nature climate change
SUPPLEMENTARY INFORMATION
DOI: 10.1038/NCLIMATE1264

Regional carbon dioxide implications of forest bioenergy production

Supplementary Methods

General Approach: We combined data from the Forest Inventory and Analysis National Program (FIA) for Oregon, Washington and California (~34 million hectares) with LandFire satellite remote sensing products [1], 200 supplementary plots [2], and a global wood decomposition database[3] to provide new estimates of US West Coast forest biomass carbon stocks, net ecosystem production (NEP, the net of photosynthesis and respiration), net biome production (NBP, the net forest carbon-sink accounting for removals) and their uncertainties. We include all forestland in our analysis. These forests range across all age classes (0-1000 years old), are on rotation management or may have never been harvested, and are both public and privately owned. Plot values were aggregated by climatic region (ecoregion), age class (succession class), and forest type and the mean values were used to assign a value to each associated 30 meter pixel. Thinning treatments were applied to each plot according to a specific set of criteria (Supplementary Fig S1b) of removed forest carbon. Life cycle assessment (LCA) was calculated at the ecoregion, state, and regional level using published values for associated fossil fuel emissions, energy conversion efficiencies, wood product pool ratios and decomposition, and fossil fuel inputs (Supplementary Table S4).

Database: Federal forest inventory data (FIA) are now being collected on an annual basis, statewide on all types of forestland in all regions. The inventory design consists of 0.404 hectare (one-acre) plots systematically placed across the landscape, encompassing a representative range of stand ages, disturbance histories, ownerships, and land cover types. The study area includes all forested land in Washington, Oregon and California for the period from 2001-2006. In addition to the traditional tree surveys, new measurements include woody detritus, understory shrubs, and litter allowing for a more complete quantification of land-based carbon stocks (excluding stocks in soils). As of 2006, there were 8889 measured plots (Supplementary Table S7) with accessible forestland (Plot Status code = 2), of which 8659 with tree increment data recorded which is required for our methods of estimating NPP. Of these 8659, only 6840 had the necessary detritus measurements to calculate NEP (Phase 3 plots). These remaining 6840 plots are still distributed across the landscape in all forest types and ecoregions with about 20% of the plots excluded. Plot means of biomass, NPP, NEP, and NBP were scaled to state totals using spatially explicit forest cover, forest type and productivity, and succession class data products available in 30 x 30 meter resolution from LandFire Landsat satellite remote sensing derived products [1]. Finally, state carbon budgets were estimated using datasets containing annual harvest removals and wood densities, fire emissions, and fossil fuel emissions (Supplementary Table 5).

Biomass stock and flux estimates: Tree and shrub carbon stocks and NPP were calculated with a combination of species-specific allometric equations, tree increment data, and supplemental plot data using methods (Supplementary Table S8) described in [2]. Wood cores collected from a subsample of trees on each plot were used to estimate plot NPP from 10 year diameter growth increment and thus the annual mean NPP is averaged over a 10 year period of growth conditions. Woody detritus carbon was calculated using the line intersect method and species- and decay class-specific wood densities [2]. Foliage litter and duff depth measurements were converted to biomass as the product of the depth and the material density. Foliage NPP was calculated by dividing foliage biomass per tree by the average foliage retention time (average number of years of foliage that a stand carries). Herb mass was estimated using a biomass conversion factor and percent cover on each plot.

We define NEP as the difference between annual NPP and heterotrophic respiration. While direct measurements of soil respiration are not available on FIA plots, we were able to calculate NEP using a mass-balance approach and supplementary plot data [4, 5]:

NEP = Aboveground NPP – dead wood decomposition – litterfall + Δ root +Δ soil C. (1)

The basic assumption is that annual soil respiration is balanced with litterfall, belowground carbon allocation and change in carbon of the roots and soils. Aboveground NPP from tree increment cores and dead wood species, diameter, and decay class are available from West Coast FIA observations. Deadwood decomposition was estimated based on a global dataset of wood decomposition rates of tree species (http://www.bgc-jena.mpg.de/bgc-organisms/pmwiki.php/Research/FET). Predictive models used genus-specific baseline rates modified by coefficients describing the sensitivity to mean annual temperature, annual precipitation sum, stem diameter and position (downed versus standing). Litterfall was estimated as foliage NPP minus an average mass retention of 21 percent (Supplementary Table 9). We assumed change in soil and fine root carbon were zero for plots older than 150 years (old growth) and used the difference between values found at our supplemental plots for younger and mature age classes and the old growth plots to calculate a delta soil carbon [4, 6].

