**FCEM**

**Forest Carbon and Emissions Model**

# THE FOREST CARBON AND EMISSIONS MODEL (FCEM) Overview and Technical Information (Beta Version)

## FCEM Report No. 1

**By**
**Thomas M. Bonnicksen, Ph.D.**

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**Prepared for**
**The Forest Foundation**
853 Lincoln Way, Suite 208
Auburn, CA 95603
(530) 823-3195 or toll-free (866) 241-8733
www.calforestfoundation.org

## Preface

The Forest Carbon and Emissions Model (FCEM) is a Rapid Estimation Model (REM) that requires a minimum of input data. It fills the need for quickly estimating forest carbon storage, sequestration, and greenhouse gas (GHG) emissions. FCEM is a deterministic biomass-based model that uses an Excel spreadsheet to compute estimates.

Forests and forestry are playing an increasingly important role in sequestering carbon and reducing greenhouse gas emissions, especially during a period of rising concerns about global warming. FCEM provides quick estimates to inventory carbon storage and assess the consequences of wildfires and insect infestations to climate change. This can help improve decision making when information is limited and budgets are restricted.

This version of FCEM applies to California. Future changes to FCEM could include expanding the list of species and vegetation types to other regions of the United States, updating equations and coefficients as scientific and technical information advances, and converting the Excel spreadsheet to a Windows program to enhance the model's flexibility and helpfulness to users.

This report provides an overview of FCEM, input requirements, and example applications and outputs. It also includes information on the structure of the model and lists scientific and technical references.

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## Applications

There are numerous applications of FCEM on public and private forestlands, including:

- Estimating the amount of biomass, carbon, and CO2 stored in a particular forest or plantation, now or in the future, including tree stems, roots, foliage, branches, litter, duff, understory, down dead, standing dead, and soil.
- Estimating and comparing the amount of biomass, carbon, and CO2 stored in a particular forest or plantation before and after thinning.
- Estimating the amount of biomass, carbon, and CO2 stored in solid wood products after thinning or harvesting.
- Estimating the amount of greenhouse gases released into the atmosphere from a wildfire or insect infestation, including emissions from combustion and decay.
- Estimating the amount of CO2 prevented, or that could be prevented, from being released into the atmosphere from decay by removing fire or insect-killed trees and storing the carbon they contain in wood products.
- Estimating the amount of CO2 recovered, or that could be recovered, from the atmosphere after being lost from a wildfire or insect infestation by planting young trees that absorb carbon through photosynthesis using a plant-and-forget strategy or a plant, manage, and harvest (plantation) strategy.
- Estimating the amount of carbon released into the atmosphere from a wildfire or insect infestation that is not recovered when brush replaces trees that could have absorbed the lost CO2.
- Estimating and comparing the amount of greenhouse gases released into the atmosphere from a wildfire or insect infestation before and after forest thinning.
- Estimating and comparing the amount of greenhouse gases released into the atmosphere from a wildfire and a prescribed burning program before and after forest thinning.

## Advantages and Limitations

Advantages of FCEM:

- The model is unique among available carbon models because of its simplicity and relevance to forest management.
- The model requires minimal data to make estimates, so it is quick and easy to use.
- The model computes estimates based on formulas and data from specific areas rather than relying on extrapolating results from case studies and applying them to other places that may or may not be similar.
- The model includes input-output tables for the original forest and four pre-determined scenarios.
- The model automatically generates numerous pre-formatted charts to display estimates.
- Estimates are precise and repeatable because it is a deterministic model where the same inputs generate the same outputs.
- The model can mimic a probabilistic model by using multiple inputs to generate a range of outputs or estimates.
- Anyone who can use Excel can run the model with little training as long as someone with knowledge of forestry is available to evaluate input data and interpret estimates.

Limitations of FCEM:

- The model uses the perimeter of a fire or insect infestation to determine the affected area.
- The model is limited to four uniform vegetation types within the area of interest.
- This is a biomass-based model that does not include timber volume as a means for estimating carbon or greenhouse gas emissions.
- The biomass estimates that drive the model come from published diameter-based allometric equations for trees, which are not available for all species, and generalized look-up tables.
- The model does not include fuel moisture, wind speed, or topography, but the user considers these fire behavior variables when estimating overstory and understory mortality.
- Published emission factors are incomplete and usually average flaming and smoldering fire.
- Carbon stored in wood products includes only solid wood products.
- The model does not include the emission benefits of burning wood waste for energy instead of fossil fuel, but it can be added.
- The model focuses on California forests and chaparral, but it can include other vegetation types.

### Introduction

The Forest Carbon and Emissions Model (FCEM) is a deterministic rather than a probabilistic model. In short, the same input generates the same output. If needed, however, FCEM can mimic a probabilistic model by using multiple simulations from different inputs to generate a range of outputs.

FCEM calculates estimates in an Excel spreadsheet that links equations, ratios, and conversion and emission factors from a variety of recently published scientific and technical sources. Discussions with scientists and professionals provided additional technical information.

This version of FCEM focuses on California forests and chaparral. Species and vegetation types include, in any combination, coast redwood, Douglas-fir, incense cedar, lodgepole pine, ponderosa/Jeffrey pine, sugar pine, true fir, oak (i.e., if alone or intermixed with conifers), shrubs, chaparral, and Western oak (i.e., a vegetation type that consists of gray pine, California black oak, Oregon white oak, blue oak, and/or coast live oak).

### Modeling Program

FCEM consists of three Sheets in an Excel spreadsheet. Sheet 1 is for input-output tables and charts related to the original forest. This forest provides the baseline for all computations and estimates. Sheet 1 includes estimates of the amount of biomass, carbon, and CO2 stored in the forest and impacts of several scenarios. Figure 1 shows an example of one of five input-output tables. This one describes the original forest, post-event plantation, and thinning. Data are entered in the white cells of the table; all other cells are locked and reserved for output. Charts also are locked.

Sheet 3 is identical to Sheet 1 except that it is associated with a thinned forest. Even though most

**Forest Carbon and Emissions Model (FCEM)**

(Beta Version)

Model for estimating biomass and carbon stored in California's forests, released into the atmosphere as greenhouse gases (GHG) by fire or insects, and recovered by removing dead trees, storing carbon in wood products, and planting young trees that absorb carbon.

