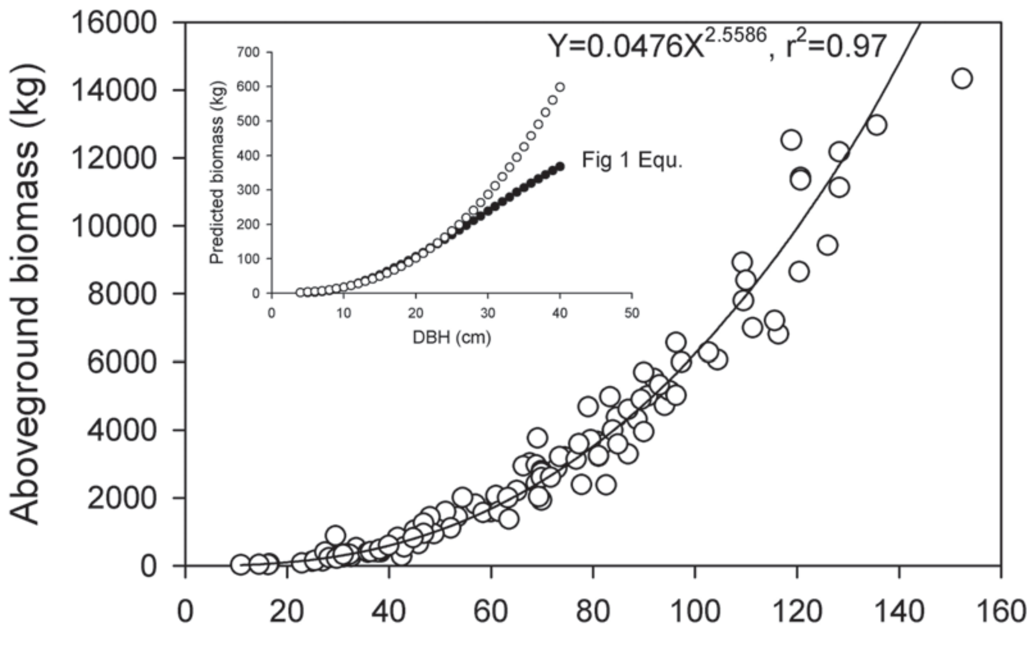

Figure 2—Ponderosa pine diameter-based biomass regression for mature trees (15-152 cm) harvested prior to the Long-Term Soil Productivity installations in northern California. The predictions from this power equation are remarkably similar with predictions from the polynomial equation established for trees with DBH less than 25 cm (inset figure).

conditions for all of our study sites in order to facilitate cross-site comparisons. Environmental conditions for fire behavior simulations were derived from climatological reports in FFP. Most variables are for 97.5 percent burning conditions (conditions exceeded only 2.5 percent of the time each year). Windspeed was set at the 97 percent condition of 8 km/hr (conservative for windspeeds in high-intensity wildfires in our study areas), but temperature and moisture conditions are mean high/low August values (35 °C, 10 percent relative humidity). Moisture contents of ground fuels were set at 2 percent, 4 percent, and 4 percent for 1-, 10-, and 100-hour fuels, respectively. Live fuel moistures were set at 30 percent, 56 percent, and 80 percent for herbaceous, woody, and foliage materials, respectively. For each simulation we used a standard fuel model from one of three sources: Rothermel (1983), Fire Program Solutions (FPS) (2005), or Scott and Burgan (2005). We did not attempt to create a custom fuel model since we did not have an opportunity to calibrate fire behavior output with an actual fire.

All fire behavior simulations were performed using the CrownMass routine of the Fuels Management Analyst Suite 3.01 (FPS 2005). This program allows the entry of a tree list from the site to estimate the canopy fuel conditions. This is then combined with a standard surface fuel model in the scenario to simulate surface fire spread and intensity as well as the potential for torching and crowning as described by Scott and Reinhardt (2001).

