

# Modeling Carbon Sequestration in Managed Forests WESTCARB Phase II Final Report

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## SUMMARY

We analyzed above- and belowground biomass in a 21-year-old research plantation typical of many sites in northern California. The Whitmore Garden of Eden installation is the oldest among the most intensively studied pine plantations in the West. Treatments included a control (C = planting and no further treatment), fertilization without vegetation control (F), vegetation control without fertilization (H), and both vegetation control and fertilization combined (HF). Total perennial biomass of planted trees spanned more than a 3-fold difference at 21 years, ranging from 54 Mg/ha (C) to 180 Mg/ha (HF), equivalent to about 27 and 90 Mg carbon/ha. However, perennial biomass differences between extreme treatments disappeared when living understory vegetation on control plots was included (C = 172 Mg/ha, HF = 181 Mg/ha). Of this, between 25% (HF) and 32% (C) occurred belowground, indicating the significance of perennial roots as a major carbon sink. Untreated plots (C) at 21 years had one-fifth greater total biomass than plots receiving vegetation control (H). However, understory shrubs accounted for two-thirds of the biomass on C plots, and one-quarter of the biomass on F plots because fertilization hastened tree canopy closure and the gradual decline of the understory. Fertilization treatments increased the carbon mass of the forest floor (13.3 and 12.2 Mg/ha for F and HF treatments, respectively; 8.7 and 9.2 Mg/ha for C and H treatments, respectively). Thus, the forest floor is a substantive, but ephemeral, carbon sink, holding between 9 and 14% of total ecosystem carbon exclusive of soil, and 12% to 19% of all aboveground carbon.

Fire behavior simulations calibrated for typical August conditions were applied to each of the treatments from the 10<sup>th</sup> to the 21<sup>st</sup> year of plantation development. Throughout this period, simulated flame lengths on C plots exceeded tree heights, leading to complete tree mortality. Fertilization (F) increased the growth of understory shrubs through the first 15 years so that simulated flame lengths exceeded tree heights, producing passive crown fires and 100% plantation mortality. By 21 years, planted pine canopies had closed on F plots and live understory shrubs had declined. Simulated flame lengths were less than tree heights, but heat convection still triggered nearly complete mortality. Fire effects in the H and HF treatments were simulated by surface litter models because these treatments lacked a shrub layer. Simulated flame lengths were always less than 1 m in H and HF treatments and less than average tree heights. However, crown scorch would be sufficient to kill about two-thirds of the trees at age 10. With time, trees grew larger and became more resistant to fire. By 21 years, mortality was projected to be 48% in H treatments, and only 42% in HF.

Additionally, three plots in the H treatment and three in the HF treatment had been thinned at age 10, removing the smallest 50% of the planted trees. Because thinning increased growth rates of the remaining trees, mortality projections from simulated wildfire were less than in the unthinned plots receiving H or HF treatments. Models predicted only surface fires with mortality ranging from a high of 56% to 61% (H and HF) at plantation age 10 years to between 32% and 39% (H and HF) at age 21. Although thinning slash was removed in this study, precommercial materials in operational thinnings sometimes are left on site. If retained, thinning slash creates ground fuels with persistent tinder-dry foliage. Simulated fire occurring two years after thinning and slash retention would produce flame lengths of 2.3 m, creating passive crown fires and nearly complete tree mortality. However, fuel loadings lessen with time. Simulated mortality from later fires fell to 45% by 15 years and to 30% by 21 years. Impacts of wildfire on carbon loss depend on the fraction volatilized during combustion and the fate of dead or dying residual material. Carbon dioxide will be released from residual slash through slow decomposition, but some will remain as inert charcoal. Estimating carbon quantities released as CO<sub>2</sub> or retained as charcoal is beyond the scope of this study.

Assuming fire-free conditions and a future climate similar to that of the present, we projected plantation development for C, F, H, and HF treatments to 50 years using the stand-level process model 3-PG. This model estimates carbon assimilation and allocation based upon leaf area, relative humidity, soil water availability and soil fertility, and accounts for self-thinning. Understory shrubs dominated total productivity on untreated C plots through the first 21 years of plantation development, but shrubs declined to possible extinction after three decades. By 50 years, total ecosystem forest biomass on untreated plots was projected at 243 Mg/ha. Stands receiving only fertilization (F) showed an initial biomass peak of 201 Mg/ha at 18 years, followed by a decline lasting about a decade. This peak was dominated by understory shrubs that declined rapidly as tree canopies closed. Biomass accumulation began to accelerate by year 22, and total biomass by 50 years was projected to be 376 Mg/ha, mostly in tree stems. Tree stems dominated the biomass throughout the life of the stand where vegetation had been controlled (H), culminating in a total ecosystem biomass of 407 Mg/ha by age 50. Combining vegetation control with fertilization (HF) projected to the greatest gains of all: 487 Mg/ha at 50 years. Thus, 3-PG simulations project carbon accumulations of between 122 and 244 Mg/ha, exclusive of gains to the soil and assuming no incidence of wildfire.

Free of fire, these projections translate conservatively to mean annual carbon sequestration rates of from 2.4 to 4.9 Mg/ha exclusive of soil, offering a broad range of carbon management options. In reality, wildfire is likely. Fuels accumulating from understory shrubs in C and F treatments create a risk of very high mortality from passive crown fires, but H and HF treatments would likely survive. Implications for carbon sequestration are profound. Modeling forest carbon fluxes with a hypothetical fire return interval of 20 years suggests a potential loss of about 50 to 100 Mg carbon/ha over a 50-year span. Lacking understory management, sites with conditions similar to those at Whitmore would probably become fire-susceptible brushfields. Should one or more commercial thinnings occur (unlikely in the C treatment, but a viable option in the H, F, and especially HF treatments), a sizable proportion of carbon would be transferred to long-lived forest products, with only a minor decline in carbon in the residual plantation.

## OVERVIEW

### 1. Objectives

Our objectives were to assess the potential for carbon sequestration in pine plantations managed under a range of silvicultural options. Data from a research plantation in Shasta County, California were used to model changes in vegetational biomass both above and below ground. Work focused on the Whitmore Garden of Eden plantation, one of a set of experimental research sites established throughout northern California (Powers and Ferrell 1996). The Whitmore plantation was chosen for two reasons: (1) it is the oldest of our Garden of Eden sites; (2) it is typical of pine plantations of average site quality in the Cascade and Sierra Nevada mountains.

### 2. The Experiment

The Garden of Eden study was established to determine how ponderosa pine (*Pinus ponderosa* Laws.) responds to a broad array of silvicultural treatments over a range of sites typifying plantation management in northern California. Plantations were established on privately managed lands converted from brushfields or natural forest. Sites were cleared and treatment plots measuring 19.7 by 21.9 m (64 by 72 feet) were established contiguously, producing 24 0.04-ha plots in four columns and six rows. In spring, each plot was hand-planted at a standard square spacing of 2.4 m (8 ft) with pine seedlings from superior stock known to perform well at each seed zone and elevation. To minimize variation among forest nurseries, seedlings were grown at the Pacific Southwest Research Station's Institute of Forest Genetics at Placerville, California. Following planting, 8 treatments were assigned randomly to the 24 plots. Treatments consisted of a control (C: planting and no further treatment); fertilization only (F: eight nutrients applied at planting, and repeated at an exponential rate over the next 6 years); vegetation control only (H: herbicides applied annually to control all understory vegetation); and fertilization and vegetation control combined (HF). An additional silvicultural treatment, systemic insecticide (I), was applied factorially as well, producing 3 replications each of 8 treatments. Each treatment plot contained 72 trees. Two rows of trees served as treated buffers and the innermost 20 were used for measurement. Treatments were applied after planting and at intervals thereafter. Details are found in Powers and Ferrell (1996) and Powers and Reynolds (1999).