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| | | | | |
|---|---|---|---|---|
| TITLE: | EXAMPLE | | | |
| **INPUT: Forest characteristics (original forest)** | | | | |
| Post-event plantation, age at harvest (years) | | 55.0 | | |
| Post-event plantation (trees/acre) | | 170.0 | 420.1 trees/ha | |
| Post-event plantation dbh at harvest (inches) | | 13.0 | 32.1 cm | |
| Acres (total) | | 2,000.0 | 809.4 ha | |
| Conifer forest density >= 2-inch dbh (trees/acre) | | 350.0 | 864.9 trees/ha (original) | |
| Shrub cover (%) | | 70.0 | 0.70 proportion | |
| Chaparral cover (%) | | | 0.00 proportion | |
| Conifer forest (% of acres) | | 90.0 | 0.90 proportion | |
| Shrubs (% of acres) | | 10.0 | 0.10 proportion | |
| Chaparral (% of acres) | | | 0.00 proportion | |
| Western oak (% of acres) | | | 0.00 proportion | |
| Thin conifer forest < 30 in dbh (% reduction) | | 50.0 | 440.5 trees/ha (thinned) | |
| | **Total acres (%)** | **100.00** | 178.3 trees/ac (thinned) | |
| **Conifer forest** | **Uneven-aged (y/n) *** | **Average dbh (in)** | **Original forest (%)** | **Plantation (%)** |
| Coast redwood | y | | | |
| Douglas-fir | y | | | 10.0 |
| Cedar | y | | | |
| Lodgepole pine | y | | | |
| Ponderosa/Jeffrey pine | y | | 60.0 | 80.0 |
| Sugar pine | y | | | |
| True fir/hemlock | y | | 40.0 | 10.0 |
| Oak/tanoak | | | | |
| Age of original forest (yrs) | | **TOTAL (%)** | **100.00** | **100.00** |
| *** Original forest, n is even-aged (default y), if n, must have average dbh by species** | | | | |
| **OUTPUT: Forest characteristics (original forest)** | | | | |
| | **Basal area (sq. ft./ac)** | **Basal area (sq. m/ha)** | **Biomass (t/ha)** | **Carbon (tC/ha)** |
| Conifer-oak trees & roots | 193.3 | 44.4 | 319.2 | 159.6 |
| Shrubs & roots | | | 26.3 | 13.1 |
| Chaparral & roots | | | 0.0 | 0.0 |
| Western oak & roots | | | 0.0 | 0.0 |
| | **Acres** | **Hectares** | **Biomass (t)** | **Carbon (tC)** |
| Conifer-oak trees & roots | 1,800.0 | 728.5 | 232,556.2 | 116,278.1 |
| Shrubs & roots | 200.0 | 80.9 | 2,124.6 | 1,062.3 |
| Chaparral & roots | 0.0 | 0.0 | 0.0 | 0.0 |
| Western oak & roots | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total (whole forest proportionate to composition; not sum)** | | | **292,136.0** | **146,068.0** |
| Soil (proportionate to composition) | | | 70,653.2 | 35,326.6 |
| **Total (sum with soil)** | | | 362,789.1 | 181,394.6 |
| Tons CO2 absorbed by conifer-oak trees & roots | | 470,401.0 | **Acres to offset car emissions (tons CO2e )** | |
| Average tons CO2 absorbed to date /ac/yr | | 2.61 | **(acres/car/yr)** | **(acres/all cars/yr)** |
| | | | 0.4713 | 6,598,597 |
| Tons CO2 stored in wood products by thinning | | 50.0% | | 31,776.5 |
| **NOTE: t is tonnes is metric tons and tons is English short tons** | | | | |

**Figure 1. Input-output table used in FCEM to enter data describing the original forest, post-event plantation, and thinning.**

data entered in Sheet 1 (i.e., the original forest) automatically transfer to Sheet 3 (i.e., the thinned forest), there are exceptions as noted under Scenarios.

Input-output tables and charts can be copied and transferred to a graphics program for printing. Sheet 2 displays all charts generated from both Sheets. These charts are not locked and can be modified as needed.

## Scenarios

FCEM includes four scenarios for estimating the impacts of fire and insect infestations, the benefits of removing dead trees and converting them into solid wood products, thinning, and planting. The model also estimates the relative impacts of wildfire and prescribed fire on emissions, before and after thinning, and thinning with and without prescribed fire. FCEM compares impacts and benefits in terms of greenhouse gas emissions and carbon sequestration and storage.

**Scenario 1.** This scenario estimates the impacts of wildfire on carbon storage and emissions for the original forest (un-thinned) and the thinned forest. Input data include acres burned and percent understory and overstory mortality. Mortality must be entered separately for the thinned forest because it is usually less vulnerable to wildfire. Outputs include estimates of biomass, carbon, and greenhouse gases emitted into the atmosphere from combustion and decay, and the equivalent in terms of various other sources of emissions displayed in tables and charts. Figure 2 shows an example chart for Scenario 1.

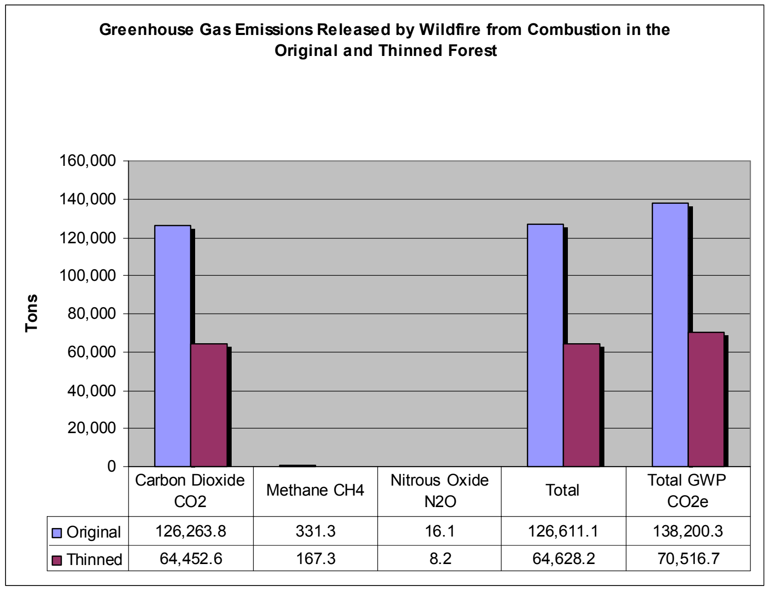


**Figure 2. Greenhouse gas (GHG) emissions from combustion caused by wildfire that burned a hypothetical forest (Scenario 1).**

**Scenario 2.** This scenario estimates the same impacts of wildfire as determined in Scenario 1, as well as offsetting these effects by removing dead trees and converting them into wood products that store carbon and/or planting young trees that

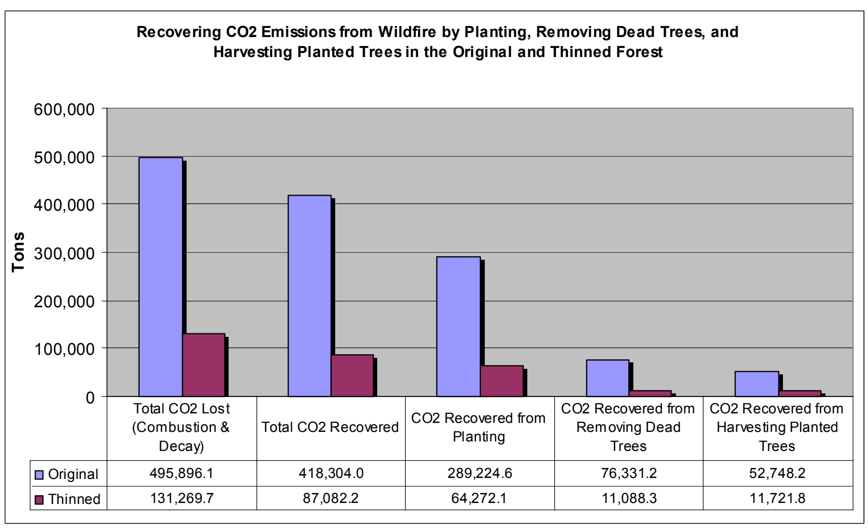


**Figure 3. Greenhouse gas (GHG) emissions from combustion and decay caused by wildfire that burned a hypothetical forest with dead tree removal and planting to compensate for losses (Scenario 2).**

absorb carbon, either to create a similar forest or a managed plantation. Acres of dead tree removal and acres planted must be entered for both the original and thinned forest because the acres available to remove dead trees and plant young trees are usually less when a forest is thinned and not as vulnerable to wildfire. Tables and charts displaying estimates are similar to Scenario 1. Figure 3 shows an example chart for Scenario 2.

