Emissions reductions from harvested wood products and management residuals

Peter Tittmann, Ph.D.

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Contents

List of Figures

List of Tables

1 California Forest Management Emissions Profile

Forest management activities in California produce logs for lumber markets while maintaining and enhancing forest health. In addition to merchantable logs, these harvest activities produce logging residuals that are either left in the stand to decompose, or pile burned as directed by forest practice rules (California Forest Practice Rules, Article 7 § 917.2). The extent to which these residuals are utilized avoiding open combustion or decomposition materially impacts emissions of GHG and SLCP..

The majority of biomass produced from forest management activities end up as residual biomass material that is either left in the woods to decompose, or aggregated at a landing where it is eventually burned. When considered alongside the accumulation of woody material from historic fire suppression activity, there exists a heightened volume of combustible woody material in excess of historic reference conditions, elevating the risk of damaging wildfire in much of California's forestland. Currently, common practice for fuel load management in California forests involves prescribed natural fire and sanitation pile burning. However, these approaches have limitations as previous studies have demonstrated that prescribed natural fire is often only effective at reducing fuel loading and maintaining fire resilient landscapes when it is coupled with mechanical treatment to remove biomass Stephens et al. (2009). Open pile burning of residual biomass can also result in greater emissions of strong radiative forcing agents (black carbon) and criteria air pollutants such as PM2.5 and Oxides of Nitrogen (NOX) when compared to controlled combustion in biomass power plants with modern emissions control technology.

Ultimately, any combustion or decomposition of residual material results in emissions of GHG, CAP, and SLCP. In the absence of forest management activity, atmospheric emissions are produced from stochastic processes such as wildfire, pest, and disease outbreaks. Utilization strategies are necessary to reduce the air quality impact of common forestry practice. The high climate opportunity cost[1] of open burning residual biomass in forestry and agriculture favor diverting residual material streams towards alternative utilization strategies such as biomass power. Figure 1 presents an overview of emissions and emissions reduction pathways for wood from California's forests.

The focus of this analysis is on deriving the net Carbon Dioxide Equivalents (CO2e) emissions and emissions reductions 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 of CO2e annually in California forests Christensen et al. (2016). Emissions from mortality are indirectly related to management activities just as wildfire is, and must be accounted for to comprehensively evaluate the climate impacts of harvesting. To estimate emissions and reductions by forest management activity, it is necessary to take the following steps:

1. Estimate CO2e emissions from burning forest management residuals using the CARB, CAP and GHG emissions inventories.
2. Estimate the volume and fate of wood that is removed, left in the forest, and burned as a result of direct anthropogenic management activities.
3. Apply life-cycle Displacement Factor (DF) for all utilized wood and apply DF to harvested wood to obtain an aggregate estimate to estimate emissions reductions from wood use.

1.1 Report Objectives

Quantifying the climate effects of wood products and forest management residuals is important to the development of the Forest Climate Plan (FCP) [2] as well as efforts underway by the California Board of Forestry (BOF) and CalFire to meet the intent of AB 1504 (2010)[3]. To inform these efforts, this report provides estimates of the following:

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

Estimates are based 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 as well as macroeconomic and policy forces. This analysis may provide insight into opportunities to more effectively utilize woody biomass residuals from current forest management activities to reduce emissions.

[1] Climate opportunity cost is used in this context to refer to the aggregate emissions of particulate and gasses with strong radiative forcing properties associated with open pile or broadcast burning.

[2] The 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.

[3] AB-1504 Forest resources: carbon sequestration.(2009-2010)