### 3. The Study Site

The Whitmore plantation was planted in spring 1986 on land managed by W.M. Beaty and Associates in eastern Shasta County (Lat. 40.62 N; Long. 121.90 W). The plantation is located in the SE ¼ Sec. 18, T32N, R1E, MDM at an elevation of 730 m. Precipitation averages 1,140 mm annually. The soil is the Aiken series (clayey, mesic Xeric Haplohumults) developed from Pleistocene volcanic mudflow and found widely through the westslope pine forest of the Cascades and Sierra Nevada. Prior to clearing, the site supported a brushfield dominated by *Arctostaphylos viscida* and *A. manzanita* that originated from a 1967 wildfire. Site index, based on measurements of older trees in surrounding stands, averages 23 m (78 ft) at 50 years. This zone is particularly susceptible to wildfire (Skinner and Chang 1996).

As at other Garden of Eden plantations, insects had little effect on pine growth to date, so in spring 1996, 10 years after planting, plots receiving the HI and HFI treatments were thinned from below to remove half the trees in the smallest sizes and trees with any appreciable snow damage. On each thinned plot, two trees per plot were felled and sampled for aboveground

biomass. In fall 2006, 21 years after planting, all twelve C, F, H, and HF treatment plots were destructively sampled to assess biomass above- and belowground (see Appendix 1 for details).

## PROCEDURES

### 1. Field sampling.

Beginning in the second year, and at approximately 2-year intervals thereafter, all plots were inventoried for tree and understory characteristics. Each tree was measured for diameter at breast height (Dbh), average diameter of the live crown at the widest point, height to the base of the live crown, and total tree height. All understory vegetation was measured for height and percent cover by line intercept along four 10-m transects per plot. Records were kept by species, or by life form (herbs, other shrubs, trees) if species were infrequent. Measurements were less frequent after year 12. Soil cores were taken in August 2005 (12 per plot for surficial samples, fewer to a maximum depth of 1 m) to estimate fine root biomass (McFarlane 2007), and forest floor samples were collected the following year to estimate the mass of the detritus (see Appendix 1 for details). In November 2006, at the end of the 21<sup>st</sup> growth year, all trees in the 12 C, F, H, and HF plots were measured for Dbh and height. A tree list was prepared for each treatment plot showing cumulative frequencies by Dbh, and six trees were identified for possible felling per plot, two each from the smallest, intermediate, and largest Dbh sizes to characterize the diameter range found within treatments at 21 years. Of these, three trees (one from each size class) were felled with selection based on ease of access by equipment. In all, 9 trees were felled and sampled per treatment (three from each replicate of four treatments). Following aboveground analysis, portions of perennial root systems were excavated, dried, and weighed. Understory vegetation was sampled separately on C and F treatments for analysis of biomass above- and below ground. Details are described in Appendix 1.

### 2. Analytic Procedures

**Forest biomass.** Tree bole volume was estimated for each of the 36 sample trees from sectional measurements. Biomass was estimated by converting oven-dry weights of disks to mass per unit volume. Densities were applied to truncated conic sections and expanded to bole biomass. Crown mass was determined by summing branch and foliar mass by crown sectors. Root mass was determined by direct weighings of root wads and by combining the estimated mass of all lateral roots from the mass/diameter relationship of sampled laterals. Details are found in Appendix 1. Both linear and nonlinear regression methods were used in estimating above- and belowground biomass of sample trees at 21 years and applied to inventory data to estimate biomass/ha. Correlations and ratios for conditions at age 21 were used in estimating biomass conditions during past inventories. Throughout, half the biomass is assumed to be carbon.

**Fire effects.** Fire Family Plus (FFP 2005) software was employed to derive weather variables for fire simulations. Data for Station 040615-Whitmore (<http://nwcg.gov/fam-web/>) provided calibrations for our study plantation. Environmental conditions for fire behavior simulations were derived from climatological reports in FFP. Most variables are for 97.5% conditions ripe for wildfire (conditions exceeded only 2.5% of the time each year). Windspeed was set at the 97% condition of 8 km/hr (conservative for windspeeds in high-intensity wildfires in this area), but temperature and moisture conditions are mean high/low August values (35°C, 10% relative

humidity). Moisture contents of ground fuels were set at 2%, 4%, and 4% for 1-, 10-, and 100-hour fuels, respectively. Live fuel moistures were set at 30%, 56%, and 80% for herbaceous, woody, and foliage materials, respectively. The primary fuelbed type used for fire behavior simulation was shrubfield in both the C and F treatments. Surface litter was the fuelbed type used for H and HF fire behavior simulations and for thinnings, because all thinning slash had been removed from plots that were thinned. However, slash retention has been common historically, so we also ran simulations in which the fuel bed type was litter + slash. All fuel models are from Scott and Burgan (2005) except for FB9 (H+F age 21) that is from Rothermel (1983).

All fire behavior simulations were performed using the CrownMass routine of the Fuels Management Analyst Suite 3.01 (FPL 2005). This program allows the entry of a tree list from the site to estimate the canopy fuel conditions. This is then included 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. The program uses outputs from the Rothermel (1983) spread model to estimate the potential for crown fire as described by Scott and Reinhardt (2001).

**Projected stand development.** We conducted 3-PG simulations (Landsberg and Waring 1997) using yearly climatic data for the Whitmore weather station available through the internet (<http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?caCWHT>). Climatic data cover 1990 to the present and we used the monthly mean for the previous four years (1986-1989) to cover the intervening period from establishment. Before 2000, solar radiation was not measured by the station, so we calculated it using the method of Landsberg and Waring (1997). We ran the model with parameters developed for ponderosa pine in Oregon (Law et al. 2000), modifying the power in stem mass vs. diameter relationship from 2.97 to 2.67 (calculated from our biomass data) and the canopy quantum efficiency from 0.04 to 0.024 adapted from the ponderosa pine plantation grown in California (Misson et al. 2005). Four treatments were run individually by adjusting the fertility rating to 0.24, 0.6, 0.5 and 0.8 for C, F, H and HF, respectively, and varying maximum available soil water from 250 to 600.

## RESULTS

### 1. Tree Mass Above Ground

**Boles.** Although the more intensive silvicultural treatments clearly produced larger trees, treatments had no influence on stem form through the first 21 years. Therefore, treatments had no apparent effect on the relationship between tree Dbh and bole biomass. Bole biomass (in kg) can be estimated by the following function:

$$Y = e^{(-2.5283 + 2.2430 \ln X)} \quad r^2 = 0.95 \quad P < 0.001$$

where  $Y$  = bole mass in kg

$X$  = Dbh in cm

$\ln$  = the natural log base  $e$

$r^2$  = coefficient of correlation

$P$  = probability that the correlation is due to chance.