Calibrating the 3-PG Model

To examine climate change effects on aboveground biomass, we needed a process-based model to predict stand dynamics by varying temperature and precipitation. Because the Whitmore "Garden of Eden" study includes vegetation control and fertilization treatments and was intensively measured with the detailed records for 20 years, we used these records to calibrate the 3-PG (Physiological Principles Predicting Growth) model (Landsberg and Waring 1997) for ponderosa pine grown in northern California. 3-PG is a process-based model to predict forest performance with climatic variables as drivers. It holds several advantages for managers. First, 3-PG is a relatively simple stand-level model. Like other process-based models, it includes subroutines to calculate photosynthesis, transpiration, respiration, growth allocation, and litter production. Notably, 3-PG differs from most process-based models in that it requires only readily available site and climatic data as inputs, and predicts the time-course of stand development in a form familiar to the forest manager. Second, it is very user-friendly; a Microsoft Excel workbook includes everything—input and code that you can change, and output results in a normal spreadsheet. Finally, it has been extensively tested in the world's major forest species, including *Eucalyptus* spp., *Picea sitchensis* (Bong.) Carrière, *Pinus ponderosa* C. Lawson, *P. radiata* D. Don, *P. taeda* L., *Pseudotsuga menziesii* (Mirb.) Franco, etc. (Landsberg and others 2001; Law and others 2000; Sands and Landsberg 2002; Waring 2000). After calibrating key parameters with one treatment at Whitmore, we applied the model to other treatments at this site, the Challenge Initial Spacing study, and the Elliot Ranch LOGS study. We used the aboveground biomass output to compare the aboveground biomass estimation from the allometric equations for the silvicultural treatments at each site. Similarly, as calculated biomass from observed DBH, biomass was converted to carbon stock.

During model calibration, we used all parameters given by Law and others (2000) as our prototype blueprint for ponderosa plantations in northern California. Based on our biomass data at Whitmore, we found that the mathematical relationship between stem mass and diameter was:

$$W_s = 0.0456*(DBH)^{2.5687}, \ r^2 = 0.99$$

Where: W_S is the stem and branch biomass in kg and DBH is diameter at breast height in cm. Therefore, both the constant and power differ from the parameters used by Law and others (2000) in Oregon.

In addition, ratios of foliage to stem partitioning differed from those for mature natural stands in Oregon. Our ratios were about 0.85 at DBH = 2 cm and 0.14 at DBH = 20 cm.

Maximum quantum use efficiency also differed from mature Oregon stands. By measuring sun and shade leaves from 36 trees grown from the different treatments at three Garden of Eden sites, quantum use efficiency was found to be 0.05 (Liang Wei, unpublished data, University of Idaho). Remarkably, there was no difference between sun and shade leaves, among treatments, or among sites.

We also added in maximum stand density of 365 as a constraint for tree mortality because stand density is strongly influenced by *Dendroctonus* bark beetles in northern California (Oliver 1995).

Climatic Data and Climate Change Scenarios

Climatic data for the model were obtained from weather stations nearest to each site. Temperature and precipitation are commonly available and are must-have variables. Incident solar radiation was calculated following Coops and others (2000). The 3-PG simulator can run with monthly data for specific years (Whitmore and Challenge) or with mean monthly data for many years (Elliot Ranch) if yearly data are not available. Whitmore Garden of Eden data were from a Remote Automated Weather Station (RAWS) at Whitmore, about a km from the study site (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?caCWHT). The data before 1990 when the station was installed were obtained from the average of 1990-2007. Two weather stations were used to make a complete climatic data for the Challenge Initial Spacing study since 1966: Strawberry Valley (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca8606) and Challenge Ranger Station (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca1653). Due to a lack of data for the last 60 years, we used station mean data for Elliot Ranch site; two stations were used: Foresthill (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?caCFOR) and Iowa Hill, CA (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4288).

After the model was calibrated, we made projection runs for each treatment with the past climate. The modeled values were compared with calculated values from the allometric equations based on periodic DBH measurements. Then, we ran the model again by increasing temperature 2 ºC, reducing precipitation by 25 percent, or both. The final changes relative to the first run were presented as the climate change effect for each treatment itself. Lastly, impact of silvicultural treatments was compared.

Case Study I: Whitmore "Garden of Eden"

Site Characteristics and Experimental Design

The Garden of Eden study was established to determine the biological response of ponderosa pine to a broad array of silvicultural treatments over a range of sites typifying plantation management in northern California. These plantations were established on lands cleared of brushfields or natural forest from 1986 to 1988. Each plot measuring 19.7 by 21.9 m was hand-planted at a standard square spacing of 2.4 m with seedlings from superior genetic stock known to perform well at each seed zone and elevation. Following planting, 8 treatments were applied to 24 plots in a completely randomized design. The standard suite of treatments consisted of a control (C: planting and no further treatment); fertilization only (F: eight nutrients applied at planting, and at an exponential rate over the next 6 years); vegetation control only (H: glyphosate herbicide applied annually to control all understory vegetation for the first 5 years); and fertilization and vegetation control combined (HF). An additional silvicultural treatment, systemic insecticide (I), was applied as well, producing 3 replications each of 24 plots. Each treatment plot of 0.04 ha consisted of 72 trees, but only the innermost 20 were used for measurement. Treatment details can be found in Powers and Ferrell (1996) and Powers and Reynolds (1999).