Net Biome Production (NBP). We followed [7] and defined net biome production (NBP) as NEP minus any losses due to fire or harvest. Average annual state timber harvest volumes provided by the respective state Departments of Forestry were converted to biomass removals using known wood densities [8]. Actual fire emissions were calculated using burn area and severity [9] and biomass specific combustion factors for the region (Supplementary Table S9). Estimates of fire emissions vary greatly depending on the approach [10-13] and combustion factors used. We use biomass specific combustion factors from studies in our region [10, 11] which include several of the dominant forest types in our region covering 67% of the forested area. For woody detritus, these factors range from 3 – 100% combustion depending on fire severity and the type of biomass. Emissions estimates using these factors compare well with modeled estimates which also distinguish between biomass components [12]. Other studies use a single combustion factor (30%) for all above ground woody biomass [13, 14] including the standing dead trees. Since the majority of the woody biomass is in standing tree boles, this results in an overestimation of fire emissions. Nevertheless, we have included additional estimates of NBP for both current and treatment emissions using the single combustion factor to determine the sensitivity of this parameter on our results (Supplementary Table S6).

Treatment Design: To test the effect of biomass thinning on land-based carbon stocks and NBP, we chose three different management scenarios designed to meet varying objectives (Supplementary Figure S1a). Basal area removals, maximum tree bole size, and areas treated were varied by the following strategies: 1) Fire Prevention: Thinning targets smaller trees [15] and is limited to areas with frequent fires or short mean fire return intervals (the latter being derived from LandFire [1] Landsat remote sensing derived data product). This scenario is unlikely to be economically feasible due to low value of the extracted biomass. 2) Economically Feasible: Thinning targets larger trees followed by smaller trees providing at least 9 Mg of dry biomass per hectare (4.5 Mg C ha^{-1}) of merchantable biomass [16]. Merchantable biomass would help pay for removing fuel ladders (understory trees that allow fire to access and ignite the canopy). Hence, this treatment is limited to areas with short mean fire return interval. 3) Bioenergy Production: Thinning targets all regions and trees to maximize biomass available for energy production [17]. This scenario is also expected to be economically feasible because merchantable wood is removed. 4) Business-as-usual (BAU): forest management remains the same as current practices

(14.7 Tg C harvested annually) with no additional thinning or harvest treatments. The biomass removal targets were defined by current or proposed practices [18]. Treatments were all designed to produce stands capable of resisting crown fire by reducing canopy bulk density and removal of understory ladder fuel [15]. Synthesis of existing fuel reduction treatment studies found that stand basal area was reduced by an average of 48% [19]. We chose to use a range of basal area reductions, 30% for the Fire Prevention treatment, 40% for Economically Feasible, and 50% for the Bioenergy treatment based on current and proposed practices [15, 16, 20-22]. These practices are designed to follow a general standard which is to alter stand conditions so that projected fire severity would result in at least 80% of the dominant and codominant residual trees surviving a wildfire under the 80th percentile fire weather conditions known as the ”80-80” rule [15].

The main difference between the Fire Prevention and the Economic Production scenario is the basal area reduction allowed and the size of the trees removed. For Economic Production, larger trees are targeted first and then smaller trees are removed to meet the basal area reduction requirements. We did not intend to predict or analyze the economic cost of any of the treatments and simply allowed for higher DBH removals to help offset the cost. There have been several studies that investigate the economic potential of forest bioenergy [16, 19, 23], with mixed results (see http://www.eenews.net/climatewire/2011/07/22/5). In the Fire Prevention scenario, trees are removed from smaller DBH classes first and then larger trees are removed until basil area reduction requirements are met. The main difference between the Economic and the Bioenergy scenario is the basal area reduction and the land area treated. Bioenergy Production treats all land regardless of fire risk or return interval while the Economic scenario only treats land with a fire return interval of less than 40 years.