**Foliage and branches.** Crown data for individual sample trees were plotted by treatment against tree Dbh. Trends were independent of treatment and the following equations were used to estimate foliar and branch wood biomass per ha as a function of tree Dbh:

$$F = e^{(-4.6394 + 2.2053 \ln X)} \quad r^2 = 0.96 \quad P < 0.001$$

$$B = e^{(-4.6029 + 2.6760 \ln X)} \quad r^2 = 0.95 \quad P < 0.001$$

where  $F$  = foliar mass in kg  
 $B$  = branch wood mass in kg  
 $X$  = Dbh in cm.

Crown mass (the sum of foliage and branch wood) increased with tree diameter. Therefore, as silvicultural intensity increased, crown mass increased as well.

## 2. Tree Mass Below Ground

The mass of lateral roots collected in our sample generally increased with treatment intensity. Individual root mass varied between 8 and 747 grams in the C treatment to between 48 and 2,309 g in the HF treatment (Table 1).

**Table 1. Estimation equations for mass (g) of individual lateral roots as a function of the square of basal root diameter ( $X$  in  $\text{cm}^2$ ). Each equation based on 9 lateral roots of mean diameter.**

Treatment	Range in mass (g)	Equation	$r^2$
Control	7.84 – 746.82	$Y = 40.1510X$	0.87
Fertilize	48.11 – 1,385.68	$Y = 32.0089X$	0.96
Herbicide	20.16 – 913.23	$Y = 27.9325X$	0.65
H+F	48.39 – 2,309.12	$Y = 36.5988X$	0.95

Arraying the data as a function of squared basal diameter of the root did not indicate that the trends were affected greatly by treatment. Therefore, a generalized equation was used to estimate lateral root mass as a function of root diameter:

$$Y = 21.96X^{1.105} \quad r^2 = 0.95$$

where  $Y$  = lateral root mass in grams  
 $X$  = the square of the basal diameter of the root in cm.

This equation was applied to squared basal diameters of all lateral roots per root wad to estimate lateral root mass per tree. Combined with the dry mass of root wads, this produced an estimate of total perennial root mass per tree at 21 years. While root masses were much less in the C treatments than in any other, the relationship to tree size was relatively constant. Consequently, one regression equation was satisfactory for estimating total root mass from the product of tree  $\text{Dbh}^2$  and height (Fig. 1).

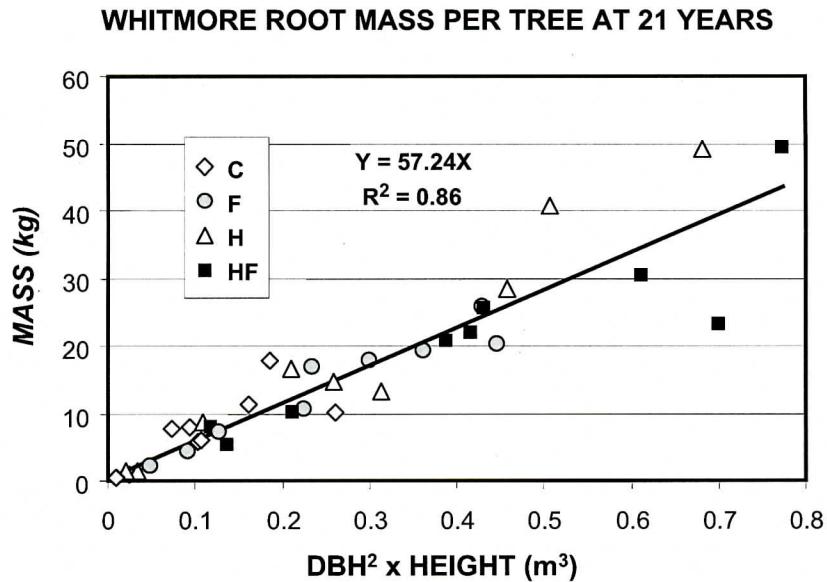
$$R = 57.24X \quad r^2 = 0.86$$

where  $R$  = total perennial root mass in kilograms  
 $X = \text{Dbh}^2 \times \text{tree height}$  in cubic meters.

Lacking height data, total root mass can be estimated from tree Dbh by the following equation:

$$R = e^{(-4.8023 + 2.6921 \ln X)} \quad r^2 = 0.95 \quad P < 0.001$$

where  $R$  = total perennial root mass in kilograms  
 $X = \text{Dbh}$  in cm.



**Figure 1. Total perennial root mass of sample trees by treatment as a function of  $\text{Dbh}^2$  and height.**

**Understory.** Miscellaneous woody shrubs (mainly *Arctostaphylos viscida*) and shade-intolerant oaks (sprouting *Quercus kelloggii*) dominated live understory ground cover throughout the first 21 years of plantation development (Fig. 2). The layered understory on control plots continued to rise through year 21 to a cumulative ground cover of just under 400% but appeared to be plateauing (Fig. 2A). Fertilization stimulated understory vegetation, particularly *Quercus* and the low-growing *Ceanothus prostratus* (Fig. 2B). Total understory cover on F treatment plots reached 900% by year 14, but showed a clear decline thereafter as the pine canopy began to close. By year 21, pine canopy cover exceeded 80% in F treatments, but had reached only 55% in C.

### 3. Total Biomass and Carbon

Trees comprised most of the aboveground biomass at 21 years on F, H, and HF treatments (89, 109, and 145 Mg/ha, respectively) (Fig. 3). But on C plots, nearly two-thirds of the total aboveground biomass was in understory vegetation, primarily *Arctostaphylos*. Understory

competition for resources clearly reduced planted tree growth (trees on C plots had only 44% of the mass of trees on H plots). In fact, understory density was sufficiently high that the sum of understory and overstory biomass on C plots was slightly greater (12%) than that of trees growing free of understory for 21 years.

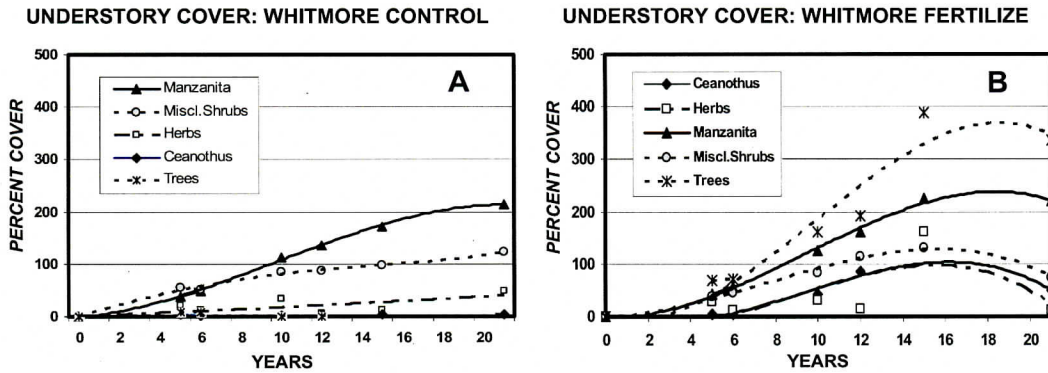


Figure 2. Trends in percent ground cover of living understory vegetation on (A) control and (B) fertilized plots at Whitmore.

