

Emissions reductions from harvested wood products and management residuals

Peter Tittmann, Ph.D.

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1 California forest management emissions profile

Utilization of wood biomass produced from forest management activity has the potential to reduce emissions from greenhouse gas (GHG) and other climate pollutant. Currently the majority of biomass produced from forest management activities are either left in the woods to decompose, or aggregated at a landing where it is eventually burned. When considered alongside woody material resulting from a history of fire suppression, the subsequent accumulation of dead woody material in excess of historic reference conditions has elevated risk of damaging wildfire in much of California's forestland. Common practice for fuel load management in California forests have evolved to include prescribed natural fire and sanitation pile burning. As demonstrated by previous studies, prescribed natural fire is often only an effective tool for reducing fuel loading and maintaining fire-resilient landscapes when coupled with mechanical treatment to remove biomass (Stephens et al 2009), and open burning can be a substantial source of strong radiative forcing agents (black carbon) and criteria air pollutants (PM, NOX) when compared to use in controlled combustion biomass power plants with modern emissions control technology. Air quality impacts of these common forestry practices as well as the opportunity cost of not using residual biomass in bioenergy energy and/or other applications weigh in favor of alternative utilization strategies.

Forest management activities in California produce logs for lumber markets while maintaining and enhancing forest health. In addition to merchantable logs, harvest activities produce logging residuals and slash that are either left in the stand to decompose or piled and burned as directed by forest practice rules (California Forest Practice Rules, Article 7 § 917.2). Combustion or decomposition of this residual material results in emissions of greenhouse gases (GHG), criteria air pollutants (CAP) and short-lived climate pollutants (SLCP). However, even with the absence of forest management activity, atmospheric emissions are produced from stochastic processes such as wildfire, pest, and disease outbreaks. Figure ref:fig:wood_{fates} presents an overview of emissions and emissions reduction pathways for wood from California's forests.

The focus of this analysis is on deriving emissions associated with management activity. This report does not assess greenhouse gas emissions from pest or disease induced mortality, which is estimated at approximately 34 MMT CO₂e annually in California forests cite:Christensen2016. Emissions from mortality are indirectly related to management activities just as wildfire is and **must** be accounted for a comprehensive evaluation of the climate impacts of harvesting.

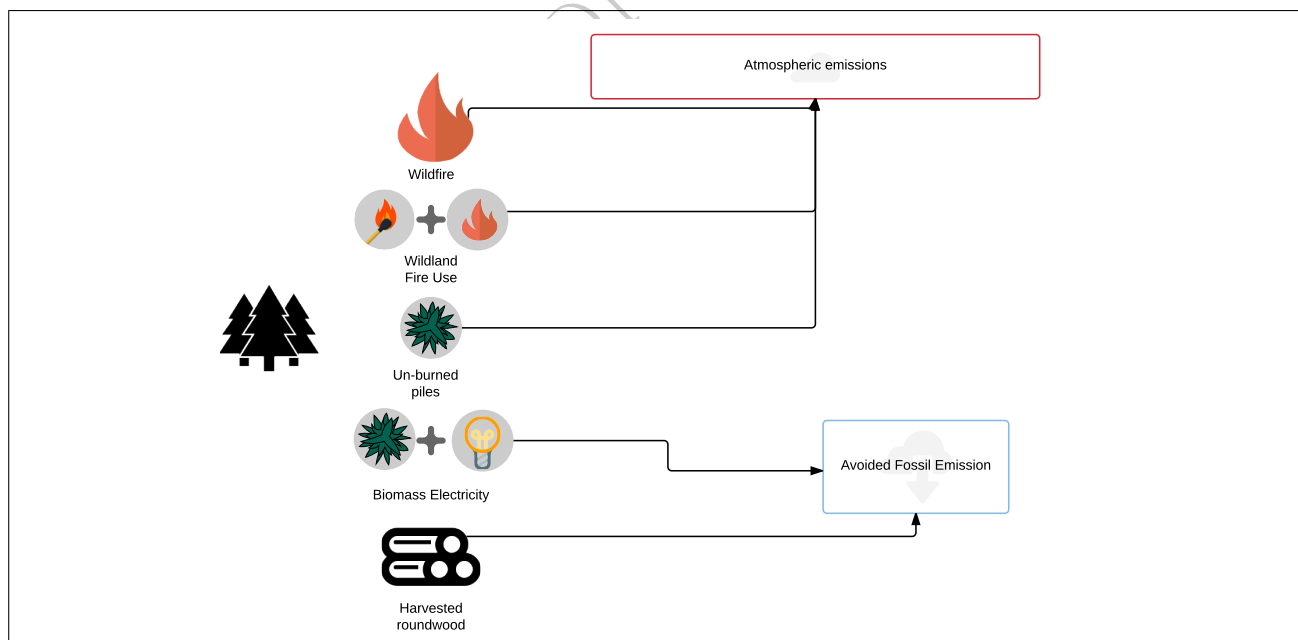


Figure 1: Overview of fates of wood resulting from harvest and mortality in California forests. Note that time is not represented in this figure. fig:wood_{fates}

Quantifying the climate effects of wood products and forest management residuals is important to the development of the Forest Climate Plan (FCP)¹ as well as efforts underway by the California Board of Forestry

¹The Forest Climate Action Team (FCAT) was assembled in August of 2014 with the primary purpose of developing a Forest Carbon Plan by the end of 2016. FCAT is comprised of Executive level members from many of the State's natural resources agencies, state and federal forest land managers, and other key partners directly or indirectly involved in California forestry. FCAT is under the leadership of CAL FIRE, Cal-EPA, and The Natural Resources Agency.

and CalFire to meet the intent of AB 1504 (2010)². To inform these efforts, this report provides estimates of the following :

1. GHG and SLCP emissions produced from the combustion or decomposition of logging residuals.
2. GHG emissions reductions from the use of wood products harvested in the state.

Estimates are based on empirical data and reflect past forest management activities. It is **critical** to note that the empirical data used in this analysis reflect point-in-time measures that are affected by a dynamic system of climate, growth, and mortality in forests as well as macroeconomic and policy forces. To effectively manage these forests for climate (and/or other) benefits, a process modeling approach is necessary.

This analysis may provide insight into opportunities to more effectively utilize woody biomass residuals from current forest management activities based on available historical data. Several steps are necessary to address the objective stated:

1. Estimate CO₂ equivalent emissions from burning forest management residuals using criteria pollutant and GHG emissions inventory published by the California Air Resources Board (CARB)
2. Estimate the volume and fate of wood removed, left in the forest, and burned as a result of direct anthropogenic management activities.
3. Establish life-cycle displacement factors (DF) for all utilized wood and apply DF to harvested wood to obtain an aggregate estimate.

1.0.1 Key Findings

- Baseline emissions of GHG and SLCP emissions from burning of forest management residuals can be estimated and should be considered in any forest management emissions baseline.
- Total emissions from pile burning of forest management residuals (including SLCP and GHG components) extrapolated from CARB emissions inventory at XXX MTCO₂e
- Wood harvested in California in 2012 resulted in avoided emissions of 2.29 MMTCO₂e
- Logging residuals not used in bioenergy production contributed emissions of:
 - XXX MMTCO₂e resulting from anthropogenic burning of logging residuals
 - XXX MMTCO₂e resulting from decomposition of logging residuals left unburned
- Un-utilized slash from non-commercial management activities on National Forest System lands contributed emissions of XXX MMTCO₂e
- Forest Inventory and Analysis re-sample data has been used in the southeast to quantify removals resulting from non-commercial management activity and could be used for this purpose in California
- The Prescribed Fire Information Reporting System (PFIRS) may be a useful tool for quantifying emissions from pile burns and prescribed fire. It is a requirement that prescribed fires and pile burns on National Forest System Lands are reported through PFIRS. However, California Air Quality Management Districts are not required to report emissions through this system at this time. Therefore, it is not possible to associate burns in the PFIRS with commercial harvest activities.