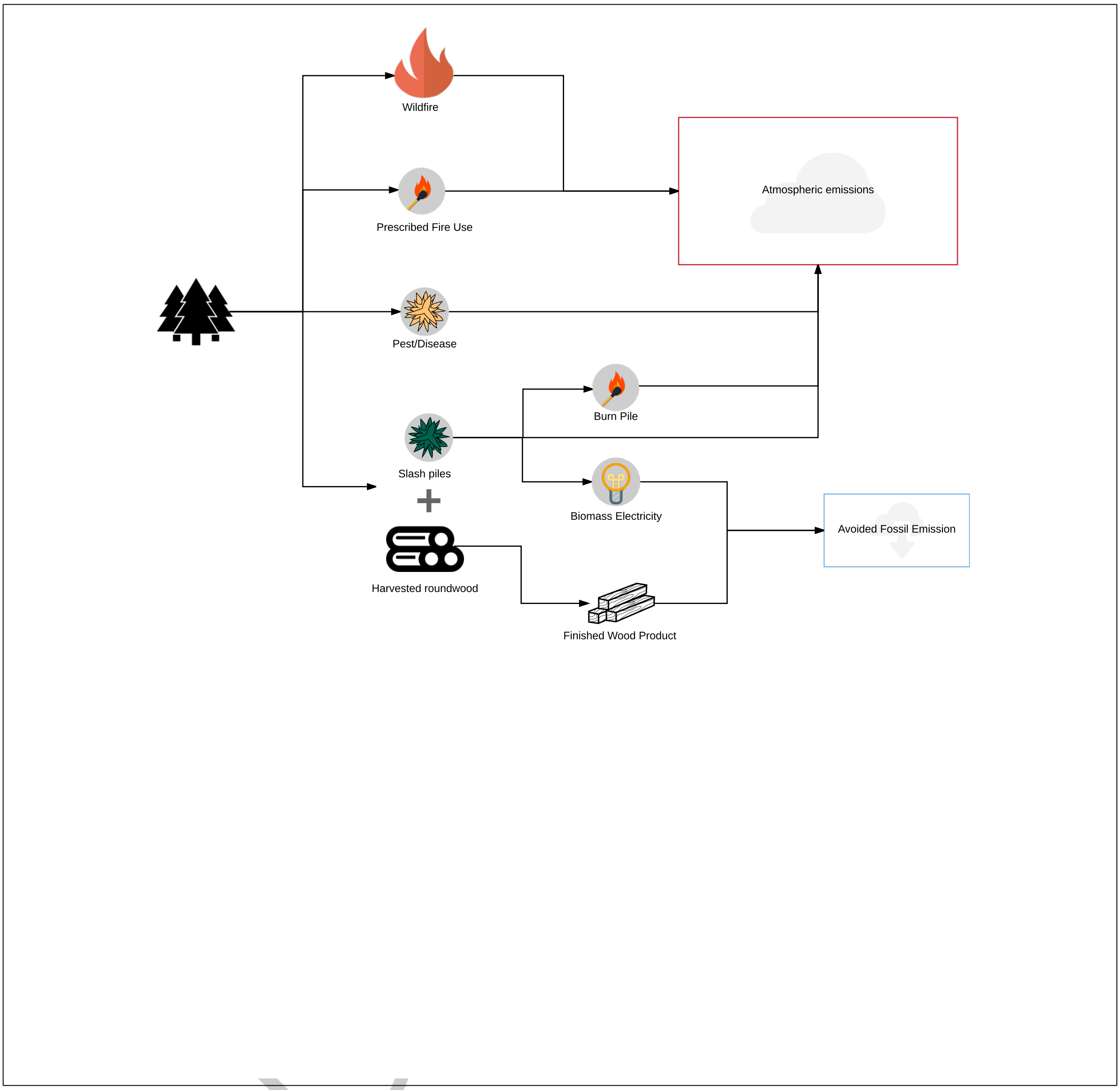

Figure 1: Overview of fates of wood resulting from harvest and mortality in California forests. Note that time is not represented in this figure.

1.2 Key Findings

- Baseline GHG and SLCP emissions from burning of forest management residuals can be estimated and should be considered in any forest management emissions baseline.
- Average annual emissions from pile burning of logging residuals from roundwood harvesting (including SLCP and GHG components) extrapolated from BOE historical harvest data between 2000 and 2015 are estimated at **0.57 MMTCO2e**
- Total annual emissions from pile burning of forest management residuals (including SLCP and GHG components) extrapolated from CARB emissions inventory are estimated at **2.5 MMTCO2e**
- Wood harvested in California in 2012 resulted in avoided emissions of **2.29 MMTCO2e**
- Timber harvest producing roundwood including emissions from pile burning of logging residuals results in a net emissions reduction of **1.93 MMTCO2e**
- 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.
- Brown or OC carbon has stronger radiative absorption than BC and is associated with biomass burning. Accosting for anthropogenic production of OC should be included in emissions baselines against which alternative utilization (energy) should be measured against.

2 Estimating CO2 Equivalent Emissions from In-Forest Biomass Combustion

The CARB reports on emissions from in-forest biomass combustion with current GHG and CAP emissions inventories. Both are necessary resources for establishing aggregate annual climate-forcing emissions (Figure 2). The GHG inventory captures gasses with radiative forcing properties including CO2 and CH4, but does not capture elemental carbon or BC emissions which also have strong radiative forcing properties (Table 1). The California Air Resources Board (2015, 2016) CAP report captures SLCP emissions from wildfire (`80.52` MMTCO2e) and prescribed fire (`3.66` MMTCO2e) from which black carbon emissions may be estimated. However, no reference in the CAP report is made to the source of these SLCP estimates. When viewed in aggregate, a comprehensive reporting of total climate impact from anthropogenic burning may be estimated.

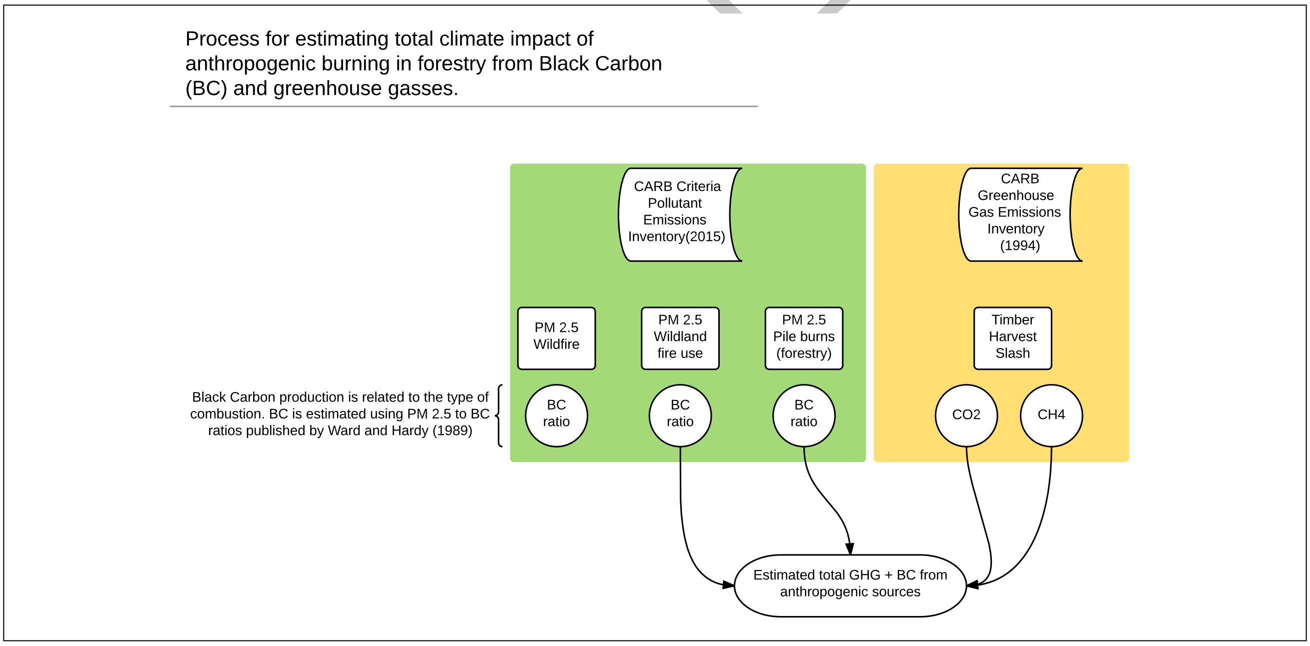

Figure 2: Data sources available from CARB for estimating GHG and SLCP emissions from forest management.