The Whitmore Garden of Eden plantation, the oldest in the series, was planted in spring 1986 on land managed by W.M. Beaty and Associates in eastern Shasta County on the southwestern slope of the Cascade Range (Lat. 40.62 N; Long. 121.90 W). Elevation of the Whitmore plantation is 730 m and precipitation averages 1,140 mm annually. The soil is the Aiken soil series (clayey, mesic Xeric Haplohumults), a widespread soil developed from a Pleistocene volcanic mudflow and typical of the west slope pine forest. Prior to clearing, the site supported a brushfield dominated by whiteleaf and common manzanitas (*Arctostaphylos viscida* Parry and *A. manzanita* Parry, respectively) that originated from a 1967 wildfire. Site index (Powers and Oliver 1978), based on measurements of older trees in surrounding stands, averages 23 m (78 ft) at 50 years.

After installation, all measurement plots were inventoried at ages 2, 5, 6, 10, 15, 21 years. Each tree was measured for DBH, height to the base of the live crown, and total tree height. In the earlier years when trees were less than 1.4 m tall, diameter at 10 cm above ground was measured. All understory vegetation was measured for height and percent cover by four line intercept transects per plot, each 10 m long. Sample trees spanning the range of tree sizes were felled at ages 15 and 21 for biomass analyses (3 trees per treatment plot). Each tree stem was measured and sectioned at several stem positions and rounds taken for determining oven-dry weights after drying to a constant weight at 70 °C. Bole mass was then estimated by applying mass/volume ratios of each round to the bole volume in each sequential sector. Crowns were divided into 5 equal-length sections and the branch of average basal area was taken from each section for dry weight analysis after separation into wood and needles. Crown mass per sector was estimated as:

$$\text{Crown sector mass} = \sum(\text{mass/basal area of sample branch x basal area of all branches})$$

Crown sector masses for each sample tree were summed for a single estimate of individual crown mass. This, added to the mass estimate for the bole, produced a mass estimate for each individual sample tree. Due to lack of an allometric equation to calculate biomass for trees that are under 1.4-m tall, we used data collected at ages 5 and older to tune the 3-PG model.

Aboveground Tree Carbon

At age 21, aboveground tree carbon stock was 73.3, 55.1, 44.2, and 20.0 Mg ha^{-1} on HF, H, F, and C, respectively (fig. 3), and treatment effects were highly significant ($P<0.001$). Relative to control trees (that is, do nothing after trees were planted), trees in the fertilizer only treatment (F) accumulated twice the mass of carbon, while the herbicide only treatment (H) nearly trebled the amount and HF treatment almost quadrupled the amount, compared with control trees. Therefore, managed stands stored much more carbon in trees than unmanaged stands.

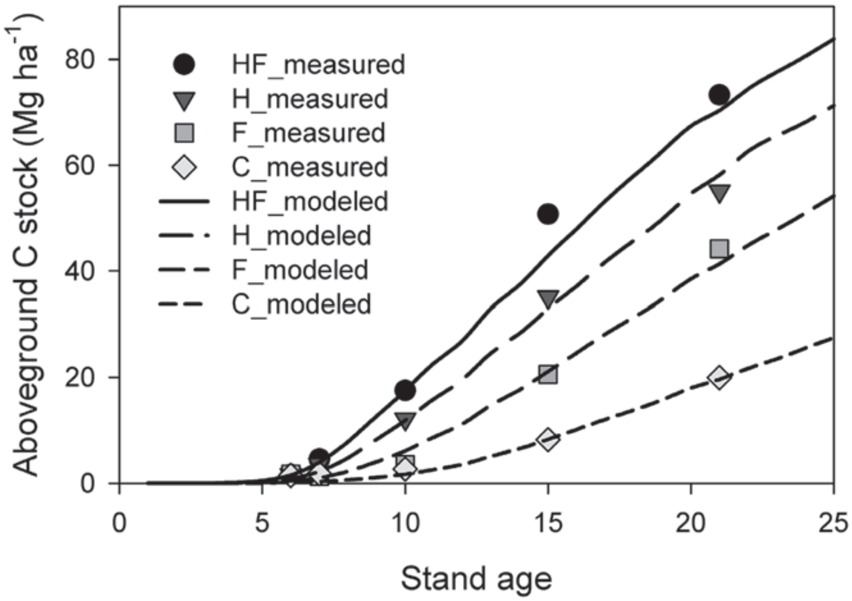

Figure 3—Age-related aboveground tree carbon stock accumulated on HF, H, F, and control plots at the Whitmore Garden of Eden study, Whitmore, California.