**Scenario 3.** This scenario estimates the impacts of insect infestations. It is similar to Scenario 2 for wildfire except only emissions from decay are considered, which is restricted to CO2. Input data include acres infested and percent overstory mortality.

Like Scenario 2, it includes the effects of removing dead trees and converting them into wood products that store carbon and/or planting young trees that absorb carbon, either to create a similar forest or a managed plantation. Acres of dead tree removal and acres planted must be entered for both the original and thinned forest because the acres available to remove dead trees and plant young trees are usually less when a forest is thinned and not as vulnerable to insects. Figure 4 shows an example chart for Scenario 3.

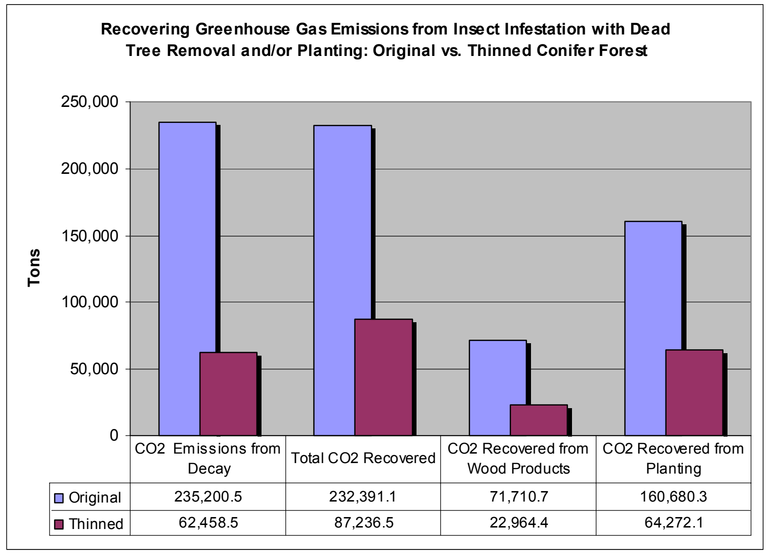


**Figure 4. CO2 emissions from decay caused by an insect infestation that killed a hypothetical forest with dead tree removal and planting to compensate for losses (Scenario 3).**

**Scenario 4.** This scenario estimates the relative effectiveness of several combinations of thinning and prescribed burning to reduce the impacts of wildfire. Input data include percent understory and overstory mortality expected from using prescribed fire. Mortality must be entered separately for the thinned forest because it is usually less vulnerable to fire. In addition, the number of prescribed fires per century, or the rotation, must be entered. For example, five prescribed fires in a century means a rotation of 20 years between burns. Tables and charts displaying estimates are similar to Scenario 1 except they include effects of both wildfire and prescribed fire. Figure 5 shows an example chart for Scenario 4.

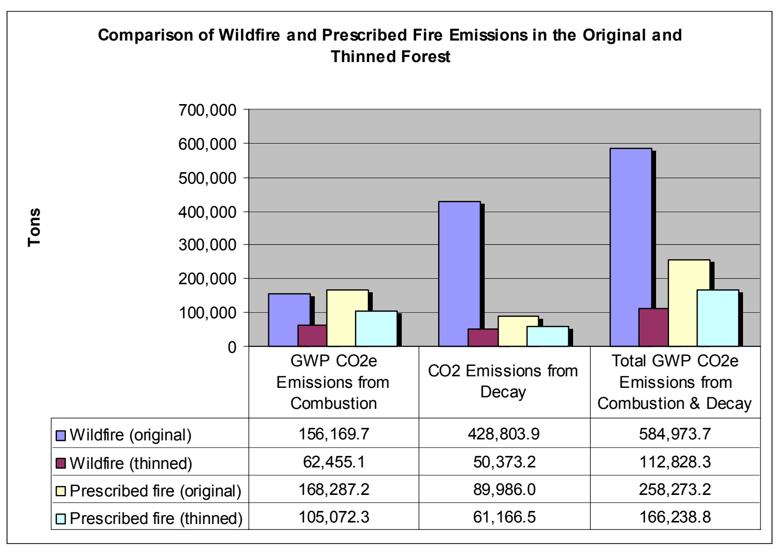


**Figure 5. Greenhouse gas (GHG) emissions from combustion and decay caused by one wildfire and prescribed fires using a 14-year rotation that burned a hypothetical forest before and after thinning (Scenario 4).**

## Computations and Equations to Describe Forest

FCEM uses accepted quantitative methods to make estimates within an Excel spreadsheet. That means FCEM computes estimates based on formulas and data from specific areas rather than relying on extrapolating results from case studies and applying them to other places that may or may not be similar. Even so, generalized look-up table data are used when no other source is available.

### Describing the Original Forest

The minimum input data required to describe the original forest and start the model include total acres, percent of acres occupied by conifers, the number of trees per acre, and the percent of trees by species (i.e., species composition) within the conifer forest. The age of the forest also can be entered. The default age is 100 years. Forests can be even-aged or uneven-aged. The default forest is uneven-aged. An even-aged forest requires entering the average diameter of each tree species.

If present, shrub and/or chaparral percent cover also are entered as well as the percentage of the acreage in shrubs, chaparral, and/or Western oak. Specifying 100 percent of the acreage means a brushfield (i.e., shrubs), chaparral, or Western oak, which FCEM treats the same way as forests. Figure 6 shows the basic input variables and the string of computed estimates generated by FCEM.