The GHG inventory captures gasses with radiative forcing properties including CO2 and CH4, but does not capture elemental carbon or BC emissions which also have strong radiative forcing properties (Table 1).

GWP_{20}	$GWP\sigma_{20}$	GWP_{100}	$GWP\sigma_{100}$	GWP_{500}	$GWP\sigma_{500}$	Source
2200.0	888.82	633.33	255.41	193.33	77.67	Fuglestvedt2010
3200.0		900.0				CaliforniaAirResourcesBoard2015

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

The California Air Resources Board (2015, 2016) CAP report captures SLCP emissions from wildfire (`80.52` MMTCO2e) and prescribed fire (`3.66` MMTCO2e) from which BC emissions may be estimated. However, no reference in the CAP report is made to the source of these SLCP estimates. When viewed in aggregate, a comprehensive estimate of total climate impact from anthropogenic burning may be made.

2.1 Estimating biomass combustion from 'Forest Management' using the CARB CAP inventory.

To estimate total biomass from PM2.5, I assume 90% consumption of biomass in piles and use the relationship of pile tonnage to PM emissions as calculated from the Piled Fuels Biomass and Emissions Calculator provided by the Washington State Department of Natural Resources (Table **??**). This calculator is based on the Consume fire behavior model published by the US Forest Service.

Pile Type	Pile Biomass (tons)	Consumed Fuel (tons)	PM2.5 (tons)	CO2 (tons)	CH4 (tons)
Half sphere	1.36018	1.22416	0.00826308	2.03664	0.00343071

Table 2: Ratios of biomass to GHG emissions from the Piled Fuels Emissions Calculator and based on the CONSUME model.

The ratio of PM2.5 to unburned tonnage used in this report are found in Table 3.

Ratio	Value
PM2.5 Δ Biomass	164.60932

Table 3: Ratio of piled biomass PM2.5 used in this report.

Using these ratios we then estimate biomass consumed based on reported PM2.5 emissions in the CARB CAP inventory (Table 4)

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

Table 4: Forest biomass burned in piles based on ARB-reported PM2.5 emissions in the 'Forest Management' category.

2.2 Estimating biomass combustion from using the CARB CAP inventory.

The estimate of biomass consumed in 'Forest 'Management' using this methodology far exceeds the total volume of biomass residuals produced from commercial timber harvesting in the state. Using the BOE historical harvest data, logging residual production rates for commercial timber harvest from Morgan and Spoelma (2008) and bioenergy consumption from Mciver et al. (2012) (Table 5) we can estimate the volume of logging residuals produced.

The availability of data for bioenergy consumption of logging residuals does not allow us to precisely estimate the consumption for years other than reported by Mciver et al. (2012). In this analysis, for years that bioenergy consumption is reported, I use that value. As the states biomass energy infrastructure began to consume substantial amounts of residual in the early 1980's (Morris, 2000), we assume that the average consumption from the 3 years reported is representative annual consumption. For years before 1980, we assume no bioenergy consumption. This approach is less than ideal as there has been a great deal of variability in the appetite for logging residuals from biomass power plants. Un-utilized logging residues are estimated from logging residuals not used in bioenergy (Table **??**). These results are based on a normal probability distribution defined by an estimate (0.0615 cf logging residuals per cf of growing-stock removals) and a range (± 0.00229 cf/cf) at the 95% confidence interval for logging residual generation from roundwood harvest. This is one of several factors contributing to instances where bioenergy consumption is greater than logging residues produced. Other factors include:

- Lack of temporal resolution in bioenergy consumption
- Consumption by biomass power plants of in-woods residuals produced from forest management that did not result in commercial roundwood harvest

In the absence of empirical data reflecting the actual combustion of logging residuals and considering that in much of the states timber producing region tree-length or log-length yarding methods are used which do not result in accumulation of logging residuals at a landing as is the case with whole-tree yarding, we might assume 50% of the logging residuals not used in bioenergy would be burned in open piles per California Forest Practice Rules.

year	Percent of roundwood harvest used in bioenergy
2000	2.4
2006	3.6
2012	8.2

Table 5: % volume of wood diverted to Bioenergy use by year

2.3 Estimating Black Carbon Emissions from Biomass Burning

Black Carbon (BC) is not directly reported by statewide emissions summaries.BC is a fraction of the TC component of PM2.5. PM2.5 emissions are published annually by CARB (Criteria air pollutant (CAP) emissions estimates). By using the 2015 CAP emissions estimates shown in Table **??** with estimated ratios of smoldering to flaming combustion for hand/machine piled burns, prescribed natural fire and wildfire from Ward and Hardy (1989), Black Carbon emissions can be calculated from PM 2.5 with Eq. (1)

Source (CARB nomenclature)	Description	PM2.5 ($t\ y^{-1}$)
ALL VEGETATION	Wildfire	137630.15
FOREST MANAGEMENT	Pile burning	5480.51
WILDLAND FIRE USE (WFU)	Prescribed natural fire	6802.43

Using the 2015 CAP emissions estimates shown in Table **??** with estimated ratios of smoldering to flaming combustion for hand/machine piled burns, prescribed natural fire and wildfire from Ward and Hardy (1989), BC emissions can be estimated from PM 2.5 using equation (1)

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

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

The ratio of smoldering to flaming combustion behavior for each biomass burning scenario means that each has a different BC Δ PM2.5 ratio. To arrive at a rough estimate of BC emissions based on PM2.5, ratios from Ward and Hardy (1989) and Jenkins et al. (1996) ratios in Table 7 are used herein.