**WHITMORE STANDING BIOMASS AT 21 YEARS**  
All Vegetation

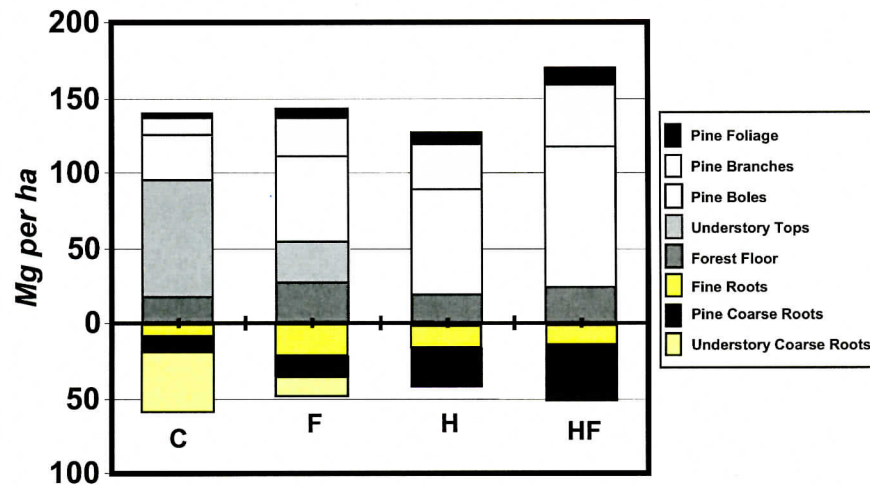


Figure 3. Biomass of forest components above- and belowground by treatment at Whitmore after 21 years of growth.

Table 2 summarizes plantation carbon content by above- and belowground components at 21 years. Total carbon storage was greatest in the HF treatment (109 Mg/ha) and least in the F treatment (83 Mg/ha). Fertilization (F), while producing twice the pine biomass carbon as in the control (C) and equivalent aboveground mass (Fig. 3), had less total ecosystem carbon. This

difference traces mainly to the large carbon mass of understory roots in untreated plots that accounted for one-fifth of ecosystem carbon (Fig. 3). On average, 26% of living biomass carbon was in roots, although the proportion was slightly higher on untreated plots. The forest floor comprised about one-tenth of plant biomass carbon across all treatments, and its mass was nearly doubled by fertilization (Table 2).

**Table 2. Estimated organic carbon in plantation components at 21 years for varying silvicultural treatments, and the proportion that each component contributes to the total.**

Component	Organic carbon (Mg/ha)--				Percent ecosystem carbon in--			
	C	F	H	HF	C	F	H	HF
Pine foliage	1.64	3.14	3.85	5.02	1.7	3.3	4.6	4.6
Pine branches	5.57	12.35	15.24	20.97	5.6	13.1	18.3	19.2
Pine stems	14.92	28.83	35.41	46.37	15.1	30.6	42.4	42.4
Understory tops	39.30	13.76	0	0	39.8	14.6	0	0
Forest floor	8.66	13.34	9.18	12.24	8.8	14.2	11.0	11.2
Fine roots	3.90	6.20	6.70	6.75	3.9	6.6	8.0	6.2
Coarse roots pine	4.75	10.60	13.08	18.02	4.8	11.2	15.7	16.5
Coarse roots shrubs	20.04	5.99	0	0	20.3	6.4	0	0
Total above ground	70.09	71.42	63.70	84.62	71.0	75.8	76.3	77.4
Total below ground	28.70	22.78	19.78	24.78	29.0	24.2	23.7	22.6
Total ecosystem	98.78	94.20	83.46	109.39	100.0	100.0	100.0	100.0

### 3. Models and Extrapolations

**Biomass.** Using the ratio of understory biomass to total understory ground cover in year 21, we estimated above- and belowground biomass in previous years for which we had ground cover data. Trends indicated a steady rise in understory biomass on C plots, reaching a peak of 79 Mg/ha at the latest measurement. Fertilization increased understory biomass, peaking at just under 100 Mg/ha in years 15 and 16, declining to only 28 Mg/ha in year 21 (Fig. 4).

After 3-PG simulation runs for each treatment, we found that modeled and measured volumes were strongly correlated at stand ages 6, 9, 10, 12, 15, and 21 (Fig. 5). And because volume and biomass are linearly linked, 3-PG could be used to predict biomass as well. Yet, the trend showed that 3-PG underestimated biomass measured at age 21. Because we are in the early phases of 3-PG tuning for northern California, we used the ratio of the measured and modeled biomass at age 21 to estimate biomass in the past and to predict biomass in the future. We apportioned biomass based on the allocation pattern at age 21 except for foliage, which maximized at an LAI (leaf area index) of 4.5.

**UNDERSTORY ABOVEGROUND BIOMASS  
AT WHITMORE OVER 21 YEARS**

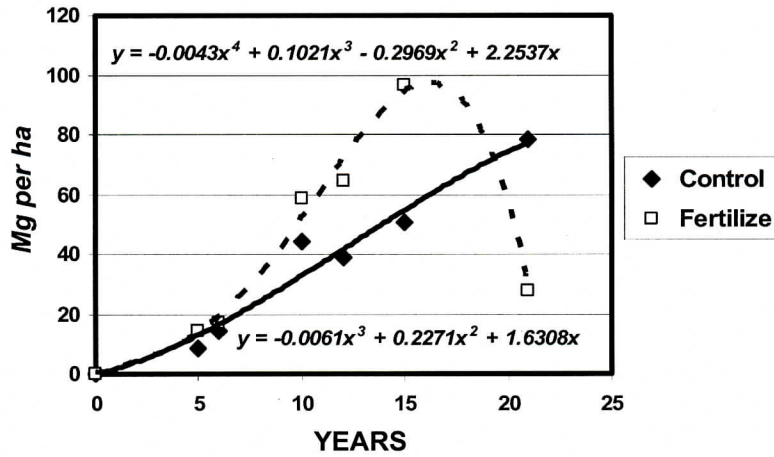


Figure 4. Estimated trend in biomass for the living understory in control and fertilized plots at Whitmore.