2 Estimating CO₂ equivalent emissions from forest biomass burning

2.0.1 Estimating black carbon emissions from biomass burning

The California Air Resources Board (CARB) reports emissions from forest biomass burning in current statewide emissions inventories. The Greenhouse Gas (GHG) and Criteria Air Pollutant (CAP) emissions inventory are

²AB-1504 Forest resources: carbon sequestration.(2009-2010)

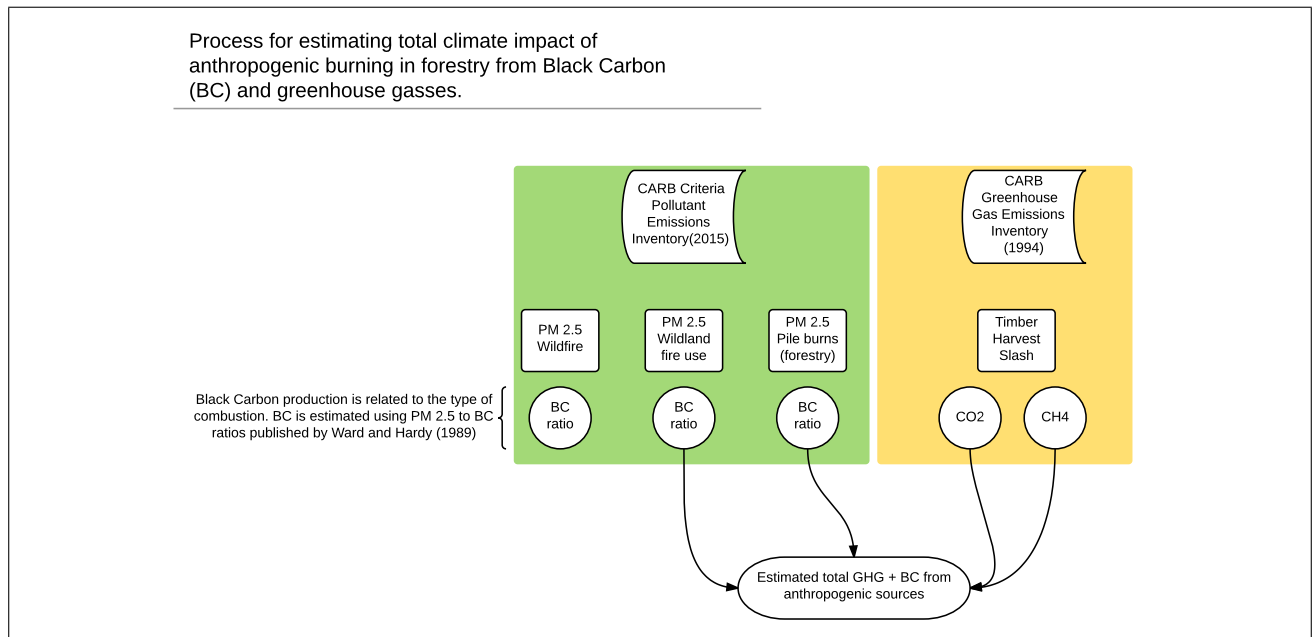


Figure 2: Data sources available from CARB for estimating GHG and SLCP emissions from forest management.

both necessary resources for establishing aggregate annual climate-forcing emissions. The GHG inventory captures gasses with radiative forcing properties but does not capture elemental carbon or black carbon (BC) emissions which also have strong radiative forcing properties. The criteria air pollutant emissions estimates for 2015 captures particulate matter (PM 2.5) including black carbon, which is a strong short lived climate pollutant.

The citet:CaliforniaAirResourcesBoard2015,CaliforniaAirResourcesBoard2016 also reports aggregated SLCP emissions from wildfire (80.52 MMTCO₂e) and prescribed fire (3.66 MMTCO₂e), but reference in the SLCP Strategy is made to the source of these estimates.

Table 1: Range of Global Warming Potential(GWP) values for Black Carbon.

| GWP ₂₀ | GWP _{σ20} | GWP ₁₀₀ | GWP _{σ100} | GWP ₅₀₀ | GWP _{σ500} | Source |
|-------------------|--------------------|--------------------|---------------------|--------------------|---------------------|---------------------------------|
| 2200.0 | 888.82 | 633.33 | 255.41 | 193.33 | 77.67 | Fuglestvedt2010 |
| 3200.0 | | 900.0 | | | | CaliforniaAirResourcesBoard2015 |

CARB reports PM 2.5 emissions in tons/day. Annual emissions as reported by CARB are shown in Table 1.

Table 2: Emissions of PM 2.5 in 2015 as reported by CARB

| Source | PM 2.5 (t y ⁻¹) |
|-------------------------|-----------------------------|
| ALL VEGETATION | 137630.15 |
| FOREST MANAGEMENT | 5480.51 |
| WILDLAND FIRE USE (WFU) | 6802.43 |

Black Carbon emissions can be estimated from PM 2.5 emissions if the ratio of smoldering to flaming combustion is known. citet:Ward1989 provide estimates of the ratio of smoldering to flaming combustion for hand/machine piled burns, prescribed natural fire and wildfire. BC is a fraction of the Total Carbon (TC) component of PM 2.5. Thus BC may be calculated from PM 2.5 by Eq. eqref:eq-bc :

$$BC = (PM_{2.5} \times F \times TC_f \times BC_f) + (PM_{2.5} \times S \times TC_s \times BC_s) \quad (1)$$

where:

BC = Black Carbon (mass units)

$PM_{2.5}$ = $PM_{2.5}$ (mass units)

F = Percent of combustion in flaming phase

TC_f = Total Carbon fraction of $PM_{2.5}$ for flaming phase

BC_f = Black Carbon fraction of Total Carbon for flaming phase

S = Percent of combustion in smoldering phase

TC_s = Total Carbon fraction of $PM_{2.5}$ for smoldering phase

BC_s = Black Carbon fraction of Total Carbon for smoldering phase

Based on citet:Ward1989 and citet:Jenk1996, the following ratios are used herein.