Given the variance in BC production from smoldering (± 15%) and flaming (± 41%) phases (Table 7), actual emissions of BC may vary substantially depending on combustion. In addition to these estimates Chow et al. (2010) provides an alternative source for estimates of BC and OC emissions in the state in 2006. Further work is necessary to evaluate the impacts of OC on the net CO2e emissions from pile burning. Pokhrel et al. (2016) estimated the absorptive properties of OC to be 1.5 - 2.5 that of BC. Chow et al. (2010) estimated that 29,530 Mt of OC was emitted from wildfires in 2006.

2.4 Estimating GHG Emissions from Biomass Burning

The CARB GHG emissions inventory resolved to combustion source (piles, prescribed, etc.) for forests and rangelands has not been updated since 2004. To provide a comparable estimate of GHG emissions from pile burning we use the ratio of PM2.5 to the net CO2e emissions from all GHG species produced from the Piled Fuels Eissions Calculator (CONSUME model equations) sources two approaches are taken. As PM2.5 is reported in the CAP for pile burning we can apply this ratio to estimate GHG emissions for the same time period.

Year	Logging Residues	Bioenergy	Unutilized Logging Residuals
1978	1.37648	0	1.37648
1979	1.1869	0	1.1869
1980	0.732729	0.348909	0.38382
1981	0.552591	0.294654	0.257937
1982	0.0132148	0.255616	-0.242402
1983	0.778638	0.370302	0.408337
1984	1.15256	0.391033	0.761526
1985	0.690508	0.421028	0.26948
1986	1.78313	0.470321	1.31281
1987	0.876609	0.496235	0.380373
1988	1.38311	0.514982	0.868128
1989	2.02822	0.487854	1.54036
1990	1.01987	0.443414	0.576451
1991	0.614629	0.352327	0.262302
1992	0.797516	0.327846	0.46967
1993	0.671715	0.316598	0.355117
1994	0.560554	0.255396	0.305158
1995	0.217133	0.254293	-0.0371602
1996	0.602055	0.250654	0.351401
1997	0.581323	0.264659	0.316664
1998	0.472128	0.230584	0.241544
1999	0.454244	0.236429	0.217815
2000	0.189259	0.109927	0.0793326
2001	0.261365	0.17677	0.0845949
2002	0.0983162	0.186364	-0.0880478
2003	0.191743	0.183387	0.00835635
2004	0.163134	0.188128	-0.0249946
2005	0.452135	0.190224	0.261911
2006	0.218927	0.136793	0.0821336
2007	0.285568	0.179306	0.106261
2008	0.0783061	0.151297	-0.0729905
2009	0.115737	0.088771	0.026966
2010	0.131594	0.128029	0.00356518
2011	0.161427	0.142034	0.019393
2012	0.0995951	0.249688	-0.150093
2013	0.1313	0.181402	-0.0501019
2014	0.188085	0.161662	0.0264229

Table 6: Probabilistic disposition of logging residuals from roundwood harvest in CA. Volume in million bone-dry tons.

To estimate GHG emissions from **pile burning**, we use the ratio of $PM_{2.5}$ to CO_2 and to CH_4 from the Piled Fuels Emissions Calculator. These ratios are then applied to CARB-reported $PM_{2.5}$ emissions to estimate GHG emissions (Table **??**).

GHG emissions from **wildfire and prescribed fire** are difficult to estimate at present but the CARB GHG emissions inventory provided estimates for years between 1994 and 2004 (Table 8).

2.5 Estimating Total Emissions from Biomass Burning

To arrive at an annual estimate of total CO_2e emissions, we combine BC emissions estimates from the CARB CAP Emissions Inventory with the USFS CONSUME model combustion ratios. Overall, this analysis demonstrates that substantial emissions from forest management residuals have been reported by CARB emissions inventories and that such inventories could be utilized to establish a baseline condition for CO_2e emissions from forest management (Table **??**).

Total emissions resulting from **pile burned** forest management residuals can then be derived for the two greenhouse gasses produced from pile burning (CO_2, CH_4) and from BC (Table **??**).

Table 9 reflects emissions from all biomass combustion meeting the definition of 'Forest Management'. It us useful in addition to understand the contribution that logging residuals from commercial timber harvesting make to this total.

Combustion	Context	TC t^{-1} PM2.5	TC_{Cv} t^{-1} PM2.5	BC t^{-1} TC	BC_{Cv} t^{-1} PM2.5	OC t^{-1} TC
f	p	0.621	0.07	0.023	0.15	0.598
s	p	0.587	0.03	0.02	0.41	0.5675
f	wf	0.608	0.09	0.1108	0.506	0.4976
s	wf	0.641	0.08	0.045	0.29	0.59625

Table 7: Factors used for calculating BC emissions. Combustion refers to flaming (f) or smoldering(s) phases and context establishes if the ratio is used in on modeling emissions from wildfire (wf) or pile burns (p). BC is a fraction of TC which is a fraction of total PM2.5. OC is reported here for reference only. Coefficients of variation (C_v) are reported here as well.

Source Category	Average annual emissions 1994-2004 MMt CO2e
Forest and rangeland fires	2.02
Timber harvest slash	0.16

Table 8: Annual GHG Emissions estimated from CARB GHG emissions inventory

The total CO2e emissions from pile burning forestry residuals as reported by CARB and pile burning logging residuals from roundwood harvesting from BOE historical data are shown in Table **??**.