**WHITMORE STAND VOLUMES AT 21 YEARS  
BOTH MEASURED AND MODELED BY 3-PG**

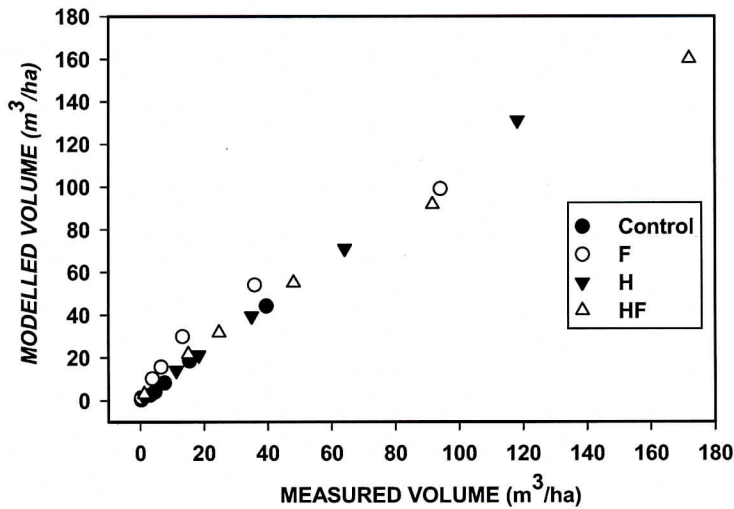
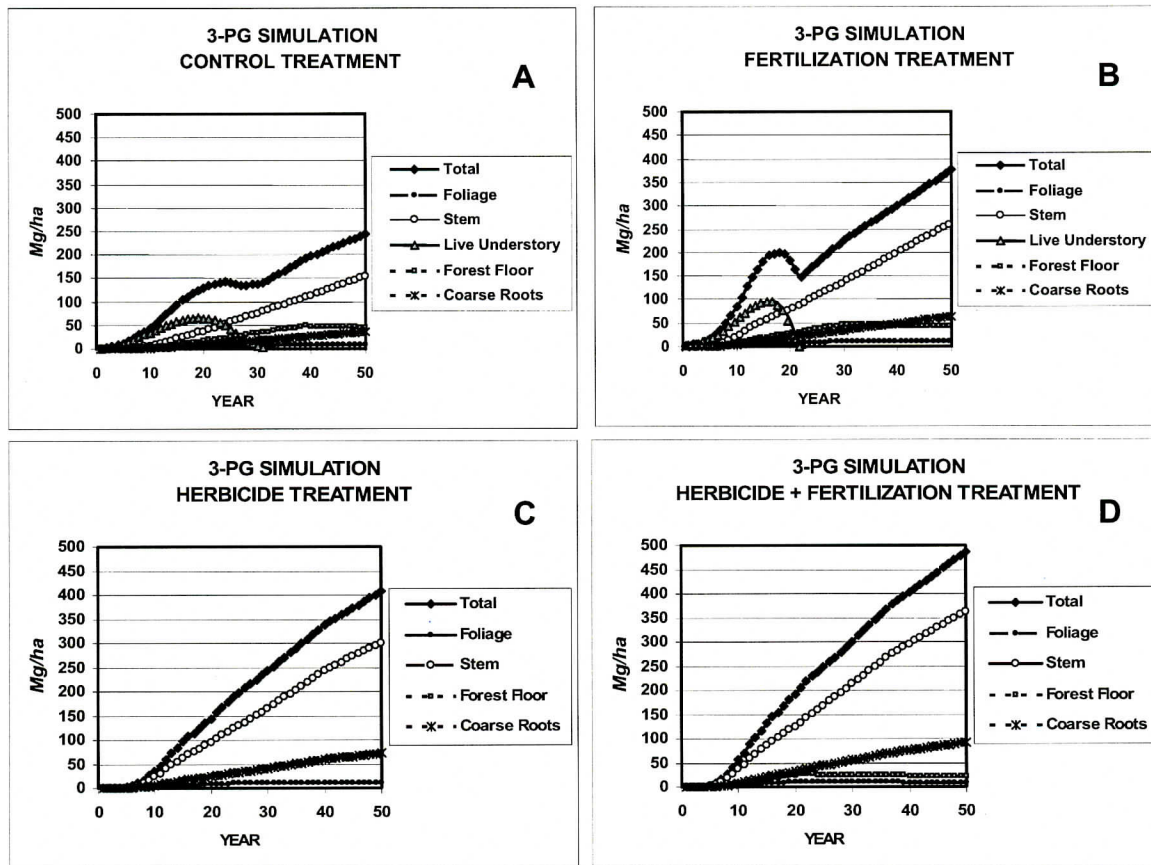


Figure 5. Comparison of 21-year measured stem volumes at Whitmore with projected volumes based on 3-PG at ages 6, 9, 10, 12, 15, and 21 years.

By age 50, total biomass was 199, 334, 383, and 465 Mg/ha for Control, F, H, and HF treatments, respectively (Fig. 6). Biomass (and thereby, carbon) accumulation increased with management intensity. Furthermore, intensively managed stands grew much larger trees than stands managed less intensively. For example, mean Dbh at 50 years is estimated at 32 cm for treatment C, 35 cm for F, 47 cm for H, and 55 cm for the HF treatment. Greater tree diameters mean greater resiliency from wildfire. Achieving larger tree sizes sooner also lessens the time to commercial thinning, meaning that much of the harvested carbon could be stored in the wood products for decades. Without deliberate thinning, natural thinning (tree mortality) started at age 37 for the HF treatment, 41 in the H treatment, and 50 in the F treatment. 3-PG simulations did not predict mortality in the control.



**Figure 6. 3-PG model projections of above- and belowground biomass at the Whitmore Garden of Eden plantation for (A) untreated controls, (B) fertilization only, (C) vegetation control only, (D) fertilization and vegetation control combined. Climate assumed unchanged. Wildfire excluded.**

We developed simple regression equations (each significant at  $P < 0.0001$ ) for estimating tree biomass ( $Y$  in Mg/ha) from stand age (in years) depicted in Fig. 6. Equations for each treatment are:

$$C: Y = \frac{363.65}{1 + \left(\frac{Age}{46.71}\right)^{-2.22}} \quad r^2 > 0.99$$

$$F: Y = \frac{724.95}{1 + \left(\frac{Age}{55.41}\right)^{-1.80}} \quad r^2 > 0.99$$

$$H: Y = \frac{673.62}{1 + \left(\frac{Age}{43.50}\right)^{-1.93}} \quad r^2 > 0.99$$

$$HF: Y = \frac{753.58}{1 + \left(\frac{Age}{39.45}\right)^{-1.87}} \quad r^2 > 0.99$$

#### 4. Fire Simulations

Only the fertilized plots had sufficient fuel loading and continuity to carry fires before age 10 (F plots were capable of carrying a fire by year 8). Therefore, all wildfire simulations were for ages 10 through 21 yrs. Results are summarized in Table 3.

**Control treatment (C).** By age 10 shrubs (primarily *Arctostaphylos*) covered >100% of the control plots (Fig. 2A) so that fire behavior was modeled as a shrubfield fuelbed. Flames exceeded tree heights in all years leading to crown ignition of both shrubs and trees. Mortality was projected as close to 100% if fire occurred at any point during the first 21 years.

**Fertilization treatment (F).** Shrubs covered >90% of the ground by 10 years (Fig. 2B) and were approximately 1 m high. These plots were modeled as shrubfields with fuels increasing enough in each age class to advance to the next higher loading fuel model for fire behavior simulation. Flames exceeded tree heights through age 12, indicating ignition of shrub and tree crowns. By age 21, trees had grown sufficiently to begin suppressing shrubs, reducing live cover considerably. However, many skeletons of dead shrubs remained to capture needle cast. The 21-yr age class was modeled as a timber stand with shrub understory and needle drape. Flames were still two-thirds of the tree height, torching the remaining shrubs and most of the trees. Mortality was expected to approach 100% in all age classes.

**Herbicide treatment (H), unthinned.** Because herbicides eliminated understory cover, surface litter models were used for fire simulations. We chose fuel models to represent slightly increased surface litter with each age class to keep pace with canopy development and needle cast. Simulated fires always had <1 m flames and were surface fires. No crowns were ignited in the simulations, but scorch was sufficient that mortality ranged from two-thirds of the trees at stand at age 10 to nearly half at age 21.