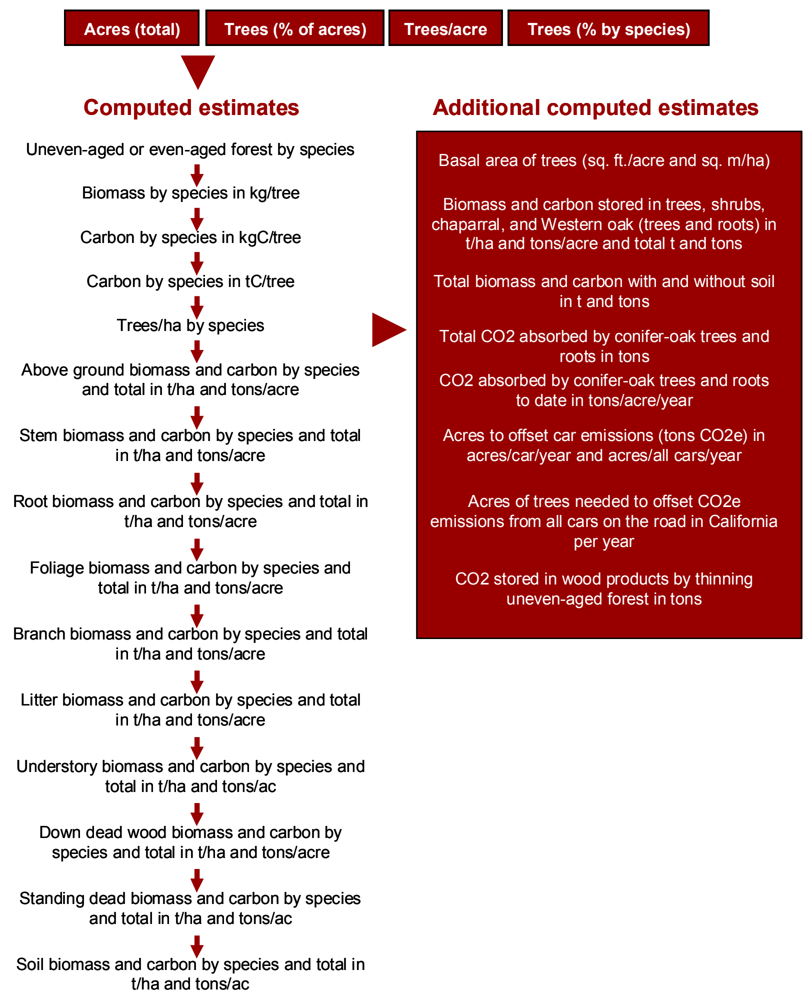


**Figure 6. Input data, computations, and estimates for the initial inventory of forest biomass, and carbon and $CO_2$ sequestration and storage.**

### Diameter Class Distribution

The fundamental variable used in FCEM, in addition to tree species and vegetation type, is the diameter at breast height (dbh) of trees by species. This requires knowing the diameter class distribution for uneven-aged forests and the average diameter by species in even-aged forests and plantations.

FCEM computes the diameter class distribution for trees in uneven-aged forests based on the number of trees per acre and species composition using equations developed from Forest Inventory and Analysis (FIA) data (Christensen et al. 2007). If the available data uses a minimum of 4- to 5-inch dbh trees for density, a weighted average coefficient can be computed based on species composition to convert the density to a 2-inch minimum diameter using coefficients in Table 1.

For example, a forest composed of 60 percent ponderosa/Jeffrey pine and 40 percent true fir would have the following weighted average coefficient:

Weighted average coefficient is
$1.42(0.6) + 1.665(0.4) = 1.518$

If the minimum diameter of trees is 4 to 5 inches, and there are 300 trees/acre, then the number of trees/acre with a minimum diameter of 2 inches is:

Trees/acre >= 2-inch dbh is
$1.518(300) = 455$ trees/acre

**Table 1. Coefficients for converting trees per acre from a minimum of 4- to 5-inch dbh to a minimum of 2-inch dbh by tree species.**

| Species | Coefficient |
|---|---|
| Coast redwood | **1.885** |
| Douglas-fir | **1.716** |
| Cedar | **1.813** |
| Lodgepole pine | **1.528** |
| Ponderosa/Jeffrey pine | **1.420** |
| Sugar pine | **1.614** |
| True fir/hemlock | **1.665** |
| Oak/tanoak | **1.719** |

Trees less than 30 inches in diameter in an uneven-aged forest also can be thinned by a percentage and the results compared with the un-thinned forest for all computed estimates.

The chart in Figure 7 shows a hypothetical uneven-aged ponderosa pine forest diameter distribution generated by FCEM. This chart only required five pieces of data to produce. They are as follows: 1,000-acre area; conifers cover 100 percent of the acreage; species composition is 100 percent ponderosa pine at 300 trees/acre; and 50 percent thinning of trees less than 30 inches in diameter.

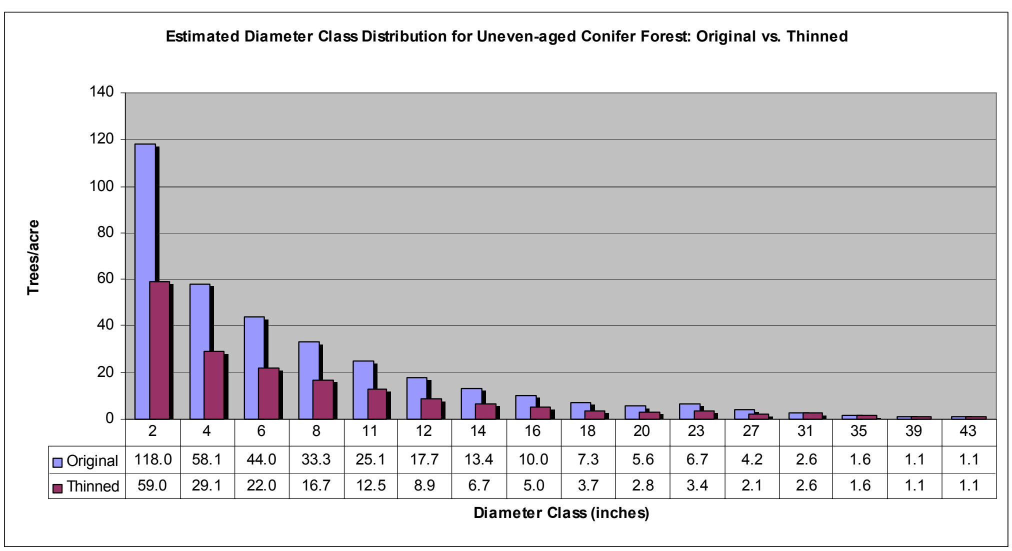


**Figure 7. Uneven-aged ponderosa pine forest diameter class distribution generated by FCEM before and after a 50 percent thinning.**

## Biomass and Carbon

FCEM generates numerous charts, including the total tons biomass and carbon stored in various forest components in the original forest and the thinned forest as well as the tons per acre for trees by forest component (i.e., independent of total forest acreage). For example, the chart in

Figure 8 shows the proportionate contribution of forest components to total biomass and carbon storage on the total acreage in the original forest.