Table 3: Factors used for calculating Black Carbon (BC) emissions from three primary combustion sources. BC is a fraction of Total Carbon (TC) which is a fraction of total PM 2.5. Coefficients of variation (C_v) are reported here as well.

| Source | $BC_f \text{ t}^{-1} \text{ PM}$ | $TC_f^{C_v} \text{ t}^{-1} \text{ PM}$ | $BC_f^{C_v} \text{ t}^{-1} \text{ TC}$ | $BC_s \text{ t}^{-1} \text{ PM 2.5}$ | $TC_s^{C_v} \text{ t}^{-1} \text{ PM}$ | $BC_s^{C_v} \text{ t}^{-1} \text{ TC}$ |
|------------|----------------------------------|--|--|--------------------------------------|--|--|
| Pile Burn | 0.046904 | 0.09 | 0.45 | 0.01624 | 0.01 | 0.49 |
| Prescribed | 0.08016309 | 0.0733 | 0.5833 | 0.020944 | 0.08 | 0.29 |
| Wildfire | 0.05870124 | 0.0867 | 0.4467 | 0.0228641 | 0.06 | 0.338 |

To arrive at a rough estimate of BC emissions based on PM_{2.5} the following steps are taken

1. Determine the amount of PM_{2.5} produced in the flaming and smoldering phases of combustion for each type (piles, prescribed, wildfire). Ratios from citet:Ward1989, table 5 are used.
2. Define 1000 normal probability distributions using the coefficient of variation from Table ref:tab:bc_{pm} for the percent of PM_{2.5} comprised of carbonaceous material (TC) and percent of TC comprised of black carbon (BC) give estimates and coefficient of variation estimates provided by citet:Ward1989, tables 2 and 3.
3. Estimate annual BC emissions based on probability distributions defined in 2.

| Source | PM 2.5 (t y ⁻¹) | BC (t y ⁻¹) | GWP (t y ⁻¹) |
|-------------------------|-----------------------------|-------------------------|--------------------------|
| ALL VEGETATION | 137630.15 | 11225.85 | 35922719.54 |
| FOREST MANAGEMENT | 5480.51 | 346.06 | 1107396.54 |
| WILDLAND FIRE USE (WFO) | 6802.43 | 687.77 | 2200877.13 |

The following plot represents estimates of total BC emissions resulting from combustion of biomass in the CARB CAP emissions categories reflecting woody biomass combustion in wildfire, pile burning, and prescribed natural fire.

To estimate GHG emissions from pile burning, we can use the ratio of PM_{2.5} to CO₂, and CH₄ used in the Piled Fuels Emissions Calculator.

The following ratios are used to estimate GHG emissions from CARB-reported PM emissions.

| Pile Biomass (t) | Consumed Biomass (t) | PM _{2.5} (t) | CO ₂ (t) | CH ₄ (t) |
|------------------|----------------------|-----------------------|---------------------|---------------------|
| 1.360178 | 1.224161 | 0.008263 | 2.0366 | 0.0034 |

In addition the http://www.arb.ca.gov/cc/inventory/archive/tables/net_co2_flux_2007-11-19.pdf CARB 1994 greenhouse gas emissions inventory estimates emissions from wildfire and slash burning through 2004 (Table ref:arb_{ghg}2004).

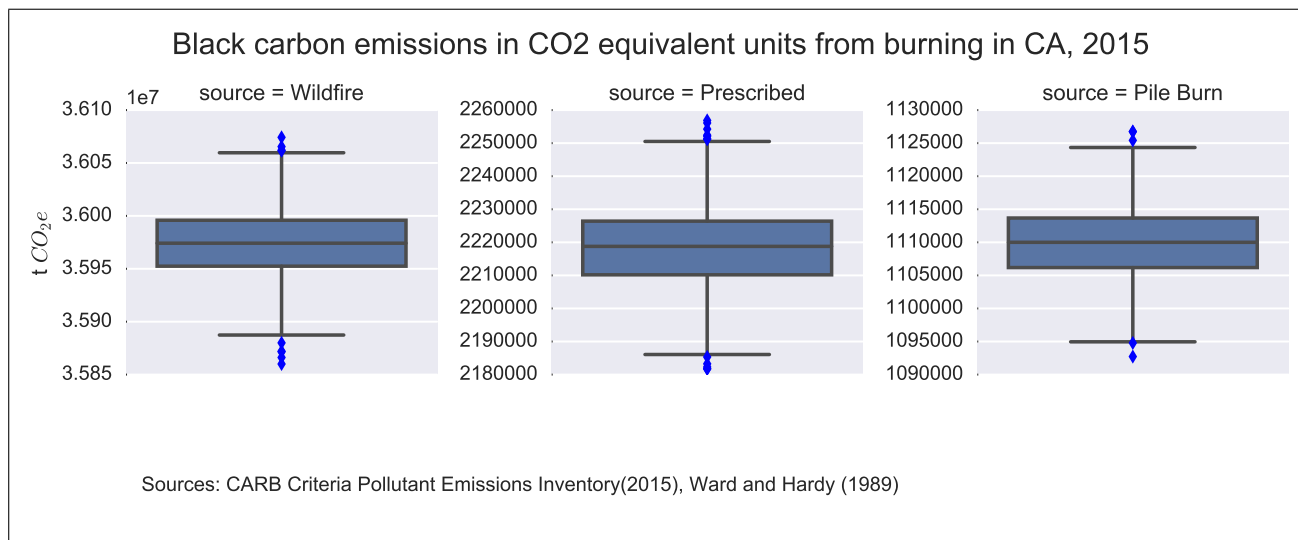


Figure 3: Short-lived climate pollution from open burning of biomass as reported by CARB criteria pollutant emissions inventory.

Table 4: something134

| Source Category | Average annual emissions 1994-2004 MMTCO _{2e} |
|----------------------------|--|
| Forest and rangeland fires | 2.0194 |
| Timber harvest slash | 0.155266666666667 |

To arrive at an estimate of total emissions in 2015 from burning forest management residuals in CO₂ equivalent terms from published CARB estimates we can combine the CO₂ emissions reported for 2004 in the LULUC Biodegradable Carbon Emissions and Sinks with black carbon emissions extrapolated from the CARB Criteria Air Pollutant Emissions inventory estimates. The time discrepancy between the 2004 and 2015 is acknowledged as an irreconcilable source of uncertainty in this estimation. Further model based estimation could be used to derive a ratio of GHG to PM using the CONSUME model. This does however show that a baseline of substantial emissions from forest management residuals has been reported in CARB emissions inventories and should be recognized as a baseline condition. We find that a rough estimate of CO₂e emissions from pile burning annual approaches 1 Mt CO₂e.

| SC _{cat} | avg(mmtco _{2e}) |
|----------------------------|---------------------------|
| Forest and rangeland fires | 2.0194 |
| Timber harvest slash | 0.155266666666667 |

| | Mt CO ₂ e | Source |
|---|----------------------|-----------------------------------|
| 0 | 0.17 | CO ₂ pile burning |
| 1 | 0.99 | CO ₂ e BC pile burning |
| 2 | 1.16 | Total Mt CO ₂ e |

BC emissions in terms of CO₂e has not been included in any GHG emissions inventory published by CARB.

3 Fate of harvested wood

Wood harvested from California's forests are used in construction, landscaping, and consumer products. Residues from the production of these wood products may be directed towards alternative product streams to generate electricity and heat with a portion going to landfills or left in the woods as slash.

3.1 Disposition wood harvested in California.

Harvested wood from California's forests is fractionated through harvest and processing and use into several categories for which the time horizon for return of carbon in biomass to the atmosphere can vary widely:

Logging Residuals Tops, limbs and sub-merchantable material produced from harvest activities in the woods

Processing (mill) residuals Sawdust, shavings, bark and off cuts from primary and secondary manufacturing.

Construction debris Fraction of finished wood from finished products that is left from construction or integration into its final use.

Demolition Wood used in construction that has reached the end of its useful life.

Each category has multiple potential fates which can greatly influence the net emissions impact attributable to the initial forest management activity. The fate of each of these pools is determined by a political and economic system which is highly dynamic. To understand how policy decisions will impact the fate and subsequent climate impact of harvested wood products, a detailed process model is necessary. To provide a rough estimate of the fate of annual round-wood harvest historically, we must use historical volumes and and apply what we know about milling efficiency improvements, logging utilization rates, and construction use efficiency.