Thinning prescriptions: Thinning prescriptions were applied to the FIA plots for each of the three treatments (Fire Prevention, Economically Feasible, and Bioenergy Production) according to the management scenarios. The primary objective in each scenario was to reduce stand density in order to reduce the risk of wildfire. The actual fuel reduction thinning treatments applied across different forest types and ownerships vary from stand to stand and are therefore prescribed on a stand-by-stand basis. In order to prevent wildfire, removal of ladder fuels and reduction in crown density are necessary [20, 24, 25]. Stand prescriptions usually involve a vegetation model simulation which takes inputs of stand characteristics such as height, species composition, understory structure, canopy bulk density, ground fuels, wind speed, temperature, and moisture conditions. While most of the necessary inputs are available for a given FIA plot at a given time, some of these conditions change over time (weather) and are too stand specific (structure) to be extrapolated to other stands spatially and temporally. We chose to use the average basal area reduction (30-50%) found in a synthesis of studies [16, 19]to insure adequate reduction in crown density and prevent removal of too much biomass.

To simulate effective removal of ladder fuels, FIA plots were treated by removing the understory non-merchantable small trees (< 12.7 cm) in all three scenarios. Thinning of overstory trees was varied by scenario. All trees on the plot were grouped into small, medium, and large DBH classes. In the Fire Prevention scenario, the majority of the trees removed were in the small DBH class and less trees were removed from the medium and large classes to a maximum of 30% basal area reduction. An upper DBH limit of 45 cm was set. In the Economically Feasible scenario, the majority of trees were removed from the medium and large DBH class followed by a smaller percentage in the smaller class to a maximum of 40% basal area reduction. In the Bioenergy Production scenario, trees were removed similar to the Fire

Prevention scenario but the maximum basal area reduction was 50%. For both the Economically Feasible and the Bioenergy Production scenarios, the DBH limit was set to 60 cm. This upper limit on DBH is currently stated in active forest policy in Oregon and California [26] and the smaller one was proposed to retain larger trees [20]. Bole, branch and bark biomass were considered 'removed' from the site and separated into merchantable and bioenergy pools. Total plot removals were aggregated and mapped by ecoregion, forest type, and age class. State and regional totals include only non-reserved, productive forestland in accessible areas (http://www.fs.fed.us/r1/gis/thematic_data/ira_us_dd.htm). Productive forestland must be capable of producing 10 Mg/ha of merchantable wood annually.

All scenarios exclude public forest reserves and remove all non-merchantable wood (diameter at breast height or DBH < 12.7 cm). A treatment period of 20 years was assumed to be the amount of time required to treat the entire landscape or 5% of the treatable forested area per year [27]. We chose the 40-year mean fire return interval because a plot that is at least half-way through a 40 year mean fire return interval could burn during a 20-year treatment period. FIA plots on forestland capable of producing 10 Mg of merchantable wood per hectare per year were thinned according to each treatment and new plot mean biomass values were scaled to state and ecoregion boundaries to determine the removal totals. The treatment removals were treated as additional harvest (harvest in addition to Business-as-Usual harvest) in further calculations accounting for the portion of biomass utilized for energy and the portion used as merchantable biomass.

Treatments were assumed to be 75% effective at reducing fire emissions [28]. Because only 5% of the landscape is treated each year, associated reductions in fire emissions increase as more forestland is treated. If treatments are 75% effective, then emissions are reduced by 3.75% each year with 75% reduction in the final treatment year. This results in reducing fire emissions by half when integrated over the whole treatment period. We also assume there is no increase in fire frequency (or probability) over the study period due to other factors such as climate change. Fire frequency and intensity are expected to increase in the western US due to climate change [29, 30], but the extent is highly unknown and limited by the capability of the climate-fire models.

Post-treatment NEP: While increased growth of the remaining trees following thinning is well documented, stand-level NPP is reduced (Law of Constant Final Yield, [31]) because ultimately resources limit growth not density [4]. Thinning effects on NEP are not well documented and response is variable [4]. However, we needed to account for regrowth, either due to the increased growth of remaining trees or the growth of the understory over the treatment period. Since we could not estimate regrowth NEP using the plot data, we decided to use the NEP associated with young-aged plots since this might most mimic the conditions following release from competition. The thinned plots were assigned an NEP equal to the observed mean NEP of stands aged between 1 and 20 years over the treatment period resulting in an overall higher NEP for thinned stands, biasing our results towards beneficial effects on the carbon-sink for forest treatments.