Fire Effect

By age 21, shrub cover was 57 percent and average height was 1.3 m (table 2) in the control plots so that fire behavior was modeled as a shrubfield fuelbed. Flames exceeded tree height leading to a crown fire. Mortality was projected as close to 100 percent if fire occurred at this age. Similar results would have occurred in the fertilization treatment with 99 percent mortality because fertilization stimulated the growth of understory shrubs before pine canopies had closed (Powers and Ferrell 1996) and left a continuum of dead and dying fuels that reached to the live crown once canopies had closed. In contrast, because herbicides eliminated understory in the H and HF plots, a surface litter model was used for fire simulation, which projected that flame length was less than 1 m and fire was confined to the surface. No crowns were ignited in the simulations, but scorch was sufficient to cause 40-50 percent mortality in lower crown classes at age 21. These results clearly suggest that managed stands are more resilient to wildfire even early in stand development.

Modeled Effects

Projections made with 3-PG predicts aboveground biomass well; an intercept and a slope of regression between modeled and measured values did not differ from zero and one, respectively (fig. 4). After applying three climate change scenarios in the 3-PG model, we found that a reduction of 25 percent precipitation for each of 21 years would have reduced aboveground tree carbon only 1.6 to 3.3 percent (table 1). Yet, a temperature increase of 2 °C would have reduced carbon accumulation by 7.2-14.5 percent. This result seems surprising because water is always considered a limiting factor during late growing season under the Mediterranean climate as at these sites in California. A possible, but unlikely, explanation is that these trees would not consume all precipitation so that the

Table 2—Results of fire behavior simulations for ponderosa pine plantations at Whitmore Garden of Eden treatment plots at age 21, Challenge Initial Spacing plots at age 30 when shrub data were available, and Elliot Ranch LOGS study at age 55. All fire behavior fuel models are standard fuel models from either (1) Rothermel (1983), (2) Scott and Burgan (2001), or (3) FPS (2005). Fire types are: PC = passive crown fire; SURF = surface fire.

Study site	Spacing/ Density	Treatment	Fuel model (source)	Stand HT (m)	Shrub HT (m)	Shrub cover (%)	Fire type	Flame length (m)	Mortality (%)
Whitmore	2.4 x 2.4 m	Control (C)	SH4 (2)	6.7	1.3	57.4	PC	7.3	100
		Fertilizer (F)	TU3 (2)	9.4	1.4	28.8	PC	6.1	99
		Herbicide (H)	TL8 (2)	9.8	0.0	0.0	SURF	0.6	48
		HF	FB9 (1)	11.6	0.0	0.0	SURF	0.5	42
Challenge	1.8 x 1.8 m	Shrub present	5A (3)	15.3	3.1	54.9	SURF	1.5	91.3
		Shrub absent	FB9 (1)	16.5	0.0	0.0	SURF	0.6	42.1
	3.7 x 3.7 m	Shrub present	5M (3)	16.8	2.3	64.0	SURF	1.4	77.6
		Shrub absent	FB9 (1)	19.3	0.0	0.0	SURF	0.6	24.8
	5.5 x 5.5 m	Shrub present	5Z (3)	20.2	2.3	86.2	SURF	1.8	84.8
		Shrub absent	FB9 (1)	22.9	0.0	0.0	SURF	0.4	12.6
Elliot Ranch	38 m^2 ha^{-1}	Shrub present	6M (3)	20.2	4.3	38.8	SURF	1.8	61.5
	16 m^2 ha^{-1}	Shrub present	6M (3)	18.0	2.4	22.1	SURF	1.4	36.6