According to citet:Morgan logging residues produced from sawlog harvest can be estimated using a factor of 0.0302 (+/-0.0123 @95%CI) times the total cubic sawlog volume delivered to a mill. Unfortunately we cannot say how logging residue production has changed over time in California. citet:Simmons2014 found that logging utilization has decreased in Idaho from 1990 to 2011 by 72%. For the purposed of this analysis we will assume that similar changes have occurred in California timber harvesting. We then estimate a logging residue production factor for years before 1990 based on the following equation wherein we assume 1990 residue ration for all years prior:

$$Vlr_x = Vrw_x (\eta_{04} + (\eta_{04}\eta_{\Delta}))$$

Where:

Vrw_x = Rundwood volume harvested in year x

$\eta_{04} = \mathcal{N}(0.0302, 0.0123)$ ratio of logging residues to roundwood harvested in CA, 2004

$\eta_{\Delta} = 0.72$ (percent change in efficiency over time period)

For logging residue production factors for years between 1990 and 2004 we calculate logging residues as a function of the percent change in logging residual rations estimated for Idaho from citet:Simmons2014 applied to the known logging residual ratio reported by citet:Morgan. To reflect the uncertainty in the estimate provided by citet:Morgan, we calculate the logging residual using a randomly selected value from a normal probability distribution defined by the estimate and upper and lower bounds of the 95% confidence interval provided:

$$Vlr_x = Vrw_x \left(\eta_{04} + \left(\eta_{04} \left((Y_1 - x) \frac{\eta_{\Delta}}{Y_{\Delta}} \right) \right) \right)$$

Where:

Vrw_x = Rundwood volume harvested in year x

$\eta_{04} = \mathcal{N}(0.0302, 0.0123)$ ratio of logging residues to roundwood harvested in CA, 2004

$Y_1 = 2004$ (year for which logging residual estimate available for CA)

x = year for which logging residues are calculated

$\eta_{\Delta} = 0.72$ (percent change in logging residue ratio over time period)

$Y_{\Delta} = 21$ (number of years over which logging residue ratio decreased)

Logging residual volume in years following 2004 are calculated as follows:

$$Vlr_x = Vrw_x \left(\eta_{04} - \left(\eta_{04} \left((x - Y_1) \frac{\eta_{\Delta}}{Y_{\Delta}} \right) \right) \right)$$

Where:

Vrw_x = Rundwood volume harvested in year x

$\eta_{04} = \mathcal{N}(0.0302, 0.0123)$ ratio of logging residues to roundwood harvested in CA, 2004

$Y_1 = 2004$ (year for which logging residual estimate available for CA)

x = year for which logging residues are calculated

$\eta_{\Delta} = 0.72$ (percent change in logging residue ratio over time period)

$Y_{\Delta} = 21$ (number of years over which logging residue ratio decreased)

Milling efficiency has increased roughly 14% in California in the period between 1970 and 2006 citet:Keegan2010. For this analysis we assume a continuous improvement such that for years prior to 1970, milling efficiency in year x is calculated as:

$$Vmr_x = Vrw_x \left(\eta_{70} - \left((Y_1 - x) \frac{\eta_{\Delta}}{Y_{\Delta}} \right) \right)$$

Where:

Vrw_x = Rundwood volume harvested in year x

$\eta_{70} = 0.42$ (milling efficiency in 1970)

$Y_1 = 1970$ (earliest year mill efficiency available for)

x = year for which milling residues are calculated

$\eta_{\Delta} = 0.06$ (increase in milling efficiency from 1970-2011)

$Y_{\Delta} = 41$ (number of years overwhihc milling efficiency increased)

For years after 1970, milling efficiency for year x is calculated as:

$$Vmr_x = Vrw_x \left(\eta_{70} + \left((x - Y_1) \frac{\eta_{\Delta}}{Y_{\Delta}} \right) \right)$$

Where:

Vrw_x = Rundwood volume harvested in year x

$\eta_{70} = 0.42$ (milling efficiency in 1970)

$Y_1 = 1970$ (earliest year mill efficiency available for)

x = year for which milling residues are calculated

$\eta_{\Delta} = 0.06$ (increase in milling efficiency from 1970-2011)

$Y_{\Delta} = 41$ (number of years overwhihc milling efficiency increased)

To estimate annualized construction waste material, we use ratios of finished wood products to construction debris and demolition debris referenced in citet:McKeever2004. This data from citeauthor:McKeever2004 is sparse and should be considered unreliable for years other than those for which it is reported. Construction debris was estimated in 2002 as approximately 15% of total wood used in construction. Demolition debris from wood produced annually from wood grown on California forestland is outside of the scope of this report.

Table ref:tab:me_and_lr presents ten year average estimates of logging and milling residuals, finished lumber, and construction debris based on BOE roundwood harvest volumes.

3.2 Wood Displacement Factors

In all of its applications, wood may be substituted by a range of other materials. For example, in residential construction, precast concrete and structural steel framing are competitive alternatives to wood. This choice of

materials has a profound impact on GHG emissions in the construction sector and is expressed as a displacement factor (DF). A displacement factor quantifies the amount of emissions reduction achieved per unit of wood used. A meta analysis conducted by citep:Sathre2010 compared empirical analysis from 21 international studies and found an average emissions reduction of 2.1 tons of carbon (3.9 t CO₂e) per ton of dry wood used. While studies ranged substantially around the average, the authors found that the majority of published displacement factors ranged between 1 and 3 tC/t dry wood. The displacement factors published in citep:Sathre2010 and used in this analysis are based on the following emission reduction sources:

1. **Reduced emissions from manufacturing:** Wood products require less total energy than to manufacture than products made from alternative materials.
2. **Avoided process emissions:** Production of wood alternatives such as cement are associated with substantial CO₂ emissions.
3. **Carbon storage in products:** Carbon in harvested wood is drawn from the atmosphere through photosynthesis and will remain fixed through the useful life of the wood product.
4. **Carbon storage in forests:** Forests producing wood continue to grow. It is assumed that forests producing wood in California are managed to sustain forest growth (not converted to non-forest land uses).
5. **Avoided fossil fuel emissions due to bioenergy substitution:** Logging and milling residuals used to produce energy avoid emissions from fossil energy sources in the energy sector.
6. **Carbon dynamics in landfills:** A fraction of carbon from wood deposited in landfills remains in semi-permanent storage. The remainder is converted to methane through biological decomposition in the landfill. Capture and use of the methane as an energy source, in turn reduces emissions from fossil energy sources.

3.3 Displacement Factors Applied to Timber Products Output

To evaluate the climate impact of harvested wood in California, I used harvested roundwood estimates from the Timber Products Output (TPO) database³. I used two estimates of the DF applied to the harvested wood reported in the TPO based on whether logging residuals were used in bioenergy or left in the woods (to decompose or burn).

Figure ref:fig:flow_{chart} reflects the flow of wood from Californias forest to its fate in-use and is the frame of reference for the following analysis.

I applied displacement factors reported by cite:Sathre2010 to the reported volumes from the TPO database. The following references are used to arrive at a displacement factor for harvested roundwood without logging residue utilization.

Table 5: Wood displacement factor without residue utilization

| reference | displacement factor |
|--------------------|---------------------|
| citet:Eriksson2007 | 1.7 |
| citet:Eriksson2007 | 2.2 |
| citet:Salazar2009 | 4.9 |
| citet:Werner2005 | 1.7 |

I applied an average of the DF reported here of **2.625** tCO₂e/t finished wood product. For harvested roundwood with logging residue utilization the following studies are used.