**Table 3. Results of fire behavior simulations. Ages are for the plantation at the time of the fire assuming that no fire had previously occurred. Fire types are: PC = passive crown fire; SURF = surface fire. Thinning occurred at age 10.**

Treatment	Age (yrs)	Fuel model	Stand ht (m)	Shrub ht (m)	Shrub cover (%)	Fire type	Flame length (m)	Mortality (%)
Control	10	SH4	2.7	0.5	89.3	PC	4.5	100
	12	SH4	3.4	0.5	79.3	PC	4.5	100
	15	SH4	4.3	0.6	83.4	PC	4.5	100
	21	SH3	6.7	1.3	57.4	PC	7.3	100
Fertilize	10	SH4	2.7	0.9	95.0	PC	4.5	100
	12	SH3	4.3	1.1	81.9	PC	7.3	100
	15	SH5	6.1	1.8	76.7	PC	9.2	100
	21	TU3	9.4	1.4	28.8	PC	6.1	99
Herbicide	10	TL2	4.3	0	0	SURF	0.2	67
	12	TL3	5.5	0	0	SURF	0.7	61
	15	TL6	7.3	0	0	SURF	0.7	58
	21	TL8	9.8	0	0	SURF	0.6	48
H Thin	12	TL2	6.1	0	0	SURF	0.2	56
	15	TL2	7.9	0	0	SURF	0.2	47
	21	TL2	11.3	0	0	SURF	0.2	39
H+F	10	TL2	4.9	0	0	SURF	0.2	61
	12	TL3	6.1	0	0	SURF	0.3	55
	15	TL3	7.3	0	0	SURF	0.3	53
	21	FB9	11.6	0	0	SURF	0.5	42
H+F Thin	12	TL2	7.0	0	0	SURF	0.2	50
	15	TL2	8.8	0	0	SURF	0.2	40
	21	TL2	12.5	0	0	SURF	0.2	32
H+F T+Slash	12	SB2	5.8	0	0	PC	2.3	99
	15	SB1	6.7	0	0	SURF	0.9	45
	21	TL2	12.5	0	0	SURF	0.2	32

**H treatment thinned, slash removed.** Because thinned trees were removed from the plots, no additional fuel was added to the surface. Thus, surface litter fuel models were used. Additionally, because fewer trees remained after thinning, the litter deposited by trees in subsequent years was less than for unthinned plots. Simulations indicated surface fires at all ages with no torching of crowns and with less cambium damage and scorch due to the slightly lower litter loads. Expected mortality ranged from 56% at age 12 to 39% at age 21.

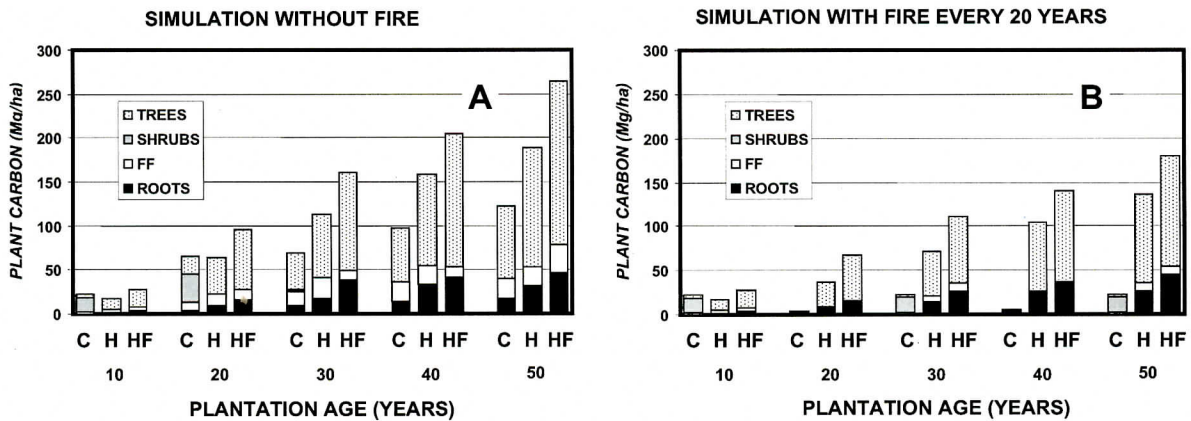
**HF treatment, unthinned.** Fire simulations were similar those for the H treatments, except that the trees grew faster. Expected mortality that ranged from 61% at age 10 to 42% at age 21.

**HF thinned treatment, slash removed.** Again, the simulations were similar to the H treatment except that trees grew faster. Expected mortality varied from 50% at age 12 to 32% by age 21.

**HF thinned treatment, slash retained.** This scenario reflected what might occur if slash from thinning at age 10 had been left on site to decompose. We assumed that red needles would persist for 2 years, making for a very flammable fuelbed. Simulations produced passive crown fires with most of the tree crowns torched, and expected mortality was 99%. However, we assumed the red needles would drop by year 15, leaving relatively low loadings of woody materials. Simulations produced surface fires with little torching of crowns, and expected mortality fell to 45%. By year 21, we assumed that woody thinning slash would essentially be gone. The stand was considered to be similar at that point to stands where thinning slash had been removed with results similar to those described above.

### 5. Fire Regimes and Carbon Sequestration

Finally, we incorporated all of these findings into a simple model of carbon dynamics over 50 years under three management regimes: C (no vegetation control); H (vegetation control, only); and HF (vegetation control + fertilization). We omitted fertilization only (F), because the treatment is not economically effective on sites of this quality without vegetation control. Using data from the biomass trends in Fig. 6, and assuming a carbon composition equivalent to half the biomass, decadal trends for trees, shrubs, forest floor and coarse roots are shown in Fig. 7.



**Figure 7. Simulations of carbon accumulations in trees, shrubs, forest floor and roots at Whitmore under three management regimes. Simulations assume (A) no incidence of wildfire, or (B) wildfire at a return interval of 20 years.**

Figure 7 simulations for trees and roots are based on 3-PG runs at the Whitmore plantation. Simulations of shrub and forest floor development are based on measured data through 21 years, and extrapolation as indicated in Fig. 6. Carbon accumulations are always positive if the site is free from wildfire (Fig. 7A). However, assuming a fire return interval of 20 years, a conservatively long period for this particular region (Skinner and Chang 1996), the likely outcome of the Table 3 scenario is depicted in Fig. 7B. In general, untreated sites (C) would be set back nearly to “zero” every 20 years, and all that remained of biomass carbon exclusive of charcoal would be living roots of shrubs or trees that resprout from fire. Assuming that the manager would replant the site, but again fail to control competing shrubs, biomass in the first

decade following fire would consist almost entirely of sprouting shrubs and trees or vegetation with hard seed coats scarified by heat. This cyclic setback and renewal would be repeated at 20 and 40 years. In contrast, stands receiving early vegetation control would suffer carbon losses, but not to the catastrophic degree as untreated stands (Fig. 7B).