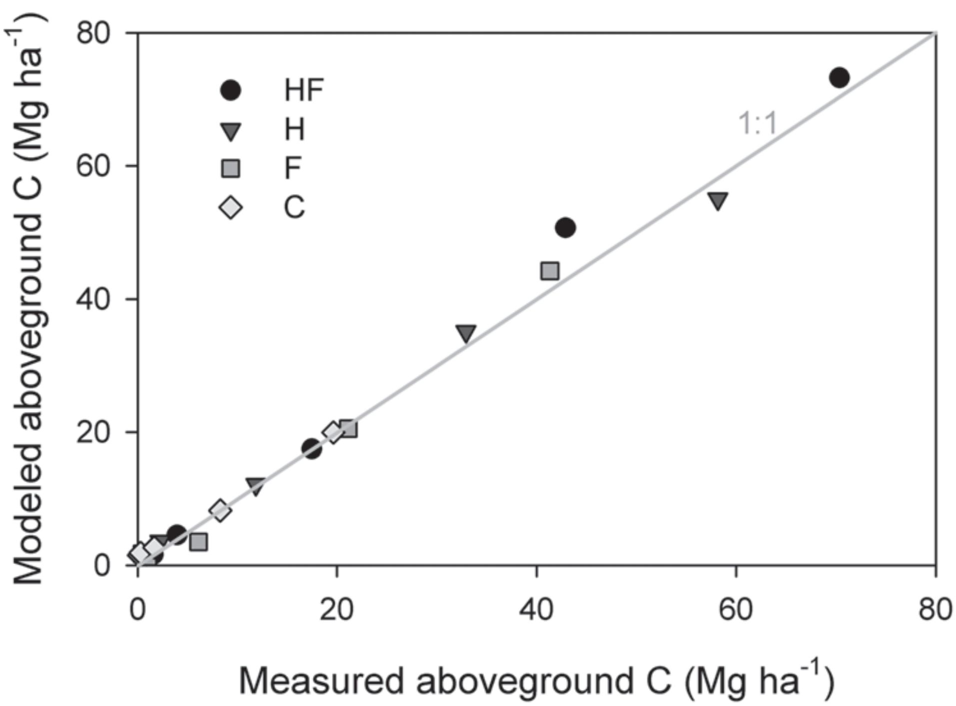

Figure 4—The relationship in aboveground tree carbon between modeled with 3-PG and calculated from measured DBH on HF, H, F, and control plots at the Whitmore Garden of Eden study, Whitmore, California.

25 percent reduction represents water lost in the system but with little effect on tree growth. Otherwise, the water relation submodel within 3-PG may need to be further improved concerning water use and transpiration. Because 3-PG is a stand model and does not account for leaf area in understory vegetation, it probably underestimates water use by trees in a droughty climate. By assuming both 25 percent reduction of precipitation and a temperature increase of 2 °C since 1986, we found that carbon storage would have reduced 6.9 to 15.2 percent. Carbon accumulation aboveground was reduced more in the control plot trees than in any managed plots, suggesting that untended plantations are particularly sensitive to climate change.

Case Study II: Challenge Initial Spacing Study

Site Characteristics and Experimental Design

This study was established with planted seedlings near the lower edge of the mixed-conifer forest, on the west slope of the northern Sierra Nevada (Lat. 39.48 N; Long. 121.22 W). Elevation is 810 m and precipitation averages 1,730 mm annually. Soil, an Aiken clayey, mesic Xeric Haplohumult, is more than 1.5 m deep. Dominant shrub species are whiteleaf manzanita, deerbrush (*Ceanothus integerrimus* Hook. & Arn.), squaw carpet (*C. prostratus* Benth.), Indian manzanita (*A. mewukka* Merriam), small numbers of Sierra gooseberry (*Ribes roezlii* Regel) and sprouts of California black oak (*Quercus kelloggii* Newberry) and tanoak (*Lithocarpus densiflorus* [Hook. & Aan.] Rehd.).

The original stand was 70-year-old ponderosa pine with a site index of 30 m at 50 years, which was clearcut for this experiment. Logging slash was raked, piled, and burned off the unit. In March 1966, ponderosa pine seedlings were planted in two randomized blocks. Each block contains five plots that were planted at square spacings of 1.8, 2.7, 3.7, 4.6, and 5.5 m. Each plot was split into two adjacent subplots. On one subplot, brush seedlings were grubbed out by hand for the first year and then herbicide 2,4,5-T (2,4,5-trichlorophenoxy acetic acid) was applied by hand sprayer in the second and fourth years after planting. Subsequent shrub seedlings were removed by hand for about five more years. On the other subplot, shrubs were allowed to develop naturally. Each subplot contained 12 measurement trees that were buffered from adjacent plots by at least 7 m, minimally two rows of trees. Because the same number of trees was used among plots, subplot size with buffer varied among treatments, covering 0.05 ha for 1.8 m spacing plots to 0.15 ha for 5.5 m spacing plots.

Height and DBH (if tree height reached 1.37 m) were measured every year from 1968 to 1975, every two years from 1975 to 1985, and every four years from 1985 to 2006. Other measurements include height to live crown, crown width, and tree condition.

Aboveground Tree Carbon

Based on our biomass equation, aboveground tree carbon stocks for shrub present and shrub absent treatments at 40 years were 78.0 and 70.3 Mg ha^{-1} on 1.8 m spacing, 80.8 and 99.2 Mg ha^{-1} on 3.7 m spacing, and 72.6 and 92.8 Mg ha^{-1} on 5.5 m spacing, respectively (fig. 5). The results suggest that control of competing vegetation enhances tree growth and carbon storage compared to the plots with shrubs present at the wider spacings. At the narrowest spacing of 1.8 x 1.8 m, the plots with shrubs absent developed so quickly that mortality occurred much earlier than the treatments leaving shrubs present. As a result, carbon stocks are higher on the shrub present plots.