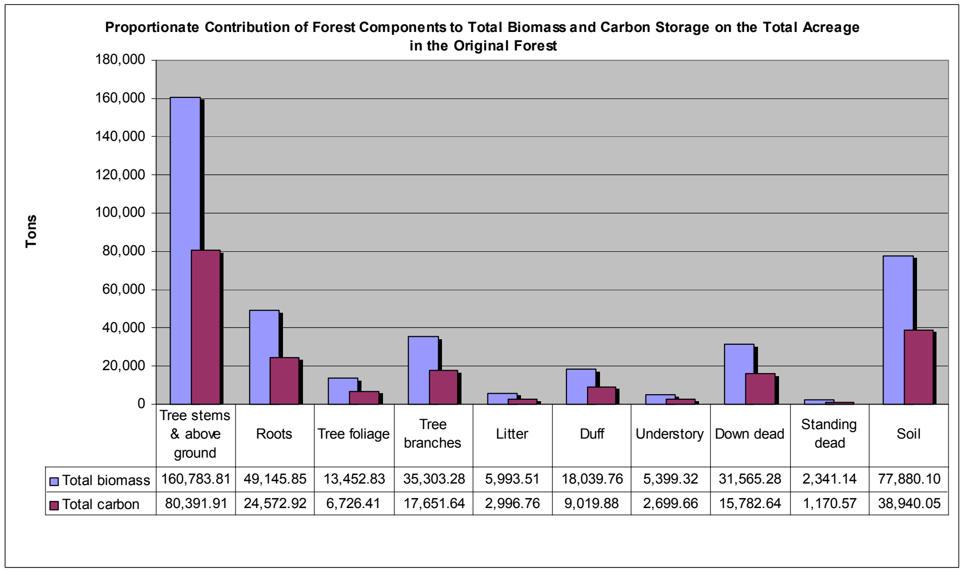


**Figure 8. Proportionate contribution of forest components to total biomass and carbon storage on the total acreage of the original un-thinned forest.**

## Above Ground Biomass

Above ground biomass includes stems, branches, and foliage. FCEM uses allometric equations to compute above ground biomass and carbon as a function of diameter for each tree species. Biomass in t/ha[1] in the forest is the sum of all biomass components for all species and vegetation types, including shrubs, chaparral, and Western oak. Biomass is 50 percent carbon.

Allometric equations of total above ground biomass, as used in FCEM, are available for many tree species, but not all. Allometric equations for tree biomass are of the form shown below (Brown et al. 2004, Jenkins et al. 2003). (See Table 2 for coefficients.)

$$\text{Biomass (kg/tree)} = e^{(-a + b * \log e\,(dbh))}$$

Where:
e = 2.718282
kg is kilograms
log e (log base e)
dbh in centimeters

**Table 2. Above ground biomass coefficients by tree species.**

| Species (kg/tree) | Coefficients a | b | Max. dbh (cm) |
|---|---|---|---|
| Coast redwood* | **-2.2304** | **2.4435** | **210** |
| Douglas-fir** | **-2.2304** | **2.4435** | **210** |
| Cedar** | **-2.0336** | **2.2592** | **250** |
| Lodgepole pine** | **-2.5356** | **2.4349** | **180** |
| Ponderosa/Jeffrey pine** | **-2.5356** | **2.4349** | **180** |
| Sugar pine** | **-2.5356** | **2.4349** | **180** |
| True fir/hemlock** | **-2.5384** | **2.4814** | **230** |
| Oak/tanoak*** | **-2.0127** | **2.4342** | **73** |

* Considered same as Douglas-fir because no allometric equation exists (Dahlgren 1998).
** Jenkins et al. 2003, and Brown et al. 2004.
*** Tanoak considered same as oak because of the lack of an allometric equation. In addition, a diameter class distribution exists for California oaks and not tanoak.

Shrubs, chaparral, and Western oak estimates are based on look-up table and other information sources because of the lack of suitable allometric equations. Therefore, above ground biomass is 30 t/ha for shrubs, which is the average of live and dead Ceanothus and Manzanita species with 100 percent cover as computed from data in Martin et al. (1981). Above ground biomass for chaparral is 35 t/ha (Birdsey 1992, U.S. Environmental Protection Agency 2002). This is consistent with the estimate by Heath and Smith (2003) of 34.2 t/ha. Similarly, above ground biomass for Western oak is 134.2 t/ha (Birdsey 1992; U.S. Environmental Protection Agency 2002, 2006).

[1] t is metric tons, or tonnes, and ha is hectares.

### Stem, Branch, and Foliage Biomass of Trees

Stem biomass of trees is computed by subtracting branch and foliage biomass from total above ground biomass. The branch biomass ratio, or that fraction of above ground biomass contained in branches, is 17 percent (Jenkins et al. 2003, Ker 1980). The foliage biomass ratio is computed as follows (Jenkins et al. 2003):

$$\text{Foliage biomass ratio} = e^{(-2.9584 + 4.4766/\text{dbh})}$$

Where:
e = 2.718282
dbh in centimeters

### Root Biomass

Tree root biomass is computed from above ground biomass as follows (Brown et al. 2004, Cairns et al. 1997):

$$\text{Tree root biomass (t/ha)} = e^{(-1.085+0.925 * \log e \text{ (t/ha above ground biomass))}}$$

Where:
e = 2.718282
log e (log base e)

Chaparral root biomass is estimated at 8.75 t/ha and shrub root biomass is estimated at 7.5 t/ha computed using a root/shoot ratio of 0.25 as recommended by Snowdon et al. (2000). These estimates are within the range reported by Rice et al. (1982) for chaparral. On the other hand, root biomass for the Western oak type was estimated as 25.6 t/ha based on average U.S. carbon density data for below ground biomass (U.S. Environmental Protection Agency 2006).

### Litter and Duff Biomass

Tree litter biomass is computed as 10 percent of foliage and branch biomass (Perez-Garcia et al. 2005) because other methods to determine biomass require litter and duff depth, which cannot be assessed without on-the-ground measurements.

Tree duff biomass is 3.7 times tree litter biomass. This conservative estimate of duff biomass is an average based on nine samples of the ratio of litter depth to duff depth computed from equations based on basal area for Southwestern Ponderosa pine forests (Fule and Covington 1994).

Shrub litter and duff biomass is 17.9 t/ha (Green 1981). Chaparral litter and duff biomass is 17.2 t/ha as computed from an average of seven-chaparral cover types (Green 1981). Western oak litter is 58 t/ha as computed by doubling average litter carbon density (U.S. Environmental Protection Agency 2006).

## Understory Biomass

Understory vegetation is defined as biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch diameter, measured at breast height. Understory biomass is computed from the understory carbon ratios shown in Table 3 (Birdsey 1992, U.S. Environmental Protection Agency 2002, 2006). For example, the biomass contained in understory vegetation in Western oak is 2.8 percent of the above ground biomass.

**Table 3. Understory carbon ratios.**

| Forest Type | Ratio of Understory Carbon to Live Tree Carbon (%) |
|---|---|
| Coast redwood | **4.4** |
| Douglas-fir | **2.3** |
| Cedar* | **4.4** |
| Lodgepole pine | **2.6** |
| Ponderosa/Jeffrey pine | **2.6** |
| Sugar pine | **2.6** |
| True fir/hemlock | **2.6** |
| Oak/tanoak** | **2.8** |
| Chaparral | **15.3** |
| Western oak** | **2.8** |

* Considered the same as coast redwood.
** Considered the same as hardwoods.

## Down Dead Wood Biomass

Down dead wood is defined as dead wood pieces not attached to trees, greater than 7.5 cm diameter, including stumps and roots of harvested trees. Down dead wood biomass is computed from the dead wood carbon ratios shown in Table 4 (Birdsey 1992, U.S. Environmental Protection Agency 2002). For example, the biomass contained in down dead wood in Douglas-fir is 15.5 percent of the above ground biomass.