## DISCUSSION AND CONCLUSIONS

Understory shrubs dominated total productivity on untreated C plots through the first 21 years of plantation development, but shrubs declined to possible extinction after three decades (possibly a conservative estimate). Stands receiving only fertilization (F) showed an initial biomass peak of 201 Mg/ha at 18 years owing to the contribution of a shrub understory. This peak diminished as trees dominated the site, and by 21 years accumulated ecosystem carbon averaged 93 Mg/ha with fertilization. Untreated plots (C) stored slightly more carbon, but two-thirds of the total was in roots and tops of understory shrubs. The allocation of carbon to perennial roots is appreciable, and a fact generally ignored in "carbon accounting."

Plots where understory vegetation had been controlled through the first two decades of plantation development showed slightly less carbon accumulation in H treatments because time was required for tree crowns to expand and capture the site's leaf area growth potential. Carbon accumulations were 11% to 31% greater in the HF treatment because fertilization increased pine leaf area rapidly. The main effect of silvicultural treatment over the first 2 decades was the distribution of biomass and carbon into pine stemwood and the likelihood of carbon retention in living materials in the event of wildfire. Compared with control treatments, bole biomass (and carbon) increased by 93%, 137%, and 211% by F, H, and HF treatments, respectively by age 21.

Stands where understory shrubs were not controlled, although assimilating carbon rapidly, would likely have a high fuel hazard and elevated fire risk well beyond the 21 years considered here. Stands where shrubs were controlled would be expected to be at much lower risk throughout the period. But regardless of treatment, small trees are susceptible to crown scorch and cambial damage during early stand development. Any treatment favoring tree growth would lessen the risk of damage from wildfire if fuelbeds are low. Thinning smaller trees will reduce fuel ladders if slash is removed, but noncommercial materials left on the site would create a fuel hazard and increase the risk of high mortality from fire for several years after thinning.

Assuming fire-free conditions and a climate similar to the recent past, plantation projections to age 50 suggest that untreated control stands (C) would accumulate 243 Mg of biomass/ha (mean annual carbon gains of about 2.4 Mg/ha/yr, exclusive of soil). Stand biomass in untreated stands followed a bimodal trend over time, with an early peak at about 24 years dominated by understory vegetation. Thereafter, standing biomass declined for nearly a decade as tree canopies closed and understory vegetation declined. Planted trees captured the site's growth capacity by the third decade and growth was nearly linear to age 50. The understory was extinguished sooner by fertilization, and biomass accumulation began to accelerate by year 22, reaching 376 Mg/ha by 50 years (about 4 Mg carbon/ha/yr), mostly in tree stems. Controlling vegetation (H) guaranteed that biomass was dominated by tree stems throughout the life of the stand, achieving a total ecosystem biomass of 407 Mg/ha (about 4 Mg carbon/ha/yr) by age 50.

Combining vegetation control with fertilization (HF) projected the greatest biomass gains of all: 487 Mg/ha at 50 years. Thus, 3-PG simulations predict carbon accumulation rates averaging between 2.4 and 4.9 Mg/ha/yr, exclusive of gains to the soil. Assuming no incidence of wildfire, vegetation control offers no carbon advantages in the short run, but vegetation control substantially increases carbon gains between 30 and 50 years. Fertilization, by improving site quality and leaf area carrying capacity, increases site carbon capture by about one-fifth, although no benefit occurs without understory control.

In reality, wildfire is likely. Dead fuels accumulating from understory shrub mortality in C and F treatments would create a high risk of catastrophic loss from passive crown fires, while H and HF treatment trees would likely survive (Fig. 7). Potential carbon losses due to recurrent wildfire in our simple model range from approximately 99 Mg/ha for untreated stands, through 52 Mg/ha for stands with vegetation control, to 84 Mg/ha for fertilized stands also receiving vegetation control. From a managerial perspective, wildfire at intervals of 20 years or less would amount to a complete loss of forest resources if understory shrubs are not controlled and it is unlikely that a forest would ever emerge. Should one or more commercial thinnings occur (unlikely in the C treatment, but a viable option in H and especially HF treatments), a sizable proportion of carbon would be held in long-lived forest products, with only a minor decline in carbon accumulating in the residual plantation.

We have high confidence in our growth models through the first 21 years of plantation development because they are based on accurate field measurements over time. Our fire models may be conservative. Wind speeds in our simulations were in the 97 percentile, but experience suggests that greater velocities occur with large fires driven by strong gradient winds from the north or pre-frontal winds from the southwest. Thus, these simulations may provide conservative estimates of potential fire behavior under those types of extreme conditions. Extrapolations to greater ages through simulation should be used with caution. We assume that climate over the next 3 decades will be similar to climate in the recent past, and this may not be so. We are still in the process of calibrating 3-PG, so projections are preliminary and should be used only in a comparative sense to suggest trends and differences among management scenarios. We believe that our findings for the Whitmore plantation will be typical for plantations and young natural stands common to this average site quality. How the models perform when site quality is lower or higher is the next thrust of our research.

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## APPENDIX 1

### Details of Biomass Analysis

**Tree Tops.** Stem diameters at 30.5 cm (1 foot) and at 1.37 m (4.5 feet) above ground line were recorded by tree number. Trees were felled above this mark making as perpendicular a cut as possible. Once felled, stem length was recorded from ground line to the top of the fresh stump, then to the base of live crown (first whorl with living branches) and to the total length of the tree. Live crown was divided into 5 evenly spaced sectors (A = lowest, E = uppermost). Within each sector, branch diameters were measured and recorded to the nearest millimeter at a standard distance (2.5 cm) from the point of attachment to the main stem. Branch diameters were recorded and squared, summed, and the branch of mean squared diameter was determined and located. The branch nearest this mean squared diameter was remeasured and its diameter recorded. It was then clipped from the stem. Foliage was stripped from the branch. Foliage and branch wood were bagged, labeled, and transported to a drying facility. Dead branches were handled similarly but separately.

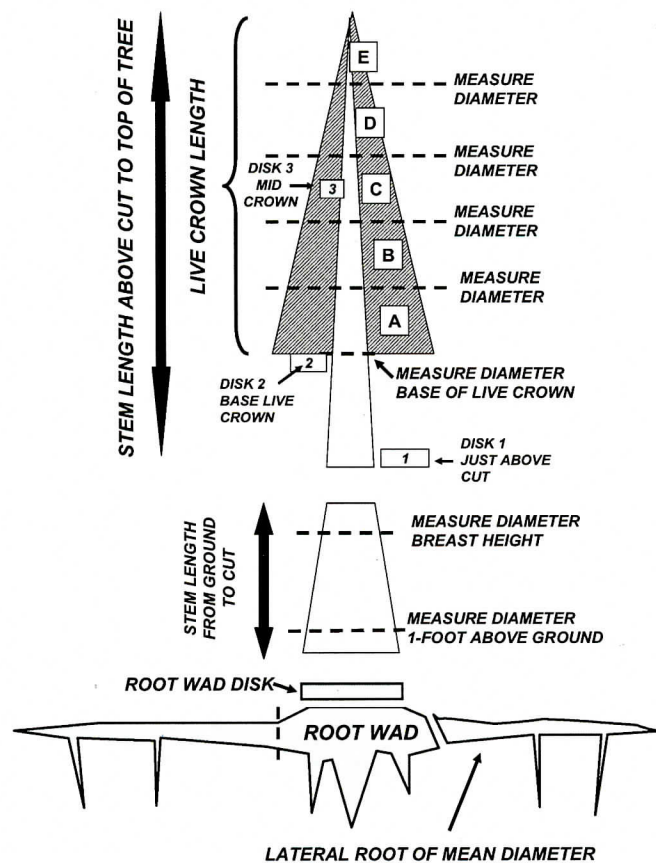


Figure A1. General diagram of tree biomass sampling.