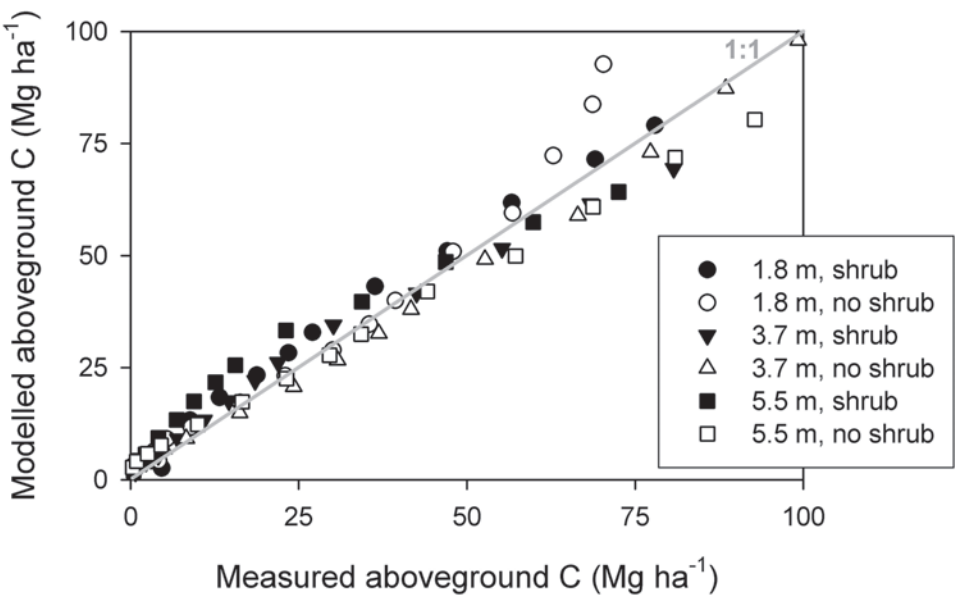

Figure 5—The relationship in aboveground tree carbon between modeled with 3-PG and calculated from measured DBH on three spacings split with either shrub present or shrub absent plots at the Challenge Initial Spacing study, Challenge Experiment Forest, California.

Fire Effect

By age 30, in plots where shrubs were not controlled, shrub cover ranged from 54.9 percent to 86.2 percent and average height varied from 2.3 to 3.1 m (table 2). These plots were modeled as a shrub-dominated fuelbed. Fire intensity in these plots was estimated to cause between 77.6 percent and 91.3 percent mortality depending on density of plantings (table 2). Where shrubs were controlled, a surface litter model was used for fire simulation, which projected fire mortality to range only from 12.6 percent to 42.1 percent—again depending on tree density. No crowns were ignited in the simulations, and mortality was caused primarily by scorch and cambium damage. Again, these results suggest that more intensively managed stands are more likely to be resilient to wildfire.

Modeled Effects

Overall, aboveground tree carbon stock based on DBH measurements was strongly correlated to 3-PG modeled aboveground tree carbon (fig. 5). Because our allometric equation was developed from trees with DBHs 3.6 cm and greater, a weaker relationship was expected at young ages. At later years, heavy mortality at 1.8 m spacing with shrub absence yielded a C stock overestimated by 3-PG.

After applying the three climate change scenarios in the 3-PG model, we found that a reduction of 25 percent precipitation for each of 40 years would have reduced aboveground tree carbon only 0 to 4.7 percent (table 1). A climate warming of 2 ºC would reduce carbon 1.3-3.4 percent and the combination of both changes would reduce carbon by 1.9 to 6.0 percent, varying with densities and whether shrubs were controlled. In general, high density stands are more sensitive to temperature increase and precipitation reduction because of greater competition for soil resources. Similarly, shrub present-plots are more sensitive to climate change.

Case Study III: Elliot Ranch Levels-of-Growing Stock Study

Site Characteristics and Experimental Design

These plots were established in a plantation that originated after the Elliot Ranch Fire, which burned a deerbrush shrub and snag field that had developed following the 1949 Elliot Ranch Burn. The area was planted at 1.8 by 2.4 m spacing in 1950 with 1-1 ponderosa pine stock from the appropriate seed zone. The plantation is located on the Foresthill Ranger District, Tahoe National Forest (Lat. 39.16 N; Long. 120.74 W) on the western slope of the Sierra Nevada. Elevation is about 1,200 m and precipitation averages 1,524 mm annually. Three clay-loam soils, Cohasset and Horseshoe Series (loamy, mesic Ultic Haploxeralfs) and an unclassified alluvium, underlie the study area (Oliver 1979). The average site index is estimated to be 35 m at 50 years. Cohasset Series is slightly more productive than Horseshoe, and trees growing in Cohasset soil in the study area are estimated to be 36.5 m tall at 50 years. Trees on the alluvial soil express a site index similar to Horseshoe Series.

The study plots were established in 1969 when the plantation was 20 years old. This is one of six installations in the west-wide levels-of-growing-stock study for even-aged ponderosa pine guided by Myers' (1967) study plan. Portions of the Elliot Ranch plantation were used in developing yield tables for managed stands of ponderosa pine (Oliver and Powers 1978).