MMt CO2e	Source
1.4133952	CO2e GHG pile burning
6.21335	CO2e BC pile burning
7.18357	CO2e BC pile burning – high
5.31602	CO2e BC pile burning – high
7.6199244	**Total MMt CO2e – Forest Management**
929052	**Total MMt CO2e – Timber Harvesting**

These emissions are substantial and represent a significant opportunity to increase emissions reduction already realized from forestry. Ensuring that piled biomass from forest management activities are chipped and used in energy applications could eliminate up to 83% (7.18 MMT CO2e) of these emissions. It is important to note, however, that this estimate derived from the CAP inventory implies that more than twice the total volume of logging residuals produced from commercial roundwood harvesting was burned in the context described by 'Forest Management' in the **AP!** (**AP!**) inventory. While some of the difference here can be explained by the burning of residuals produced from non-commercial management activities, it is unlikely that the the full compliment of burned residuals from non-commercial activity is approximately the same as the total volume of loggin residuals produced from commercial roundwood harvest. As the CAP inventory is based on reporting from local air districts it would seem that the margin of error in the CAP estimate of PM2.5 emissions could be substantial.

3 Estimating Emissions Impact from Utilization of Harvested Wood

Wood harvested from California's forests are utilized in a variety of construction, landscaping, and consumer products. During the manufacture of these products, this wood is fractionated through a multi-stage process of harvesting, processing, and utilization to reside in several residual biomass fates (below).

Logging Residuals Tops, limbs, and sub-merchantable material produced from harvest activities in the woods. These residuals may be left on site to naturally decompose or disposed of by anthropogenic pile burning or wildfire.

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

Year	Emissions source	CO2 (t)	CH4 (tCO2e)	BC (tCO2e)	BC-h (tCO2e)	BC-l (tCO2e)
2000	FOREST MANAGEMENT	1.34928 (+06)	63639.8	6.21335 (+06)	7.18357 (+06)	5.31602 (+06)
2005	FOREST MANAGEMENT	1.34928 (+06)	63639.8	6.21335 (+06)	7.18357 (+06)	5.31602 (+06)
2010	FOREST MANAGEMENT	1.34928 (+06)	63639.8	6.21335 (+06)	7.18357 (+06)	5.31602 (+06)
2012	FOREST MANAGEMENT	1.35002 (+06)	63674.6	6.21674 (+06)	7.18749 (+06)	5.31892 (+06)
2015	FOREST MANAGEMENT	1.35081 (+06)	63712	6.22039 (+06)	7.19171 (+06)	5.32204 (+06)

Table 9: Emissions of SLCP and GHG from the 'Forest Management' CAP PM2.5 emissions inventory.

% burned	LR burned (MBDT)	PM2.5 (t)	CO2 (t)	CH4 (tCO2e)	BC (tCO2e)	Total c{CO2e}
0.25	12502.3	75.9516	18720.2	882.951	86205.1	105808
0.5	80239.3	487.453	120145	5666.73	553260	679071
0.75	160479	974.906	240290	11333.5	1.10652 (+06)	1.35814 (+06)

Table 10: Three emissions scenarios for pile burning of logging residuals from timber harvesting based on average annual harvest (2000 - 2015).

may be directed towards alternative product streams (i.e. wood pellet, wood chip, power and heat generation) or sent to a landfill.

Construction Debris Fraction of wood used in construction or finished products that are not integrated into its final form. These residuals are most commonly sent to a landfill.

Demolition Wood used in construction that has reached the end of its useful life. These residuals are most commonly sent to a landfill.

These biomass fates have widely variable time horizons for the return of fixed carbon to the atmosphere. The extent to to which harvested wood is utilized can greatly influence the net emissions impact attributed to the initial forest management activity. While wood products used in construction, finished products, or other stable environments may sequester carbon for a long period, residues sent to landfills or left in the woods as slash emit climate forcing gasses to the atmosphere. Some of these wood residues may be redirected towards alternative controlled combustion applications (i.e., pellet production, power and heat generation)to avoid emissions.

Ultimately the fate of these pools are determined by a highly dynamic political and economic system. To understand how policy decisions will impact the fate and subsequent climate impact of harvested wood products, a detailed process model is necessary to track the distribution of harvested wood material. Figure **??**

3.1 Disposition of Harvested Wood in California.

To provide a rough estimate of the fate of annually harvested roundwood material, we estimate the volume of wood biomass residing in logging, processing, and construction residuals. To estimate current values, we apply known milling efficiency improvements, logging utilization rates, and construction use efficiency to historical production volumes.

3.1.1 Logging Residues

According to Morgan and Spoelma (2008), logging residues produced from sawlog harvest can be estimated using a factor of 0.0302 (+/-.0123 @95%CI) times the total cubic sawlog volume delivered to a mill. Simmons and Morgan (2014) found that logging utilization has decreased in Idaho from 1990 to 2011 by 72%. Unfortunately, we cannot say how logging residue production has changed over time in California. For the purpose of this analysis, we will assume that similar changes have occurred in California timber harvesting.

We estimate logging residue production factor for years before 1990 based on the following equation. We assume 1990 residue ratios for all years prior.

$$V\text{-}lr_x = V\text{-}rw_x\left(\eta_{04} + (\eta_{o4}\eta_{\Delta})\right)$$

Where:

$V\text{-}rw_x =$ 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 between 1990 and 2004, we calculate logging residues by adjusting the logging residual ratio reported by Morgan and Spoelma (2008) with the percent change in logging residual ratios estimated for Idaho by Simmons and Morgan (2014). To reflect the uncertainty in the estimate provided by Morgan and Spoelma (2008), we estimate 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:

$$V\text{-}lr_x = V\text{-}rw_x \left(\eta_{04} + \left(\eta_{04} \left((Y_1 - x)\, \frac{\eta_\Delta}{Y_\Delta} \right) \right) \right)$$

Where:

$V\text{-}rw_x =$ Roundwood 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:

$$V\text{-}lr_x = V\text{-}rw_x \left(\eta_{04} - \left(\eta_{04} \left((x - Y_1)\, \frac{\eta_\Delta}{Y_\Delta} \right) \right) \right)$$