Given the large uncertainty associated with predicting future fire [32], we assume that in BAU, fire will occur with variability that has been observed in the past (no increases in fire). Since FIA plots include those that have within fire perimeters, post-fire NEP is part of the current flux estimates. However, because we assume no increase in fire, we do not predict a new post-fire NEP, which would beyond the appropriate use of the data. In a recent study by [33], post-fire NEP for the 5 years prior to the Oregon Biscuit fire averaged the same as the five years after the fire. In this study, we have shown that a doubling of fire emissions by using different combustion coefficients still does not compensate for the emissions associated with bioenergy production (Supplemental discussion of sensitivity analysis).

Life-cycle assessment (Fig S1b; Supplementary Tables 4 and 5): Life-cycle assessment of forest carbon removals includes forestry related sinks and sources of carbon to and from the atmosphere and the associated impact on total fossil fuel emissions (FFE). The C emissions to the atmosphere for each scenario (FCO_2) over 20 years were calculated as the difference between the sources and the sinks following this process:

FCO2 = NBP + Total Harvest – WD1 – WD2 – Wood Industry FFE – Bioenergy Emissions + Bioenergy Substitution + FF Well-To-Tank Emissions displacement+ (Wood Substitution) (2)

Where, WD1 is the wood lost during manufacturing processes, WD2 is the wood decomposed over time from product use and wood substitution is included with the assumption that there is an increased demand for wood supply.

To quantify the change in FCO_2 for each scenario we calculate the difference between each scenario and the BAU FCO_2 emissions. The physical sinks are forest net uptake (NBP) and wood products (Harvest) and the added virtual sinks of bioenergy and wood product substitution (FF Substitution). Because the benefits of wood substitution require an increase in wood use and this saturates quickly, we calculate the change in CO_2 with and without a wood substitution benefit [34]. We exclude imports and exports from the study region since we are only interested in quantifying domestic wood production emissions and exports are less than 1% of harvested merchantable wood (http://www.fs.fed.us/pnw/ppet/). 'Emissions' include release of carbon from woody biomass combustion, and FFE associated with harvest [35], transport of both harvested material and end-use products[19, 36], and processing and manufacturing of wood products [36] and bioenergy [37, 38]. 'Decomposition' includes loss of material through decomposition or combustion during the manufacturing of wood products [39], and the percentage of wood products that are expected to no longer be in-use at the end of the treatment period [39].

Biomass utilized for wood products can end up in a long term storage product (structural wood) or a short term product (paper). Some wood product carbon reenters the atmosphere through rapid (paper) or slow (wood) decomposition or combustion while some is eventually disposed in landfills where it is very slowly decomposed. West Coast harvests generate merchantable bole wood at rates of 50-60% of the total wood harvested [40] and an average of 54% of this wood remains in use or is in landfills after 20 years [39]. Using tables provided by [39] we determined the amounts of long and short term wood products that could be generated by the merchantable wood harvested accounting for the losses along the way and multiplied this by 54% to determine the wood product storage [39]. Because this ratio could increase or decrease due to changes in manufacturing efficiency, product use, or recycling, we allowed for a 10% increase and decrease of this percentage for the additional harvest *only* as part of the sensitivity analysis [36, 41]. The remaining non-merchantable wood (including understory trees) from harvest was used for biofuel biomass and associated emissions.

Fossil fuel substitution with bioenergy was calculated as a 50/50 energy mix of ethanol conversion and biomass combustion compared to fossil fuel derived automotive gasoline. Woody biomass provides less energy per unit of carbon emitted than fossil fuels (i.e. wood has an energy content of 20 GJ per ton versus 43.5 GJ per ton in automotive gasoline because fossil fuels have a lower heating value [42]). Under maximum yield conditions, the potential energy of woody biomass is 78% of fossil fuel if combusted and 36% if converted to cellulosic ethanol [43]. These maximum values are highly unrealistic as they have yet to be obtained [43] and ratios up to 30%

lower have been suggested [44]. Nevertheless, we use the maximum values in our estimates under optimum conditions and reduce the ratios by 10 and 20% to provide a range of conditions in the sensitivity analysis (Supplementary Table 7). State annual fossil fuel emissions were acquired from the Vulcan Project Database (http://www.purdue.edu/eas/carbon/vulcan/index.php) and from the Oregon Department of Energy (http://www.oregon.gov/ENERGY/GBLWRM/CCIG.shtml, Appendix A).