**Table 4. Down dead wood carbon ratios.**

| Forest Type | Ratio of Down Dead Wood Carbon to Live Tree Carbon (%) |
|---|---|
| Coast redwood | **9.7** |
| Douglas-fir | **15.5** |
| Cedar* | **9.7** |
| Lodgepole pine | **15.2** |
| Ponderosa/Jeffrey pine | **15.2** |
| Sugar pine | **15.2** |
| True fir/hemlock | **15.2** |
| Oak/tanoak** | **11.5** |
| Chaparral | **3.5** |
| Western oak** | **11.5** |

* Considered the same as coast redwood.
** Considered the same as hardwoods.

## Standing Dead Biomass

Standing dead biomass includes dead trees or snags. Standing dead biomass is computed from above ground biomass as follows (Brown et al. 2004):

$$\text{Standing dead carbon density (tC/ha)} = ((\text{tC/ha above ground biomass})/75)^{2.5}$$

Where:
tC/ha is metric tons or tonnes of carbon per hectare

## Soil Carbon Density and Biomass

Soil includes mineral soils and organic soils; carbon densities are to a depth of one meter. Soil biomass is computed as twice the average U.S. soil carbon density because biomass is 50 percent carbon, as shown in Table 5 (U.S. Environmental Protection Agency 2002, 2006; Heath and Smith 2003).

**Table 5. Soil carbon densities.**

| Forest Type | Soil Carbon (tC/ha) |
|---|---|
| Coast redwood | **53.8** |
| Douglas-fir | **40.1** |
| Cedar* | **41.3** |
| Lodgepole pine | **35.2** |
| Ponderosa/Jeffrey pine | **41.3** |
| Sugar pine* | **41.3** |
| True fir/hemlock | **51.9** |
| Oak/tanoak | **27.6** |
| Shrubs** | **38.0** |
| Chaparral | **58.7** |
| Western oak | **27.6** |

* Considered the same as ponderosa pine.
** Considered the same as “minor/non-stocked” land.

## Computations for Scenarios

Scenarios used in FCEM require computing estimates of the following: impacts of fire and insect infestations; the benefits of removing dead trees and converting them into solid wood products and planting; the relative impacts of wildfire and prescribed fire on emissions, before and after thinning; and thinning with and without prescribed fire. Computations involve the use of percent mortality, as well as biomass consumption, decay, emissions, and harvest efficiency factors.

Dividing forest biomass into various components permits forest attributes such as fuels and related mortality to be considered. These structural elements are important ecologically and have a major influence on fire behavior and insect infestations, as well as management alternatives.

### Mortality

FCEM Scenarios 1, 2, and 4, which focus on fire, require specifying a percent understory and overstory mortality for both thinned and un-thinned forests. Scenario 3, which focuses on insect infestation, only uses overstory mortality. Understory mortality caused by insect infestation is not considered in Scenario 3 because it plays an incidental role that is difficult to determine. Mortality is then partitioned into forest components according to the source (i.e., fire involves all components and insects involve above ground tree biomass and roots that decay when a tree dies).

Mortality occurs once per simulation for wildfire and insect infestation. However, mortality can occur one or more times in 100 years for prescribed fire (Rx fire). The number of times prescribed fire affects a forest depends on the rotation specified, or the number of burns per century. For example, five burns per century is the equivalent of using prescribed fire on a 20-year rotation. FCEM assumes the initial prescribed fire affects the forest according to the specified understory and overstory mortality. The effect of each subsequent prescribed fire is reduced because of the reduction of fuel. FCEM uses the following formulas to adjust the effect of prescribed fires on biomass lost to combustion and decay:

Initial biomass lost + Biomass lost after n Rx fires

And:

$$\text{Biomass lost}_{n\ \text{Rx fires}} = \sum_{i=1}^{n} \text{Biomass}\ ((100/\text{Rx fire rotations})/100)_i$$

Where:
n = rotations - 1

For example, five rotations, or burns per century, means the first prescribed fire consumes fuel in proportion to the specified understory and overstory mortality. The remaining four prescribed fires consume only 20 percent as much fuel per burn because of fuel reduction from the first burn. Even though the fuel consumed and carbon released by each prescribed fire diminishes with an increase in the number of burns, total greenhouse gas emissions still increase because each prescribed fire adds to the emissions from the previous fire. In short, multiple prescribed fires have a cumulative impact on the atmosphere that may be less than, equal to, or exceed the impact of a single wildfire.

## Model Structure

The model structure follows a logical progression that starts with a few input variables and proceeds through a series of calculations that lead to numerous estimates (Figure 9). This is a biomass-based model that requires a minimum of input data about the forest. The model structure used to calculate greenhouse gas (GHG) emissions follows the general approach of Battye and Battye (2002).

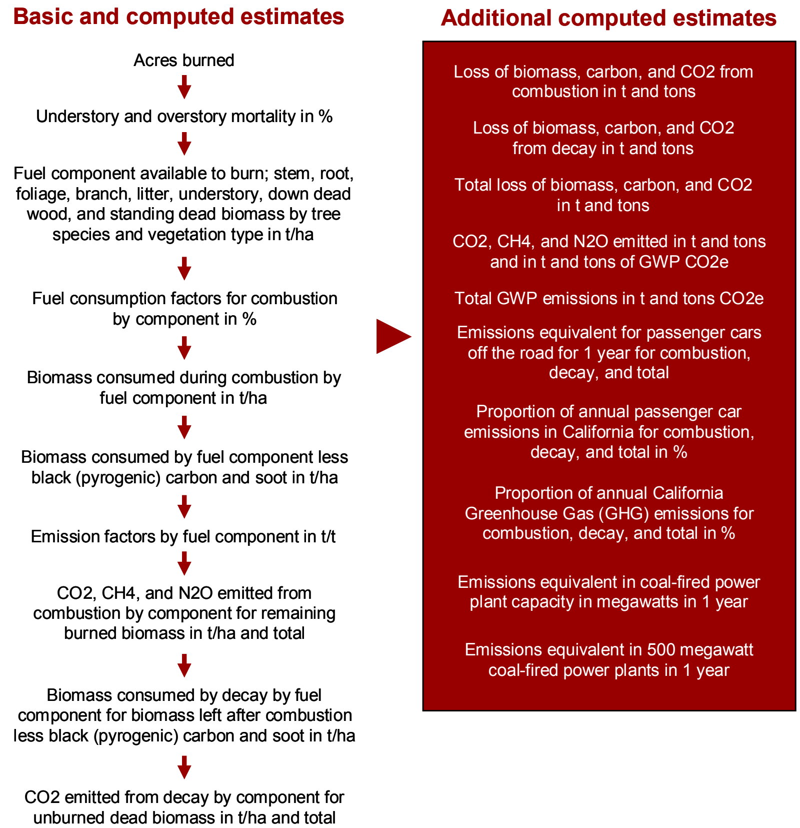


**Figure 9. Computations and estimates for the impact of wildfire on forest biomass, carbon, and greenhouse gas (GHG) emissions without dead tree removal or planting (Scenario 1).**

## Fuel Consumption

Table 6 illustrates how fuel consumption by fire is related to structural elements of the forest. This table is based on the California Air Resources Board revised methodology (Sotolong-Lowery 2004). Percent consumption only applies to the proportion of the component killed in the fire as specified by percent mortality.