All plots are buffered with a 9-m isolation strip. The study design is fully randomized with three replications. All plots are 0.2 ha in size, exclusive of buffer. Five thinning treatments of 9, 16, 23, 30, and 37 m^2 basal area per ha were applied in 1969. Rethinnings in 1974 and 1979 restored the original basal area stand densities. The third rethinning in 1989 used Stand Density Index as the measure of stand density and resulted in an increase of approximately 10 percent in growing stock for each density treatment.

All trees within the plots were measured for DBH. Stem deformities and evidence of insect and disease attack were also noted. Total height and height to live crown were measured on a 20 percent systematic sample of the trees during all but the last measurement in 2004. At that time, all trees were measured for total height. A probability-proportional-to-size sample of six trees per plot was measured with an optical dendrometer for stem volumes during several remeasurements.

Aboveground Tree Carbon

To demonstrate effect of treatments, we only calculated tree carbon for two stand densities: 16 m^2 ha^{-1} (70 ft^2 ac^{-1}) and 38 m^2 ha^{-1} (160 ft^2 ac^{-1}); the latter similar to that of the natural untreated stand. Treatment plots were installed when the plantation was 20 years old and stand densities were achieved with repeated thinning. After each thinning, only bole wood was removed from the site. Thinning slash from the original thinning was piled and burned in the isolation strips between the measurement plots, while that from subsequent thinnings was lopped and scattered. We calculated live-tree carbon using a specific gravity of 0.38 Mg m^{-3} in converting wood volume to biomass. Collectively, there was 201 Mg ha^{-1} carbon stock (current live trees, 156; initial thin, 16; repeated thins, 30) on 16 m^2 ha^{-1} plots and 185 Mg ha^{-1} (current live trees, 166; initial thin, 2.4; repeated thins, 17) on 38 m^2 ha^{-1} plots. Not only did moderately thinned plots produce large-sized healthy trees within 55 years, but also they stored about 16 Mg ha^{-1} more carbon than lightly thinned plots. The National Forests across the Sierra Nevada consider 76 cm (30 in.) trees as must-keep "old growth" trees during fuel reduction projects (fig. 6). With an appropriate silvicultural treatment, some trees can reach that category of apparent "old growth" in only 55 years. In addition, higher density plots suffered greater mortality, mainly caused by bark beetles, than lower density plots (fig. 6). These dead materials have become hazardous fuels for the forests.

Fire Effect

Shrubs were present in both stand conditions at this site and cover varied from 22.1 percent to 38.8 percent. Where shrubs were present, the fire simulation estimated flame lengths exceeding 1 m. Fire mortality was estimated to be 36.6 percent in the lower density plots and 61.5 percent in the higher density plots (table 2). This difference is due primarily to greater shrub height and cover, and smaller trees in the later plots leading to greater area experiencing the higher intensity fire. As at Challenge, the fire simulation indicated mortality was due mainly to crown scorch and cambium damage.