There are also emissions associated with crude extraction and manufacturing, sometimes called the wells-to-tank emissions (WTT). Fossil fuel LCA total emissions (wells to wheels; WTW) include both WTT and tank-to-wheels (TTW) emissions. The amount of C emitted per unit of fossil fuel energy varies widely by oil field, but generally WTT emissions are about 15%[45] of total emissions (WTW), or 12 g CO_2 per MJ of energy. We have included theses emissions in the Wood Industry FFE and we have added a WTT displacement benefit along with the bioenergy substitution benefit.

An additional estimate of the LCA was calculated for a wood product substitution benefit. Wood product substitution for a 50/50 mix of aluminum and steel used in residential American housing generates a 36% reduction in fossil fuel emissions assuming a maintained rate in new residential housing [46]. We applied a wood substitution benefit as 36% of the final structural wood product pool.

Uncertainty Analysis: Monte Carlo simulations were used to conduct an uncertainty analysis using the mean and standard deviations for NPP and Rh calculated using several approaches. For NPP, three alternative sets of allometric equations were used to estimate the uncertainty due to variation in region and/or species-specific allometry. The full suite of species-specific equations that use tree diameter (DBH) and height (preferred) were compared to a DBH-only national set [47] and to a grouped forest type set. For, Rh, the variation in the calculated decomposition rate was used to quantify the uncertainty. A species-specific lookup table of decay constants was compared to decay constants that were allowed to vary by genus, precipitation, and temperature or by class, precipitation and temperature. Finally, uncertainty in NBP was calculated as the combined uncertainty of NEP, fire emissions (10%) [10], harvest emissions (7%) [48], and land cover estimates (10%) using the propagation of error approach [49]. Uncertainty estimates are represented in the figures by the grey error bars and in tables with '±'.

Sensitivity analysis of most of the LCA parameters is summarized below (Table S6). The most sensitive parameters in this study that affect net emissions and NBP are land area treated, allowable removals (DBH limit and basal area reductions) per unit area, and to some extent, fire emissions. First, we present a range of scenarios that vary by land area and allowable removals. Removals are varied by basal area reduction limits of 30, 40, and 50% for the FP, EC, and BP scenarios respectively. These reductions equate to removal rates of 25-53% of live biomass. To test the sensitivity of the reduction in fire emissions, we also calculated NBP and net emissions assuming 50% and 75% effectiveness of the treatments. Additional parameters that affect only net emissions is the ratio of wood products that are in use at the end of the treatment period, the efficiency of the conversion to energy, and the fossil fuel inputs required for energy conversion. For the in-use product ratio, we calculated net emissions for a 10% increase and decrease to the ratio. For the conversion efficiencies, we varied each of these factors by 100, 90 and 80% of the maximum possible values to present a range of results reflecting the most optimum conditions (100% efficiency) to the least optimum (80% efficiency) (Supplementary Table S6). Values for the most optimum conditions are represented in the figures unless otherwise noted.

In addition to evaluating the sensitivity of the proposed treatments to the parameter estimates, we also explored the effect of varying the range of harvest to NEP ratios, wood product to bioenergy biomass ratios, percent combusted versus converted to cellulosic ethanol, fossil fuel inputs required, and amount of wood product in the short-term product pool with subsequent recapture as bioenergy. We determined the hypothetical ratios where the forest net carbon flux was zero (neutral) or greater than or equal to the current flux (BAU) and compared the net carbon flux for each scenario with the range of ratios (Supplementary Fig S6).

Supplementary Discussion

State-level Estimates: Forest carbon stocks (excluding soil carbon) for the entire region are 5.0 ± 0.8 Pg C with 31% in Washington, 36% in Oregon, and 33% in California (Supplementary Table S2). NPP ranges from 100 to 900 g C m^{-2} across the region and falls within the range of 100 to 1600 g C m^{-2} yr^{-1} reported for temperate and boreal forests [50] and Rh ranges from 100 to 600 g C m^{-2}. Our estimates are in line with previous work: Our mean NEP ranges from -50 to 400 g C m^{-2} yr^{-1} similar to the range of -50 to 800 g C m^{-2} yr^{-1} reported for temperate forests [50]. Using a simulation model, the total NEP of Oregon in the late 1990's was estimated to be 17 ± 11 Tg C yr^{-1} (vs. 15.3 ± 1.6 Tg C yr^{-1} in this study) most of which was attributed to forests [8]. Furthermore, recent estimates from [33] predict an NEP of 25.5 Tg C yr^{-1} (vs. 29.2 Tg C yr^{-1} for the same area in this study) in the northwest forest plan area of Washington, Oregon, and California. Also using a simulation model, the total NEP of California [51] for 2001-2004 ranged from 14-24 Tg C yr^{-1} (vs.18.1 Tg C yr^{-1} in this study). Previous regional estimates of NEP were not found for Washington.