Where:

$V\text{-}rw_x =$ 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)

3.1.2 Processing Residues

Milling efficiency has increased by roughly 14% in California in the period between 1970 and 2006 Keegan et al. (2010). For this analysis we assume a continuous improvement such that for years prior to 1970, milling efficiency in year x is calculated as:

$$V\text{-}mr_x = V\text{-}rw_x \left(\eta_{70} - \left((Y_1 - x) \frac{\eta_\Delta}{Y_\Delta} \right) \right.$$

Where:

$V\text{-}rw_x =$ 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:

$$V\text{-}mr_x = V\text{-}rw_x\left(\eta_{70} + \left((x - Y_1)\frac{\eta_\Delta}{Y_\Delta}\right)\right)$$

Where:

$V\text{-}rw_x$ = 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)

3.1.3 Construction Residues

To estimate annualized construction waste material, we apply the ratio of construction and demolition debris to finished wood products from McKeever (2004) to roundwood harvest volumes from the BOE (California State Board of Equalization (2015)). In 2002, construction debris was estimated as approximately 15% of the total wood used in construction. Of note is that the data from McKeever is sparse and should be considered unreliable for years other than those for which it is reported.

3.1.4 Demolition Debris

Debris from wood produced from wood grown on California forestland is outside of the scope of this report.

3.1.5 Harvested Wood Residue Summary

The following Table **??** presents ten year average estimates of logging and milling residuals, finished lumber, and construction debris based on BOE roundwood harvest volumes.

10-year start	10-year end	RW	LR	MR	FL	CD
1978	1988	681.701	71.2062	299.522	382.179	57.3269
1979	1989	680.582	70.0131	300.229	380.353	57.0529
1980	1990	681.083	85.4163	301.528	379.555	56.9333
1981	1991	681.601	80.9655	302.612	378.989	56.8483
1982	1992	686.631	85.6518	305.606	381.025	57.1538
1983	1993	695.872	61.338	310.422	385.451	57.8176
1984	1994	678.459	59.5059	303.4	375.059	56.2589
1985	1995	657.737	64.8848	294.892	362.845	54.4267
1986	1996	631.918	53.8304	284.093	347.825	52.1738
1987	1997	600.752	55.9357	270.919	329.833	49.4749
1988	1998	560.495	62.1744	253.572	306.923	46.0384
1989	1999	518.282	53.7261	235.308	282.975	42.4462
1990	2000	477.206	34.9406	217.442	259.764	38.9645
1991	2001	436.798	31.2871	199.72	237.078	35.5618
1992	2002	411.648	28.5456	188.838	222.81	33.4214
1993	2003	389.756	33.309	179.386	210.37	31.5555
1994	2004	370.287	23.5758	171.013	199.274	29.8912
1995	2005	360.411	20.2482	166.982	193.429	29.0143
1996	2006	349.131	22.3163	162.271	186.86	28.0291
1997	2007	338.319	20.1057	157.756	180.563	27.0845
1998	2008	321.14	20.4011	150.231	170.909	25.6364
1999	2009	299.649	19.3104	140.54	159.109	23.8663
2000	2010	283.222	15.1886	133.256	149.966	22.4949
2001	2011	271.892	16.5729	128.347	143.545	21.5318
2002	2012	266.945	15.0393	126.396	140.549	21.0823
2003	2013	266.193	12.2908	126.488	139.705	20.9558

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10-year start	10-year end	RW	LR	MR	FL	CD
2004	2014	262.901	13.9031	125.34	137.561	20.6341

Table 11: Ten-year average logging and mill residual estimates based on BOE harvest volumes in Million Cubic Feet (MCF). RW:Roundwood harvested, LR: Logging residues, MR: Mill Residues, FL: Finished Lumber, CD: Construction Debris

3.2 Emissions from Un-Utilized Residues

Residuals not utilized in bioenergy applications or sent to a landfill eventually produce emissions through combustion or biological decomposition of the material over time. Most of these residues originate from logging activity. To calculate CO2e emissions from unutilized residues, I first estimate the total volume of biomass pile burned in forests using the CARB estimate of PM2.5 (Section 2.5).

To establish the fraction of logging residue that is left to decompose, one needs to know the volume of residues burned and used in bioenergy. To estimate the emissions from decomposition of logging residuals that are not burned, an estimate of consumption of biomass in pile burns would be necessary. In theory, the CARB **(!** (**(!**)CAP} inventory could provide an estimate using the ratio of **PM!** (**PM!**) to biomass consumed. However the CARB-derived pile burn estimate far exceeds the volume of logging residuals from the BOE historical harvest data (Table **??**)

CARB estimate (BDT)	BOE estimate (BDT)
901423.23	576008.93

Table 12: Comparison of annual pile-burned biomass from forestry by CARB with BOE-derived estimate of loggin residuals produced from timber harvest.

This is likely due to in part to the fact that the CARB estimate includes non-commercial forest management activity.

3.3 Emissions of Residuals from non-commercial managenent Activity

The Timber Products Output (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. Robust estimates for volume of removals from these sources are very difficult to obtain. In this report we only estimate unutilized residuals from 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.

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 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 (mean 22.5) 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.

	NFNC	NFC	P	FI	OP
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

(a) **Private industrial timber lands:** CalFIRE's Forest Practice Geographical Information System. **TODO**

3.4 Avoided Emissions from Wood Product Displacement Factors

For each product application, 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. The displacement factors published in (Sathre and O'Connor, 2010) 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.

A meta analysis conducted by (Sathre and O'Connor, 2010) 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.

//** 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) database[4]. 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 decompse or burn).

Figure 3 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 Sathre and O'Connor (2010) to the reported harvest volumes from the TPO database.