Bole disks of approximately 10 to 15 cm thickness were sawn from the main stem at the following locations: just above stump, at the base of the live crown i.e. just below sector A, and at the midpoint of the crown in sector C. Saw cuts were made as clean and perpendicular as possible, taking care not to dislodge any bark. Each disk was measured for diameter with a D-tape at the midpoint of the disk, and disk thickness was measured at four perpendicular points and recorded to the nearest millimeter. Disks were placed in labeled bags and transported to a drying facility.

**Fine roots.** Soil cores (12 per treatment plot) were collected using a Eijkelkamp bi-partite root auger (7.6 cm cylinder diameter) at continuous depth increments from the soil surface to a total depth of 100 cm. Roots of 2 mm or less were separated from the soil by depth, labeled, and bagged for further analyses. No attempt was made to separate tree roots from those of understory vegetation.

**Tree coarse roots.** Root wads and residual stumps were loosened using explosive charges placed strategically beneath the root crown. Once the root wad had been loosened by detonation, stumps and root wads were elevated vertically from the soil by gripping the stump with an excavator bucket and raising the root wad free of the soil. Once elevated, lateral root diameters were measured and recorded to the nearest millimeter. Lateral root diameters were squared, summed, and the lateral root of average squared diameter was marked for individual excavation. All laterals were then severed to free the root wad which was then transported to a washing and drying facility.

Using hand tools, the lateral root of mean squared diameter was traced and carefully excavated. For sinker roots branching from the lateral, diameters of each sinker were measured and recorded. The sinker of average squared diameter was then excavated to a minimum diameter of 2-3 mm. Lateral and sinker roots were bagged, labeled, and transported to a washing and drying facility.

**Understory tops.** Five fixed area circular plots (1.0 m<sup>2</sup>) were established randomly within each treatment plot replicate. All understory vegetation existing within each plot was clipped, sorted by species and as living or dead, labeled and bagged, and transported to the drying facility.

**Understory roots.** Soil in the fixed area plots was loosened by small backhoe and coarse roots remaining from harvested shrub tops were excavated. Samples were bagged, labeled, and transported to the drying facility.

**Forest floor.** Five 0.25 m<sup>2</sup> samples were collected of the forest floor at a central and four corner points from each measurement plot using a rigid metal frame. Materials were bagged, labeled, and transported to the drying facility.

**Laboratory procedures.** All aboveground biomass and lateral root samples were dried for at least 3 days at 70°C, then weighed periodically until reaching a stable weight to the nearest gram or less. Root wads were cleaned of soil with high pressure hose, taking care not to dislodge any bark. Wads were then dried on pallets in the open through summer 2007. Stumps were sawn

from root crowns at a standard distance of 5 cm above the uppermost lateral root to approximate ground line. Disks were also sawn from just above this point at the final weighing and oven-dried, providing an oven-dry/air-dry correction factor. Air-dry root wads were then weighed on a platform balance to the nearest gram and corrected for oven-dry weights.

### Estimating Whole Tree Biomass

**Crowns.** Foliage and wood mass were estimated for each treatment and crown sector by regressing mass of each branch component against the square of the basal branch diameter (Table A1). These regressions were then applied to the squared diameters of all branches measured in each sector.

<b>Table A1. Mass equations for foliage (F) and branch wood (B) as a function of the square of branch basal diameter (X in mm<sup>2</sup>) in relation to position in the live crown (A = base, B = top). Basis: 9 limbs in each category.</b>									
Crown sector	Foliage or Branch	Control		Fertilize		Herbicide		HF	
		Equation	r <sup>2</sup>	Equation	r <sup>2</sup>	Equation	r <sup>2</sup>	Equation	r <sup>2</sup>
E	F	0.3268X <sup>0.8881</sup>	0.90	0.0055X <sup>1.6133</sup>	0.95	0.3207X <sup>0.8980</sup>	0.87	0.0220X <sup>1.4165</sup>	0.86
	B	0.0232X <sup>1.2309</sup>	0.83	0.0115X <sup>1.3814</sup>	0.93	0.1802X <sup>0.8696</sup>	0.88	0.0006X <sup>1.9391</sup>	0.82
D	F	0.2250X	0.95	0.4498X <sup>0.9163</sup>	0.87	0.2099X	0.94	0.1390X <sup>1.1291</sup>	0.93
	B	0.0062X <sup>1.5755</sup>	0.97	0.0099X <sup>1.4810</sup>	0.99	0.0594X <sup>1.2059</sup>	0.95	0.0057X <sup>1.6137</sup>	0.93
C	F	0.0034X <sup>1.6173</sup>	0.95	0.01393X <sup>1.0805</sup>	0.85	0.0030X <sup>1.5897</sup>	0.90	0.2592X	0.81
	B	0.0244X <sup>1.3685</sup>	0.98	0.0128X <sup>1.4719</sup>	0.97	0.0372X <sup>1.3263</sup>	0.98	0.0265X <sup>1.3802</sup>	0.97
B	F	0.0010X <sup>1.7402</sup>	0.91	0.0393X <sup>1.1639</sup>	0.80	0.0006X <sup>1.7404</sup>	0.84	0.0004X <sup>1.8274</sup>	0.90
	B	0.0168X <sup>1.4488</sup>	0.98	0.0119X <sup>1.5037</sup>	0.97	0.0303X <sup>1.3645</sup>	0.97	0.0352X <sup>1.3557</sup>	0.98
A	F	0.0003X <sup>1.4393</sup>	0.86	0.0063X <sup>1.2914</sup>	0.70	0.00005X <sup>1.9738</sup>	0.85	0.00003X <sup>1.8037</sup>	0.87
	B	0.0181X <sup>1.4391</sup>	0.98	0.00078X <sup>1.5682</sup>	0.95	0.00096X <sup>1.5443</sup>	0.99	0.02640X <sup>1.4090</sup>	0.98
Dead	B	0.0186X <sup>1.4368</sup>	0.98	0.0047X <sup>1.6712</sup>	0.95	0.0051X <sup>1.6237</sup>	0.95	0.0125X <sup>1.4980</sup>	0.87

Mass summed for each sector estimates total branch wood and foliage mass per tree. Crown mass was regressed against the square of stem Dbh to produce estimation equations from crown mass by treatment.

**Boles.** The volume of the tree bole was estimated by summing the truncated cones depicted in Fig. 1A and extended to ground line. Each section was assigned a density based on the oven-dry mass and volume of the nearest sample disk (1-3 in Fig. 1A). The sum of the mass estimated for each bole section equals the mass of the entire bole.

**Roots.** Root wad mass was determined by adjusting air-dry mass by the oven-dry/air-dry ratio of disks. The mass of all lateral roots was estimated from regressions of the mass/squared diameter relationship of sampled laterals. Combined, this produced an estimated perennial root mass.