We explored four scenarios, three treatments and business-as-usual (Supplementary Fig S1a). The removal limits of 30-50% of stand basal area resulted in 25– 53 % removal of aboveground live tree biomass per plot which is typical for fuel reduction treatments [16, 20]. These treatments do not replace current management practices. They result in additional harvest above the current harvest in the region. Statewide removals were much lower (by 5-10 Tg C yr^{-1}) in Washington than the other two states for the Fire Prevention and Economically Feasible scenarios due to a higher median MFRI (91-100 years versus less than 60 years) resulting in a reduced treatment area (Supplementary Table S2). The Bioenergy Production scenario results in 264, 220, and 92% reductions in NBP in Washington, Oregon, and California respectively with Washington and Oregon forests becoming a carbon source (Supplementary Table S2). The Fire Prevention and Economically Feasible scenario had the most impact on California NBP compared to Oregon and Washington (decreased from 13.6 Tg C yr^{-1} to 5.6 and 9.4 Tg C yr^{-1} respectively). Furthermore, at the state level, Washington NBP was not significantly different from BAU for either the Fire Prevention or the Economically Feasible scenario because a smaller percentage of the forested area is in a high fire risk area compared to the other two states resulting in lower harvest levels. Washington removals were balanced by the assumed reduction in fire emissions and increased NEP from regrowth. These findings suggest that in regions where proposed harvest is low there may be little effect on NBP compared with BAU.

Comparing California and Oregon, the area-weighted state level differences in NEP, fire and harvest, are respectively 20, 3.1 and 30 g C m^{-2} y^{-1} summing to a difference in NBP of 46.4 g C m^{-2} y^{-1} (Supplementary Table S3), indicating the largest differences were in NEP and harvest removals. Coastal Redwood forests in California, for example, contribute 16.5 g C m^{-2} y^{-1} more to the state-wide NBP per unit area than the same forest type in Oregon. However, the opposite was observed in, for example, North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest. This forest type has a 19.9 g C m^{-2} y^{-1} higher NBP in Oregon than in California. Although there are considerable differences in fire emissions between Oregon and California (1.3 and 1.8 Tg C in OR vs CA), the difference in NEP and harvest between similar forest types within the same ecoregions appears to be the dominant reason of the observed differences in NBP between the two states. Some of the possible causes of the difference in NBP are: (1) A productive forest type is present in California but absent in Oregon (i.e. Lower Montane Blue Oak-Foothill Pine Woodland and Savanna), (2) A forest type with an above-average NBP is managed similarly in California and Oregon but is more abundant and productive in California (i.e. Coastal Redwood Forest and Mediterranean (Dry-)Mesic Mixed Conifer Forest and Woodland) and (3) The losses through harvest are lower in California than Oregon in forest types that cover a large area (North Pacific Sitka Spruce, Dry-Mesic and Wet-Mesic Douglas-fir-Western Hemlock Forests). Additionally, our estimates of NBP rely on our estimates of NEP using the mass balance approach. For stands older than 150 years, we have assumed a steady-state for the soil carbon pool (i.e. delta soil carbon is zero). For stands younger than 150 years, we used the best available data to estimate a delta soil carbon value for each plot depending on the age. We may be overestimating by a larger amount if the loss of soil carbon due to disturbance is higher (or gain is slower) in ecoregions (i.e California) not represented in our soils dataset. If we are overestimating NEP and subsequently overestimating NBP, the biomass removal impact on NBP is underestimated.

Previous estimates of forest biomass potentially available for energy supply in Oregon and California vary widely, from 0.4 – 14 Tg C yr^{-1}, depending on assumptions of area needing treatment, volume removed per hectare, and the number of years over which treatments are conducted [27, 52, 53]. While these estimates are in general agreement with our estimates from all three treatments (3.8 – 17 Tg C yr^{-1} for Oregon and California combined), they only addressed a portion of the potential biomass removals i.e. that used for energy production. In our scenario analysis, we go beyond previous approaches by accounting for the fate of all biomass removals and assess their effect on forest NBP. The thinning treatments result in additional biomass removals of 11- 44 Tg C yr^{-1} from current inventory biomass levels for the entire region (Supplementary Table S5) of which only 7 – 24 Tg C yr^{-1} would be used for energy supply. Since current harvest levels are half of what they were in 1980s, three times current harvest rates are possible in this region as has been suggested in government and industry reports and given the current level of effort that is going into developing a biomass industry[17, 23]. The proposed harvest intensities are simply scenarios that are being considered in one region, and the application of such scenarios over other regions or subregions may not be appropriate given the forest type, climate, and management history. For example, in fire prone or beetle killed areas, it may be necessary to apply moderate harvest levels. Our approach lends itself to testing the carbon consequences of location-specific management activities.