I used an average of the DF reported here of **3.243** tCO₂e/t finished wood product.

The TPO reports values in terms of roundwood harvested for products, but the displacement factors presented in Sathre and O'Connor are in terms of tons of carbon in wood products. Therefore we must assume a milling efficiency to convert TPO volume estimates to finished wood product volume. I assumed a milling efficiency of 0.5.

³Timber Products Output Reporting Tool http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php

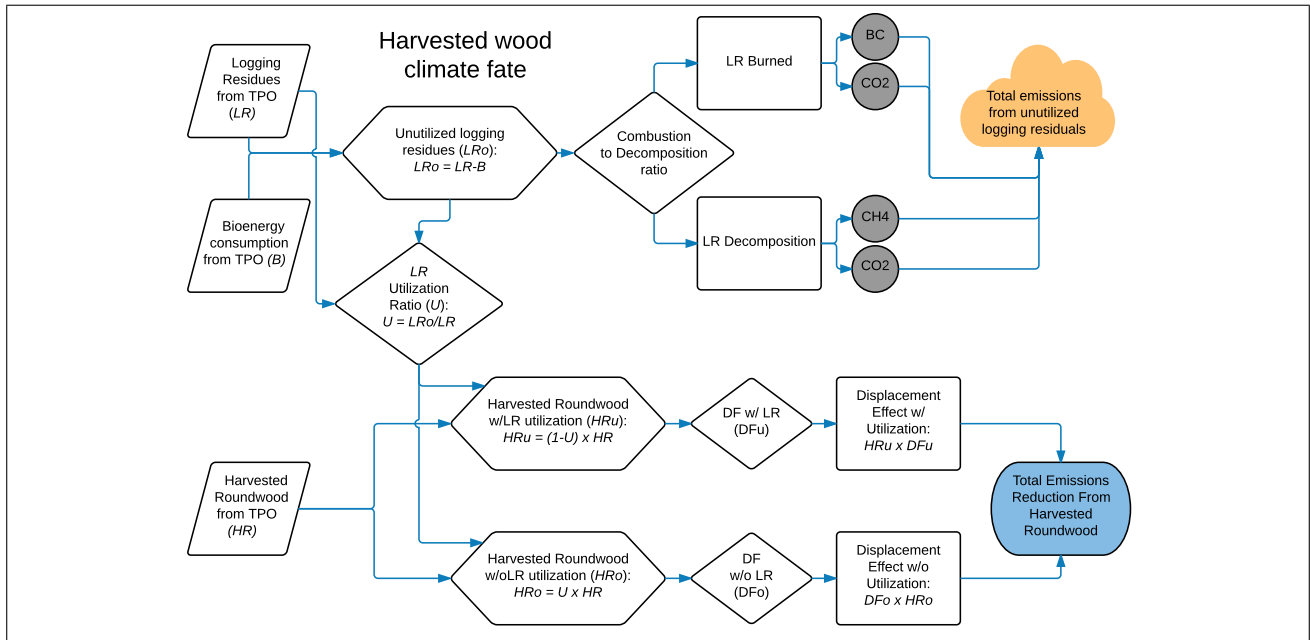


Figure 4: Wood flows from timber harvest in California

Table 6: Wood displacement factor with residue utilization
reference displacement factor

| | |
|-----------------------|-----|
| citet:Eriksson2007 | 1.9 |
| citet:Eriksson2007 | 2.5 |
| citet:Gustavsson2006a | 4 |
| citet:Gustavsson2006a | 5.6 |
| citet:Gustavsson2006a | 2.2 |
| citet:Gustavsson2006a | 3.3 |
| citet:Pingoud2001 | 3.2 |

Further, TPO is reported in cubic feet and the DF implies a mass unit. To convert cubic meters to a mass unit, we used the average wood density of harvested volume in California weighted by species. Harvest volume by species is reported in citet:Mciver2012. The resulting weighted average wood density used here is **27.94 lbs/cuft**.

McIver and Morgan report the percent of harvested wood used in bioenergy feedstocks. From personal communications with Chelsea McIver, all bioenergy feedstock reported is sourced in-woods (ie, not mill residues).

Table 7: % volume wood diverted to Bioenergy use

| year | bioenergy % of harvest |
|--------|------------------------|
| 0 2000 | 0.024 |
| 1 2006 | 0.036 |
| 2 2012 | 0.082 |

| | Ownership | Roundwood Products | Logging Residues | Year |
|----|-----------------|--------------------|------------------|------|
| 0 | National Forest | 72.4 | 20.7 | 2012 |
| 1 | Other Public | 16.2 | 3.4 | 2012 |
| 2 | Forest Industry | 328.9 | 72.4 | 2012 |
| 3 | Other Private | 53 | 11.2 | 2012 |
| 4 | National Forest | 52.8 | 16.3 | 2006 |
| 5 | Other Public | 1.1 | 0.3 | 2006 |
| 6 | Forest Industry | 274.3 | 59.6 | 2006 |
| 7 | Other Private | 139.2 | 33.2 | 2006 |
| 8 | National Forest | 90.8 | 22.6 | 2000 |
| 9 | Other Public | 5.2 | 1.6 | 2000 |
| 10 | Forest Industry | 372.5 | 70.6 | 2000 |
| 11 | Other Private | 159.4 | 49.1 | 2000 |
| 12 | National Forest | 132.1 | 11.2 | 1994 |
| 13 | Other Public | 24.7 | 4.3 | 1994 |
| 14 | Forest Industry | 396.1 | 63.1 | 1994 |
| 15 | Other Private | 174.7 | 22.3 | 1994 |

In addition to the TPO, the California Board of Equalization (BOE) also reports historic timber harvest volumes. Comparing between years where both sources report data, the BOE on average reports 8% less volume than the TPO (Table ref:tab:tpo_{boe}) database. This is reasonable considering that:

1. BOE data may be under-reported, as there may be a financial incentive to reduce tax burden
2. BOE does not include volume harvested from native American tribal lands in the state

Table 8: Total annual harvest reported by citet:Mciver2012 and California Board of Equalization.

| year | McIver, et. al. (2012) MMBF | BOE MMBF | BOE/M&M |
|------|-----------------------------|----------|---------|
| 1978 | 4606.0 | 4491 | 0.98 |
| 1979 | 4044.0 | 3991 | 0.99 |
| 1980 | 3478.0 | 3164 | 0.91 |
| 1981 | 2832.0 | 2672 | 0.94 |
| 1982 | 2488.0 | 2318 | 0.93 |
| 1983 | 3638.0 | 3358 | 0.92 |
| 1984 | 3701.0 | 3546 | 0.96 |
| 1985 | 4093.0 | 3818 | 0.93 |
| 1986 | 4416.0 | 4265 | 0.97 |
| 1987 | 4667.0 | 4500 | 0.96 |
| 1988 | 4847.0 | 4670 | 0.96 |
| 1989 | 4699.0 | 4424 | 0.94 |
| 1990 | 4264.0 | 4021 | 0.94 |
| 1991 | 3439.0 | 3195 | 0.93 |
| 1992 | 3192.0 | 2973 | 0.93 |
| 1993 | 3041.0 | 2871 | 0.94 |
| 1994 | 2814.0 | 2316 | 0.82 |
| 1995 | 2520.0 | 2306 | 0.92 |
| 1996 | 2515.0 | 2273 | 0.9 |
| 1997 | 2640.0 | 2400 | 0.91 |
| 1998 | 2420.0 | 2091 | 0.86 |
| 1999 | 2429.0 | 2144 | 0.88 |
| 2000 | 2244.0 | 1966 | 0.88 |
| 2001 | 1801.0 | 1603 | 0.89 |
| 2002 | 1691.73 | 1690 | 1.0 |
| 2003 | 1667.95 | 1663 | 1.0 |
| 2004 | 1704.0305 | 1706 | 1.0 |
| 2005 | 1738.5 | 1725 | 0.99 |
| 2006 | 1960.35 | 1631 | 0.83 |