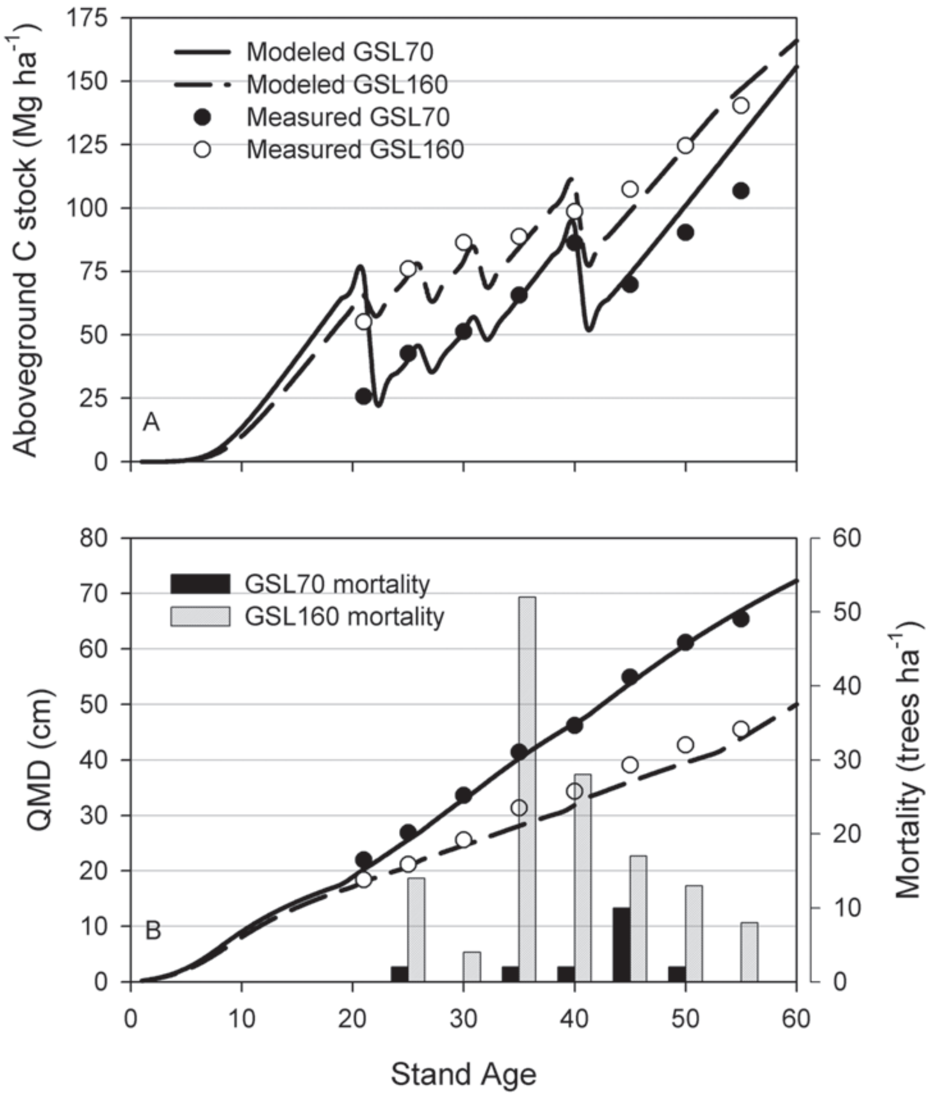

Figure 6—Measured and modeled aboveground tree carbon stock (A) and quadratic mean diameter (QMD) and tree mortality (B) on two growing stock levels at 16 m^2 ha^{-1} (70 ft^2 ac^{-1}) and 38 m^2 ha^{-1} (160 ft^2 ac^{-1}) plots across the last 55 years at the Elliot Ranch Level-of-Growing-Stock study, near Foresthill, California.

Modeled Effects

The 3-PG projection also tracked the thinning events well (fig. 6). We performed 3-PG runs based on the three scenarios of climate change that included the initial and repeated thinning treatments. Interestingly, the 25 percent precipitation reduction yielded the most reduction of carbon stocks with 8.4 percent for 16 m^2 ha^{-1} plots and 21 percent for 38 m^2 ha^{-1} plots, respectively (table 1). After 55 years, 2 ºC increases would have reduced C by 0.3-16 percent. Together, lower precipitation and higher temperature would have reduced C storage by 6.2 percent and 18.9 percent for the two densities. However, the higher density plots are more sensitive to climate change.

Concluding Remarks

Results from these case studies indicated that silviculture can play a significant role on managing forests for carbon and for mitigating the deleterious effects of climate change. Although what we presented here are results from plantations, the concept should hold for natural stands, especially when we consider wildfire as a part of ecosystem processes.

Managed stands accumulated more aboveground tree carbon than unmanaged stands. The result should not surprise forest managers because the goal of silviculture in earlier years was to maximize the highest wood production on a given land unit (Fernow 1914) and carbon stock is directly related to stem volume. We concentrated only on the aboveground tree carbon in this chapter because this represents stabilized carbon that varies considerably with stand ages. Understory vegetation and forest floor components are also important, but relatively unstable carbon because they are more susceptible to wildfire.

Managed stands are more resilient to wildfires or bark beetle infestation than unmanaged stands. This result supports the experience of seasoned forest managers, and echoes a major conclusion reached by Agee (2007) in his keynote at an earlier National Silviculture Workshop. In the past few decades, federal land management agencies and private land owners have treated millions of hectares of hazardous fuels using mechanical thinning, prescribed fires, and other means in order to create forests resilient to intensified wildfires or insect infestation. The challenge facing us is how we can use silviculture in meeting the multiple-use objectives for our forests.

Unmanaged stands are more sensitive to global climate change than managed stands in terms of carbon accumulations. Our three study sites are located near the lower edge of the mixed-conifer forest, on the western side of the Sierra Nevada and are dominated by a Mediterranean climate with wet and mild winters and hot and dry summers. Weather patterns suggest that growing season is controlled by water availability. Any management tools that improve availability of water and other resources during the growing season will benefit individual trees as well as stands.

Western ponderosa pine ecosystems have changed dramatically in structure and composition over the past century. More open forests with fewer trees and wider crown spacing have often been replaced by forests dominated by dense thickets of saplings and pole-sized trees due to various reasons. More than ever, these forests need to be managed in order to preserve their ecosystem services for this and future generations.

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