**Table 6. Percent consumption by fuel component.**

| Fuel Component Consumed by Fire (t/ha) | Consumption (%) |
|---|---|
| Tree stems, live and dead (above ground less foliage & branches)* | **7.5** |
| Tree foliage** | **90.0** |
| Tree branches | **50.0** |
| Roots (sprouting potential included)** | **5.0** |
| Litter | **100.0** |
| Understory | **60.0** |
| Down dead | **82.0** |
| Standing dead (trees)* | **7.5** |
| Shrubs (above ground) | **60.0** |
| Chaparral (above ground) | **60.0** |
| Western oak (above ground) | **60.0** |

* Considered as 7.5 percent because personal observations on many fires show only ½ of the bark is consumed in most wildfires and bark is about 15 percent of tree stem biomass.
** Consultation with colleagues and personal observation.

## Combustion and Emissions

FCEM computes emissions only for forestry related greenhouse gases (GHG) recognized by the U.S. Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change (IPCC) (U.S. Environmental Protection Agency 2006). These greenhouse gases include carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Therefore, particulates and short-lived gases like carbon monoxide are excluded from FCEM emissions.

Biomass consumed by combustion is converted to greenhouse gases (GHG) by FCEM according to percent mortality and emission factors for particular fuel components. The initial emission factors published by the California Air Resources Board (2006) and Hardy et al. (1996) were adjusted to fit fuel components in FCEM and converted from pounds/ton to metric tons/metric ton (Table 7).

**Table 7. Emission factors by fuel component.**

| Fuel Component<br>Biomass Less Solid Char and Soot<br>(t/ha) | Emission Factors* (t/t of fuel)<br>CO2 | <br>CH4 | <br>N2O |
|---|---|---|---|
| Above ground (trees less foliage & branches) | **1.6277** | **0.0035** | **0.00020** |
| Foliage, branches, & roots (trees) | **1.5581** | **0.0050** | **0.00020** |
| Litter (trees) | **1.7414** | **0.0011** | **0.00025** |
| Understory (trees) | **1.5581** | **0.0050** | **0.00020** |
| Down dead (trees) | **1.6277** | **0.0035** | **0.00020** |
| Standing dead (trees) | **1.6277** | **0.0035** | **0.00020** |
| Shrubs | **1.5581** | **0.0050** | **0.00020** |
| Chaparral | **1.696**** | **0.00285**** | **0.00020** |
| Western oak | **1.5581** | **0.0050** | **0.00020** |

* Above ground biomass, standing dead wood, and down dead wood considered the same as wood 3+ inches in diameter; foliage and branches considered the same as canopy fuels; litter excludes duff; understory fuels considered the same as shrubs.
** Hardy et al. (1996). All other emission factors from California Air Resources Board (2006).

The amount of biomass converted to greenhouse gas emissions by fire using emission factors (see Table 7) is reduced by the amount of black (pyrogenic) carbon, or solid char and soot, created during combustion. This carbon decomposes and erodes over a long period. Therefore, biomass available for emissions is reduced by 3 percent for solid char and 0.25 percent for soot (Preston and Schmidt 2006).

Each greenhouse gas also has a Global Warming Potential (GWP). GWP is the ratio of global warming radiative forcing from one kilogram of a greenhouse gas to one kilogram of carbon dioxide over 100 years. CO2 has a GWP of 1, CH4 has 21 times the impact on global warming as CO2, and N2O has 310 times the impact of CO2 (Houghton et al. 1996, U.S. Environmental Protection Agency 2002). Therefore, the equation used in FCEM to compute the global warming potential of emissions of CO2 equivalent (CO2e) is:

$$GWP\ (tCO2e) = tCO2 + 21(tCH4) + 310(tN2O)$$

**Car equivalents.** FCEM converts emissions from combustion into passenger car equivalents. According to the U.S. Department of Transportation, the average passenger car emits approximately 5.03 metric tons of CO2e per year (U.S. Environmental Protection Agency 2005). As an example, a wildfire that releases one million metric tons of CO2e is the equivalent of the emissions from 198,807 passenger cars driving for one year or 1.4 percent of the 14 million passenger cars on the road in California (California Air Resources Board 2006). This is the same as saying that compensating for emissions from the fire would require removing the same number of cars from the road for one year.

In addition, FCEM computes the percentage of annual greenhouse gas emissions in California that wildfire contributes from combustion. For instance, one million metric tons of $CO_2e$ released by fire or insect infestation is equivalent to 0.02 percent of the 493 million metric tons of $CO_2e$ emitted each year in California (Bemis and Allen 2005).

**Coal-fired power plant equivalents.** FCEM converts emissions from combustion into coal-fired power plant equivalents. A coal-fired power plant emits approximately 5,825.4 metric tons of $CO_2$ per megawatt per year. This is based on 6,132 hours of operation per year at 70 percent efficiency. Therefore, a wildfire that releases one million metric tons of $CO_2e$ into the atmosphere is the equivalent of the annual emissions from generating 172 megawatts of electricity from a coal-fired power plant (Nuclear Energy Institute (NEI) 2007; Sustainable Energy & Economy Network (SEEN) 2007; U.S. Department of Energy and U.S. Environmental Protection Agency 2000).

## Decomposition and Emissions

Biomass decay is treated in FCEM as a process of oxidation of dead vegetation that is complete by the end of 100 years. Even though numerous studies show that the rate of decay varies according to local climate, species, and other factors (Mackensen and Bauhus 1999), they agree that above ground and below ground tree biomass generally decomposes within 100 years or less. For example, loblolly pine roots decompose in as little as 60 years (Ludovici et al. 2002). Logs lying on the ground also decompose within 100 years, with some exceptions.

A decomposition constant "k" is used to compute the decay rate in a single-exponential model. These include lodgepole pine (Busse 1994; k=0.027), Douglas-fir (Spies et al. 1988; k=0.029), ponderosa pine (Erickson et al. 1985; k=0.037), and white fir (Harmon et al. 1997; k=0.049). The model is:

$$x_{t+1} = x_t \, e^{(-kt)}$$

Where:
- $e = 2.718282$
- $x_{t+1}$ is biomass at time t+1
- $x_t$ is the initial biomass at time t
- t is time
- k is a decomposition constant

Computations using this model and the above decomposition constants show that, starting with a hypothetical biomass, decay is nearly complete in about 100 years (Figure 10).

Root decomposition is reduced if the tree or shrub sprouts. Sprouting potential is estimated at 90 percent for coast redwood, oak, and Western oak, and 50 percent of shrubs and chaparral (Olson et al. 1990; Sampson and Schultz 1956). Therefore, only the non-sprouting portion of root biomass decomposes after a fire or insects kill the above ground parts of the tree, shrub, or chaparral. Total root biomass decomposes if plants do not sprout.

Decomposition, or oxidation, releases carbon dioxide. Therefore, FCEM decomposes biomass left after a fire or insect infestation within 100 years and computes the amount of CO2 released. Black char and soot are not subtracted from decomposing biomass because they eventually oxidize by mechanisms that are poorly understood (Preston and Schmidt 2006). Based on the ratio of the molecular weight of CO2 (i.e., 44) and the molecular weight of carbon (i.e., 12), 3.67 times the carbon content of biomass is released as CO2 during decomposition.