Continued on next page

Table 8: Total annual harvest reported by citet:Mciver2012 and California Board of Equalization.

| year | McIver, et. al. (2012) MMBF | BOE MMBF | BOE/M&M |
|------|-----------------------------|----------|---------|
| 2007 | 1759.6 | 1626 | 0.92 |
| 2008 | 1476.0745 | 1372 | 0.93 |
| 2009 | 911.19 | 805 | 0.88 |
| 2010 | 1302.38 | 1161 | 0.89 |
| 2011 | 1432.5 | 1288 | 0.9 |
| 2012 | 1421.3 | 1307 | 0.92 |

The TPO reports harvest from tribal lands, which produces an average 0.74% of the total annual harvest in the state for the 37 years of parallel data. For this analysis we used TPO data to include harvest volume from tribal lands.

Table 9: Annual harvest by ownership from citet:Mciver2012 (MCF)

| year | State | Federal | Private | Tribal |
|------|-------|---------|---------|--------|
| 1947 | 0.0 | 0.0 | 569.85 | 0.0 |
| 1948 | 0.0 | 0.0 | 735.29 | 0.0 |
| 1949 | 0.0 | 0.0 | 698.53 | 0.0 |
| 1950 | 0.0 | 0.0 | 808.82 | 0.0 |
| 1951 | 0.0 | 0.0 | 900.74 | 0.0 |
| 1952 | 2.57 | 113.79 | 808.82 | 4.78 |
| 1953 | 3.31 | 117.65 | 977.94 | 2.76 |
| 1954 | 2.94 | 141.54 | 880.51 | 4.6 |
| 1955 | 2.57 | 191.73 | 906.25 | 6.07 |
| 1956 | 4.41 | 206.99 | 862.13 | 5.33 |
| 1957 | 4.96 | 170.59 | 801.47 | 6.62 |
| 1958 | 5.51 | 208.27 | 821.69 | 6.99 |
| 1959 | 4.96 | 279.6 | 788.6 | 9.19 |
| 1960 | 5.15 | 250.37 | 680.15 | 8.82 |
| 1961 | 5.33 | 259.74 | 707.72 | 10.11 |
| 1962 | 6.25 | 259.01 | 744.49 | 8.64 |
| 1963 | 4.04 | 311.76 | 678.31 | 9.93 |
| 1964 | 4.6 | 348.16 | 643.38 | 9.01 |
| 1965 | 5.7 | 363.05 | 591.91 | 9.74 |
| 1966 | 5.88 | 360.85 | 545.96 | 8.27 |
| 1967 | 6.43 | 355.51 | 562.5 | 7.54 |
| 1968 | 8.82 | 440.44 | 542.28 | 14.52 |
| 1969 | 7.35 | 372.61 | 529.41 | 9.93 |
| 1970 | 6.25 | 345.4 | 481.62 | 5.15 |
| 1971 | 7.17 | 383.09 | 476.1 | 12.87 |
| 1972 | 6.8 | 411.58 | 591.91 | 12.13 |
| 1973 | 6.07 | 371.69 | 516.54 | 9.38 |
| 1974 | 7.35 | 322.79 | 525.74 | 9.38 |
| 1975 | 6.43 | 287.87 | 498.16 | 3.31 |
| 1976 | 7.35 | 348.53 | 507.35 | 6.99 |
| 1977 | 5.15 | 323.35 | 544.12 | 6.99 |
| 1978 | 5.15 | 332.35 | 509.19 | 8.64 |
| 1979 | 4.78 | 321.32 | 417.28 | 8.82 |
| 1980 | 3.68 | 279.04 | 356.62 | 7.72 |
| 1981 | 2.76 | 201.65 | 316.18 | 4.04 |
| 1982 | 7.72 | 173.9 | 275.74 | 1.47 |
| 1983 | 7.9 | 313.42 | 347.43 | 2.57 |
| 1984 | 6.25 | 288.05 | 386.03 | 3.86 |
| 1985 | 6.62 | 339.52 | 406.25 | 0.92 |
| 1986 | 5.33 | 365.26 | 441.18 | 4.96 |
| 1987 | 7.72 | 364.89 | 485.29 | 7.54 |

Continued on next page

Table 9: Annual harvest by ownership from citet:Mciver2012 (MCF)

| year | State | Federal | Private | Tribal |
|------|-------|---------|---------|--------|
| 1988 | 5.7 | 403.68 | 481.62 | 2.57 |
| 1989 | 6.8 | 373.53 | 483.46 | 2.02 |
| 1990 | 4.41 | 283.09 | 496.32 | 2.57 |
| 1991 | 6.99 | 248.35 | 376.84 | 4.41 |
| 1992 | 4.23 | 190.99 | 391.54 | 5.88 |
| 1993 | 6.25 | 137.32 | 415.44 | 2.39 |
| 1994 | 3.12 | 152.02 | 362.13 | 2.76 |
| 1995 | 7.35 | 101.1 | 354.78 | 2.94 |
| 1996 | 10.11 | 86.4 | 365.81 | 2.39 |
| 1997 | 8.64 | 101.65 | 375.0 | 2.76 |
| 1998 | 4.78 | 83.46 | 356.62 | 2.94 |
| 1999 | 0.0 | 97.24 | 349.26 | 0.0 |
| 2000 | 3.49 | 63.42 | 345.59 | 1.84 |
| 2001 | 2.94 | 56.07 | 272.06 | 1.84 |
| 2002 | 0.18 | 31.38 | 279.41 | 2.5 |
| 2003 | 0.18 | 28.85 | 277.57 | 3.29 |
| 2004 | 0.18 | 20.78 | 292.28 | 3.05 |
| 2005 | 0.18 | 43.66 | 275.74 | 1.95 |
| 2006 | 0.74 | 41.61 | 318.01 | 2.37 |
| 2007 | 0.18 | 58.57 | 264.71 | 3.55 |
| 2008 | 0.18 | 37.7 | 233.46 | 2.48 |
| 2009 | 0.18 | 30.37 | 136.95 | 0.72 |
| 2010 | 0.18 | 49.89 | 189.34 | 1.79 |
| 2011 | 0.18 | 55.42 | 207.72 | 2.1 |
| 2012 | 5.13 | 37.39 | 218.75 | 1.49 |

To use the TPO data to estimate emissions reductions using the DF, we apply a conversion factor of **5.44** MCF/MMBF. This is an approximation as the actual sawlog conversion factor varies with average harvested log size, which has changed over time.

Using the ratio of logging residuals consumed by bioenergy (mciver), to the total logging residuals reported in the TSP, we can calculate the harvest volume the ratio of harvest volume to logging residuals used in bioenergy, we calculated based on the ratio of reported consumption of logging residuals in bioenergy by citeauthor:Mciver2012 to the total logging residuals reported in the TPO. citeauthor:Mciver2012 report bioenergy consumption from 2000 forward. For years previous, we use the average bioenergy consumption from 2000 – 2012. These results assume bioenergy consumption throughout the reporting years. Bioenergy use of residuals did not begin until the late 1970. Further analysis is necessary to modify these results to reflect the development of the bioenergy industry.