The following references are used to arrive at an average displacement factor of **2.625** tCO2e/t finished wood product for harvested roundwood without logging residue utilization.

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.

[4] Timber Products Output Reporting Tool `http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php`

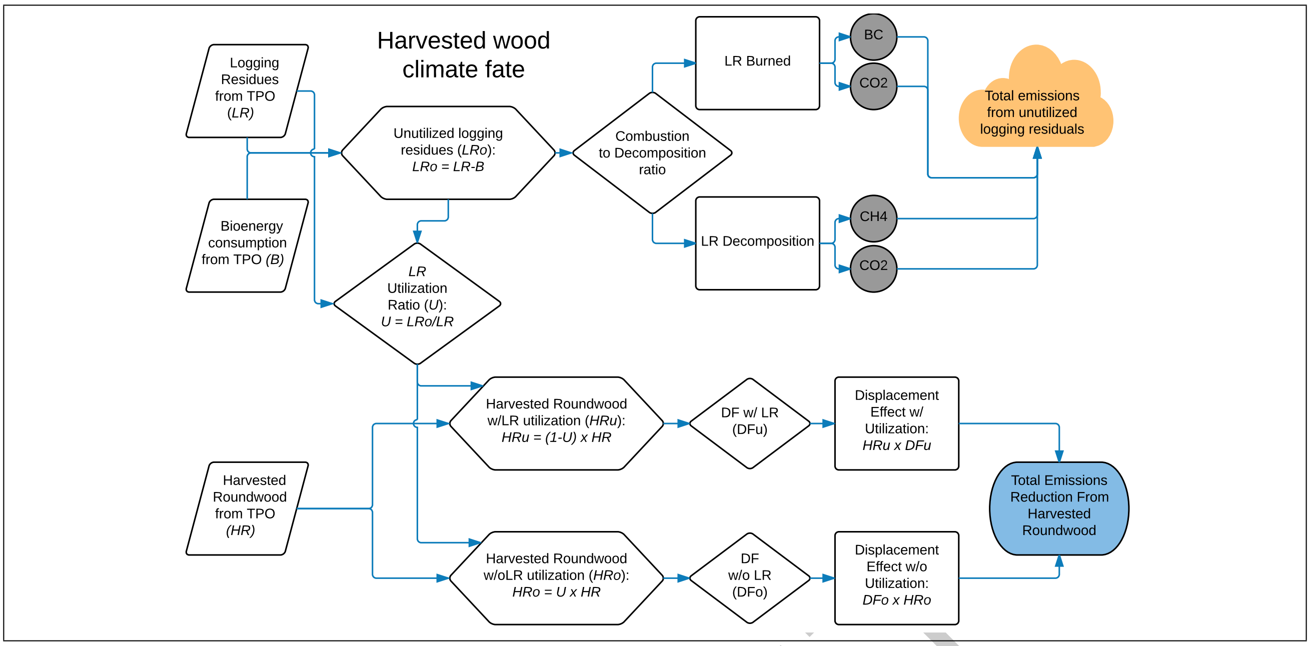

Figure 3: Wood flows from timber harvest in California

reference	displacement factor
Eriksson et al. (2007)	1.7
Eriksson et al. (2007)	2.2
Salazar and Meil (2009)	4.9
Werner et al. (2005)	1.7

Table 13: Wood displacement factor without residue utilization

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.

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 as reported in Mciver et al. (2012). The resulting weighted average wood density used here is **27.94 lbs/cuft**.

We use the fraction of harvested roundwood used in bioenergy from Mciver et al. (2012) (Table 5) to determine 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).

reference	displacement factor
Eriksson et al. (2007)	1.9
Eriksson et al. (2007)	2.5
Gustavsson et al. (2006)	4
Gustavsson et al. (2006)	5.6
Gustavsson et al. (2006)	2.2
Gustavsson et al. (2006)	3.3
Pingoud et al. (2001)	3.2

Table 14: Wood discplacement factor with residue utilization

	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 database reports on average, 8% less volume than the TPO (Table 15) 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

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
2007	1759.6	1626	0.92
2008	1476.0745	1372	0.93
2009	911.19	805	0.88

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year	McIver, et. al. (2012) MMBF	BOE MMBF	BOE/M&M
2010	1302.38	1161	0.89
2011	1432.5	1288	0.9
2012	1421.3	1307	0.92

Table 15: Total annual harvest reported by Mciver et al. (2012) and California Board of Equalization.

// move to appendix?//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.

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
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

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year	State	Federal	Private	Tribal
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

Table 16: Annual harvest by ownership from Mciver et al. (2012) (MCF)

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 calculated the harvest volume the ratio of harvest volume to logging residuals used in bioenergy, we calculateted based on the ratio of reported consumption of logging residuals in bioenergy by Mciver et al. to the total logging residuals reported in the TPO. Mciver et al. 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 varios ownership categories to the aggregate is shown in Figure 5.

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.