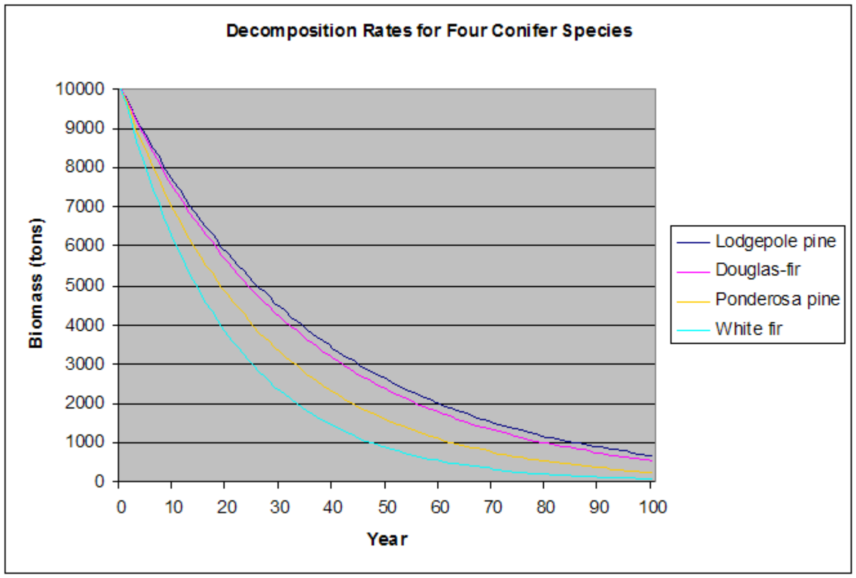


**Figure 10. Decomposition rates for four conifer species starting with a hypothetical biomass and using a single-exponential model.**

Like combustion, FCEM converts emissions from decomposition after wildfire or insect infestation into passenger car equivalents and megawatts of coal-fired power plant equivalents, as well as comparing them to total greenhouse gas emissions in California.

### Wood Products and Recovering Emissions

FCEM computes biomass, carbon, and CO2 stored in solid wood products produced by removing trees, by species, through thinning, harvesting, or dead tree removal after a wildfire or insect infestation. Biomass, carbon, and CO2 stored in wood products are deducted from combustion and decomposition emissions and shown in the input-output tables and charts for each scenario that includes dead tree removal and/or harvesting.

The amount of biomass harvested is 43 percent of the pre-harvest above ground biomass (Brown et al. 2004c). The amount of stem wood biomass that is processed is 85 percent of the biomass that arrives at the mill (bark is 15 percent) (Brown et al. 2004c). Finally, the amount of biomass converted into solid wood products is 62 percent of the stem wood after bark removal (Milota 2004). FCEM then converts the carbon fraction of wood product biomass into CO2 storage. For example, if the potential harvested biomass (above ground biomass) is 200 t/ha then the CO2 absorbed and stored in solid wood products is:

Step 1: Biomass harvested = 0.43(200) = 86 t/ha
Step 2: Biomass processed = 0.85(86) = 73.1 t/ha
Step 3: Biomass in solid wood products = 0.62(73.1) = 45.3 t/ha
Step 4: Carbon in solid wood products = 0.5(45.3) = 22.65 t/ha
Step 5: CO2 absorbed and stored in solid wood products = 3.67(22.65) = 83.1 t/ha

These estimates are conservative. In addition, this analysis does not consider the use of wood waste, a renewable resource, for generating electricity that can substitute for electrical energy produced by burning non-renewable fossil fuels. The savings in greenhouse gas emissions can be significant.

**Planting and Recovering Emissions**

Planting a young forest to replace one killed by wildfire or insects can recover most if not all the $CO_2$ lost to the atmosphere from combustion and/or decay. FCEM provides two options: the plant-and-forget strategy and a plantation or plant and manage strategy. Both strategies include only the biomass, carbon, and $CO_2$ stored in the stems, branches, foliage, and roots of trees on the acres planted. Biomass, carbon, and $CO_2$ stored in the planted forest are deducted from combustion and decomposition emissions and shown in the input-output tables and charts for each scenario that includes planting.

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**Table 8. Input data to describe original and thinned forest and post-event plantation.**

| Scenario | Forest | Description * | Unit |
|---|---|---|---|
| **Baseline** | **Original** | **Title** | **text** |
| | | **Acres** | **total** |
| | | **Conifer forest >= 2 in dbh** | **trees/acre **** |
| | | **Shrub cover** | **%** |
| | | **Chaparral cover** | **%** |
| | | **Conifer forest** | **% of acres** |
| | | **Shrubs** | **% of acres** |
| | | **Chaparral** | **% of acres** |
| | | **Western oak** | **% of acres** |
| | | **Uneven-aged conifer forest** | **y/n by species** |
| | | **Even-aged conifer forest** | **average dbh by species** |
| | | **Conifer forest species composition** | **% by species** |
| | | **Age of original forest** | **default is 100 years** |
| | **Thinned** | **Thin conifer forest < 30 in dbh** | **% reduction** |
| **Plantation** | **Post-event** | **Age at harvest** | **years** |
| | | **Density at harvest** | **trees/acre** |
| | | **Average dbh at harvest** | **inches** |
| | | **Plantation species composition** | **% by species** |

* Data required depends on characteristics of original forest.
** If data are for trees >= 5 in dbh then multiply trees/acre by coefficients in Table 1, otherwise use total known trees/acre.

**Table 9. Input data for scenarios.**

| Scenario | Forest | Description | Unit |
|---|---|---|---|
| **Scenario 1** | **Original** | **Area burned** | **acres** |
| | | **Understory mortality** | **%** |
| | | **Overstory mortality** | **%** |
| | **Thinned** | **Understory mortality** | **%** |
| | | **Overstory mortality** | **%** |
| **Scenario 2** | **Original** | **Dead tree removal** | **acres** |
| | | **Area planted (public)** | **acres** |
| | | **Area planted (private)** | **acres** |
| | **Thinned** | **Dead tree removal** | **acres** |
| | | **Area planted (public)** | **acres** |
| | | **Area planted (private)** | **acres** |
| **Scenario 3** | **Original** | **Area infested** | **acres** |
| | | **Overstory mortality** | **%** |
| | | **Dead tree removal** | **acres** |
| | | **Area planted (public)** | **acres** |
| | | **Area planted (private)** | **acres** |
| | **Thinned** | **Overstory mortality** | **%** |
| | | **Dead tree removal** | **acres** |
| | | **Area planted (public)** | **acres** |
| | | **Area planted (private)** | **acres** |
| **Scenario 4** | **Original** | **Rx fire - understory mortality** | **%** |
| | | **Rx fire - overstory mortality** | **%** |
| | | **Rotation (Rx burns)** | **# per 100 years** |
| | **Thinned** | **Rx fire - understory mortality** | **%** |
| | | **Rx fire - overstory mortality** | **%** |