To calculate the total emissions reduction resulting from California's timber harvest, we apply the appropriate displacement factor (with or without logging residual utilization) to the commensurate fraction of harvested roundwood. The results are shown in the following chart.

Contribution of the various ownership categories to the aggregate is shown in Figure ref:em_reducown.

3.4 Emissions from un-utilized logging residues

From logging residuals not used in bioenergy, emissions are produced from combustion of or from biological decomposition of the material over time. To calculate the ratio of burned to decomposed logging residues I begin with the CARB estimate of PM_{2.5} produced from forest management.

1. Estimate biomass from PM_{2.5} To estimate total biomass from PM_{2.5} I assume 90% consumption of biomass in piles and use the relationship of pile tonnage to PM emissions calculated using the Piled Fuels Biomass and Emissions Calculator provided by the Washington State Department of Natural Resources.

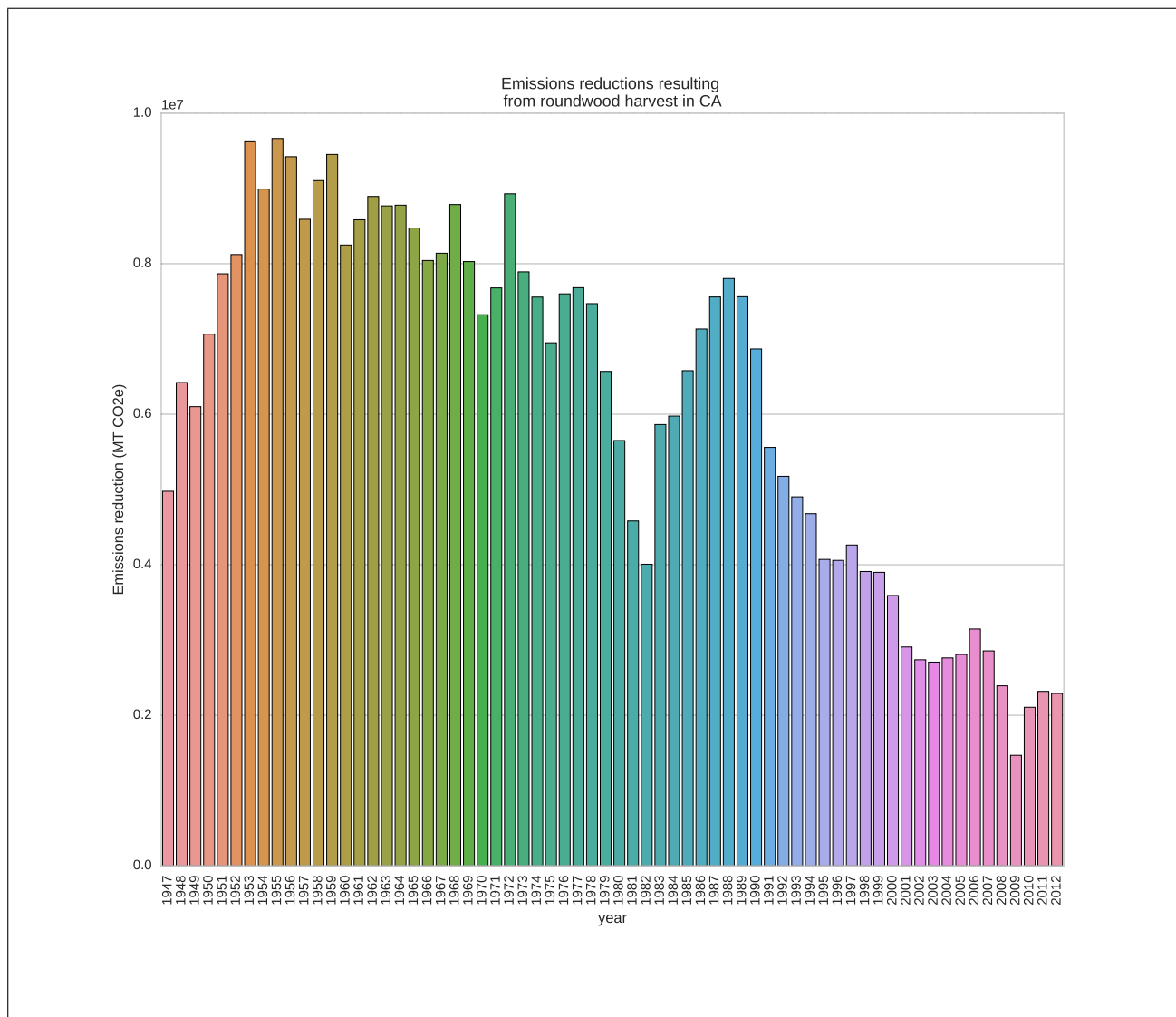


Figure 5: Historical emissions reductions resulting from harvested roundwood using displacement factors from citep:Sathre2010 applied to TPO data.

This calculator is based on the Consume fire behavior model published by the US Forest Service. The ratio of PM2.5 to unburned tonnage of biomass used below is 0.00605508984853. Ratio of PM2.5 to consumed fuel is 0.00672787321276.

Table 10: Forest biomass burned in piles based on ARB-reported PM2.5 emissions in the 'Forest Management' category using a ratio of 164.610674089 ton biomass per ton PM2.5.

| YEAR | PM2.5 (t) | Pile-Burned Biomass (t) |
|------|-----------|-------------------------|
| 2000 | 5474.31 | 901129.28 |
| 2005 | 5474.31 | 901129.28 |
| 2010 | 5474.31 | 901129.28 |
| 2012 | 5477.3 | 901621.96 |
| 2015 | 5480.51 | 902150.69 |

Total emissions resulting from pile burned forest management residuals can then be derived for the two greenhouse gasses produced from pile burning (CO₂, CH₄) and from BC:

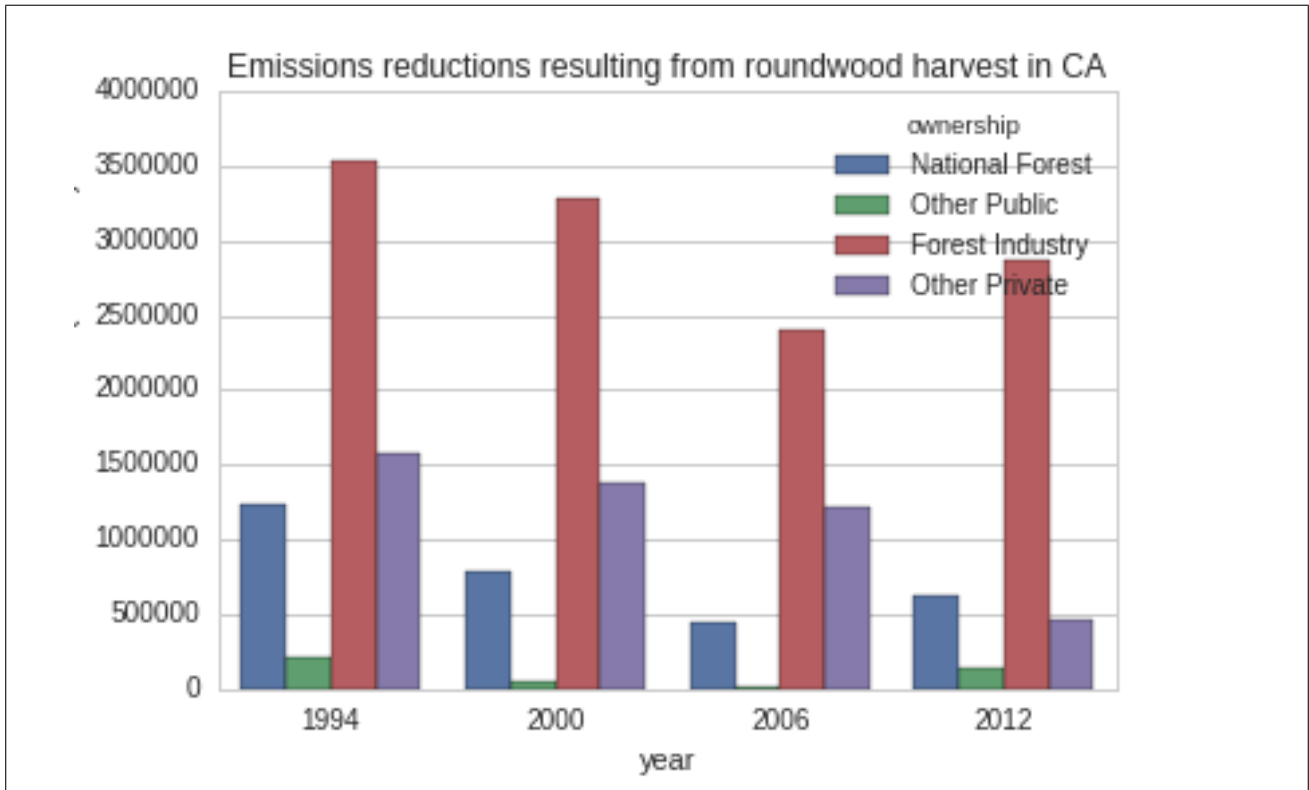


Figure 6: Historical emissions reductions by ownership for selected years resulting from harvested roundwood using displacement factors from citep:Sathre2010 applied to TPO data.

| Year | Emissions source | CO ₂ (t) | CH ₄ (tCO ₂ e) | BC (tCO ₂ e) | Pile Burn | Total (tCO ₂ e) |
|------|-------------------|---------------------|--------------------------------------|-------------------------|-----------|----------------------------|
| 2000 | FOREST MANAGEMENT | 1.34928(+06) | 127280 | 248255 | | 1.72481(+06) |
| 2005 | FOREST MANAGEMENT | 1.34928(+06) | 127280 | 248255 | | 1.72481(+06) |
| 2010 | FOREST MANAGEMENT | 1.34928(+06) | 127280 | 248255 | | 1.72481(+06) |
| 2012 | FOREST MANAGEMENT | 1.35002(+06) | 127349 | 248391 | | 1.72576(+06) |
| 2015 | FOREST MANAGEMENT | 1.35081(+06) | 127424 | 248536 | | 1.72677(+06) |

2. Emissions from decomposition of un-utilized forest management residuals

Un-utilized residual biomass not consumed in pile burns decomposes over time resulting in emission of methane and carbon dioxide. To provide a full picture of the emissions from residual material produced from commercial timber harvesting in California, decomposition of unutilized logging residuals left on-site that are not burned must be accounted for. To establish the fraction of logging residue that is left to decompose, residues burned and used in bioenergy are subtracted from the total reported by the TPO:

$$LR_d = LR - LR_{piles} - LR_{bio}$$

where:

LR_d = Logging residuals subject to anerobic decomposition

LR = Total logging residue reported by TPO

LR_{piles} = Logging residues combusted in anthropogenic pile burns

LR_{bio} = Logging residues used to produce bioenergy

To calculate the GHG emissions from decomposition of piles we use the following equation.

$$CO_2e_{decomp} = (LR_d \times C_{LR} \times CO_2ratio) + (LR_d \times C_{LR} \times CH_4ratio \times GWP_{CH_4})$$

where:

CO_2e_{decomp} = Carbon dioxide equivalent emissions from decomposition of logging slash

C_{LR} = Carbon fraction of biomass: 0.5

CO_2ratio = Fraction of carbon released as CO_2 : 0.61

CH_4ratio = Fraction of carbon released as CH_4 : 0.09

GWP_{CH_4} = Global warming potential of methane: 56

3.5 Emissions from non-commercial management residuals

/Note: Residues from non-commercial management activities are assumed to be small in comparison with logging residues. In addition, there is presently no empirical data available. As such, estimating these volumes has not been prioritized. I have attempted to provide an estimate for public lands in the National Forest System./

The TPO in California does not report wood volume produced from non-commercial management activities. This includes management activities such as pre-commercial thinning, sanitation thinning, and fuels reduction thinning. To estimate the volume of material produced from these activities we use the following sources:

1. **Public lands:** The USFS Forest Service Activity Tracking System (FACTS) reports management activities conducted on National Forest System Lands. To ensure estimates of biomass volume using FACTS are not duplicative of reported volume in the TPO a series of filters are applied to the FACTS attributes to identify only non-commercial management activities.
2. **Private industrial timber lands:** CalFIRE's Forest Practice Geographical Information System.
TODO

1. Forest Service Activity Tracking System (FACTS)

Data from TPO does not account for forest management activities that do not result in commercial products (timber sales, biomass sales). The USFS reports Hazardous Fuels Treatment (HFT) activities as well as Timber Sales (TS) derived from the FACTS database. I use these two data sets to estimate the number of acres treated that did not produce commercial material (sawlogs or biomass) and where burning was not used. The first step is to eliminate all treatments in the HFT data set that included timber sales. I accomplish this by eliminating all rows in the HFT data set that have identical **FACTS_ID** fields in the TS dataset. I further filter the HFT dataset by removing any planned but not executed treatments (**nbr_units1** > 0 below – **nbr_units1** references **NBR_UNITS_ACCOMPLISHED** in the USFS dataset, see metadata for HFT here), and use text matching in the 'ACTIVITY' and 'METHOD' fields to remove any rows that contain reference to 'burning' or 'fire'. Finally, we remove all rows that reference 'Biomass' in the method category as it is assumed that this means material was removed for bioenergy. I use a range of 10-35 BDT/acre to convert acres reported in FACTS to volume. The following table presents descriptive statistics for estimates of residual unutilized wood biomass on an annual basis in million cubic feet.

| | nf\l _n | nf\l _r | opriv\l _r | fi\l _r | opub\l _r |
|-------|-------------------|-------------------|----------------------|-------------------|---------------------|
| count | 11 | 4 | 4 | 4 | 4 |
| mean | 12.0194 | 17.7 | 28.95 | 66.425 | 2.4 |
| std | 4.68948 | 5.07346 | 16.1593 | 6.07639 | 1.79444 |
| min | 2.37421 | 11.2 | 11.2 | 59.6 | 0.3 |
| 25% | 8.92407 | 15.025 | 19.525 | 62.225 | 1.275 |
| 50% | 13.3557 | 18.5 | 27.75 | 66.85 | 2.5 |
| 75% | 14.5349 | 21.175 | 37.175 | 71.05 | 3.625 |
| max | 17.8532 | 22.6 | 49.1 | 72.4 | 4.3 |

4 Further questions

This analysis is a first step towards a broader analysis of the climate impacts of harvested wood in California. The following are key questions which follow from this analysis.

5 References

`bibliographystyle:IEEEtranSN bibliography:fcab.bib`

DRAFT