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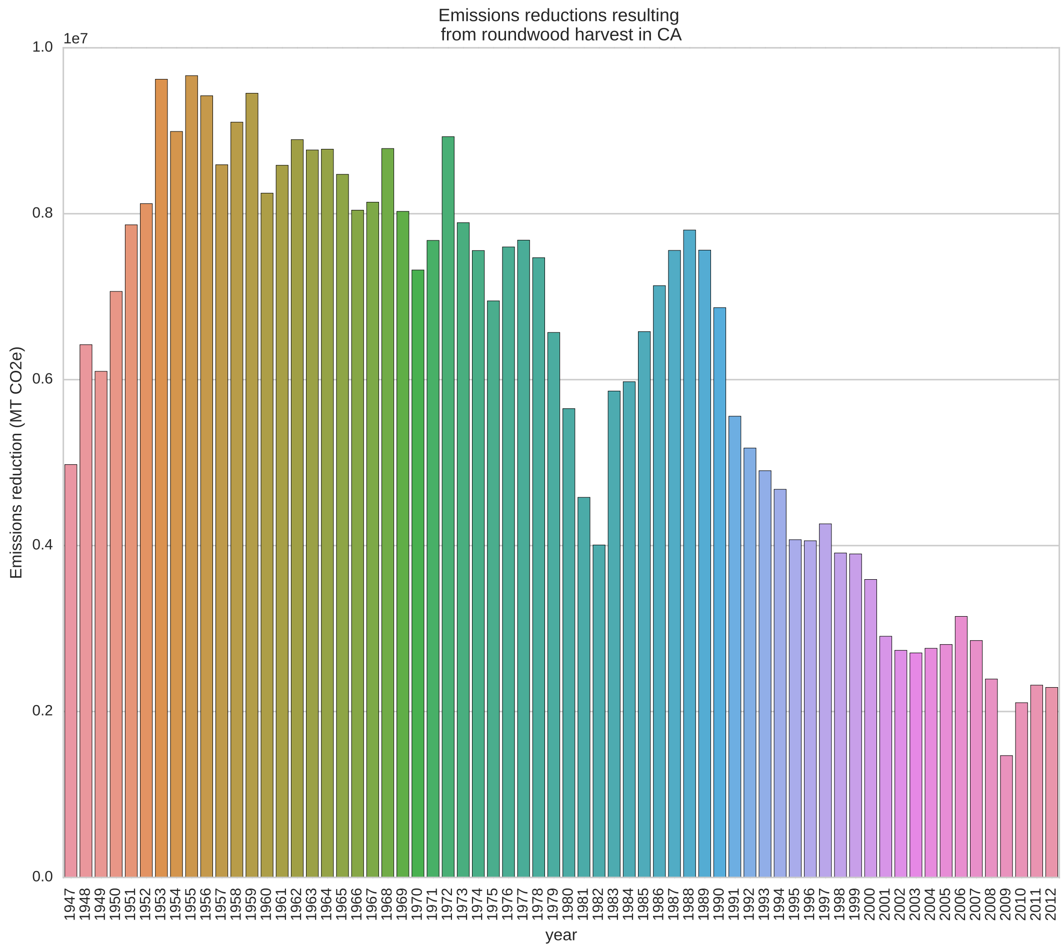

Figure 4: Historical emissions reductions resulting from harvested roundwood using displacement factors from (Sathre and O'Connor, 2010) applied to TPO data.

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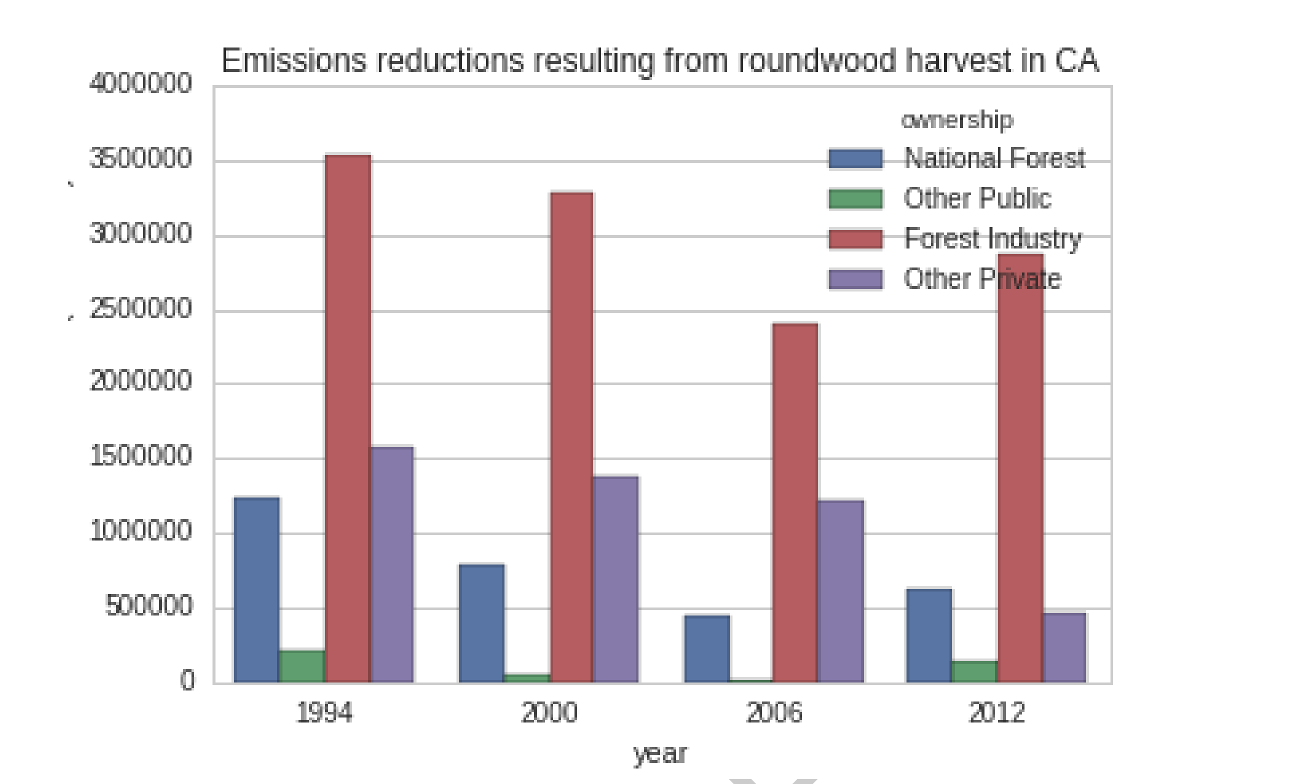

Figure 5: Historical emissions reductions by ownership for selected years resulting from harvested roundwood using displacement factors from (Sathre and O'Connor, 2010) applied to TPO data.

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