Additional LCA analysis: Proper accounting of the *in-situ* NBP in LCA reveals the effects of forest management on atmospheric CO_2 when considering mitigation options for reducing CO_2 emissions. Towards this aim, we developed a conceptual model to determine the outcomes of mitigation options which may include different ratios of wood product to energy mixes, higher or lower BAU harvest to NEP ratios, or efficiency of fossil fuel usage. The conceptual LCA model addresses the main determinants of the forest sector carbon budget i.e. forest management and wood processing. This conceptual model reveals that the largest decreases in the forest sector emissions are accomplished by reducing the harvest to NEP ratio (Supplementary Figure S3, red line).

We analyzed the sink-strength of the forest sector for varying management intensities where intensity was expressed as the ratio of harvest to net ecosystem productivity (H/NEP), the latter including forest growth and regrowth. The current H/NEP ratio is about 0.3. Wood processing was described by the ratio of wood products to total harvest (P/H). We then investigated the combinations of P/H ratios varying from 0 to 1 with different combinations of bioenergy (combustion versus ethanol), 0-100% reduction in fossil fuel inputs, and recycling of manufactured waste for bioenergy production to determine if biomass end-use affected the forest sector CO_2 emissions. Changing the ratios for the percentage used in wood products versus bioenergy (Supplementary Figure S3a), the mix of energy used for combustion versus cellulosic ethanol (Supplementary Figure S3b), the efficiency of fossil fuel inputs (Supplementary Figure S3c), and the reduction of the short-term product pool (Supplementary Figure S3d) has very little impact compared to the increase in removals.

Furthermore, this analysis suggests that a reduction of net CO_2 emissions compared to BAU can only be realized if harvest remains at current levels or increases to a maximum of 20% more than BAU, but this requires that either all bioenergy is produced by means of combined heat and power rather than ethanol (Supplementary Figure S3b), or wood-use results in 100% reduction of fossil fuel emissions from this process (Supplementary Figure S3c), or 100% of waste wood is used for bioenergy production (Supplementary Figure S3d). These measures are definitely unlikely to take place within the proposed 20-year time-frame.

Sensitivity Analysis: The differences in NBP and emissions due to land area treated and allowable removals are shown in Supplementary Table 2. The amount of land area treated has a significant impact on NBP. In the life-cycle assessment, the range in efficiencies changed the impact of the scenarios by 3-28% (Supplementary Table S6). For example, if the amount of wood products in use are reduced by 10%, bioenergy production is at 80% of optimum conditions (least effective), and fire emissions are reduced by 50%, net emissions to the atmosphere increase by a larger amount: 101, 251, and 579 Tg C for the Fire Prevention, Economically Feasible, and Bioenergy Production scenarios respectively (compared with 44, 175, and 421 Tg C for 100% of optimum conditions; Supplementary Table S5). Using the alternative combustion estimates reduces the impact of the FP and EC scenarios by 6-9%, and increases the impact in the BP scenario. This increase in initial fire emissions eliminates the net increases in emissions for the FP scenario (very small annual increase), but only under optimum conditions. The impact is greatest in the Klamath Mountains. Inclusion of wood substitution reduces atmospheric emissions by 2-10% across the scenarios, but only under optimum conditions and assuming there is a demand for the wood use.

Finally, our estimates of BAU harvest practices may decrease in the future, in which case, we could be overestimating removals over the next 20 years. However, this is unlikely because harvest declined significantly since 1990 due to restrictions placed on harvest on federal lands as part of the Northwest Forest Plan.

Supplementary References

1. USGS. in U.S. Department of Interior, Geological Survey. http://gisdata.usgs.net/website/landfire/ (U.S. Department of Interior, Geological Survey, 2009).
2. Hudiburg, T. et al. Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. Ecological Applications 19, 163-180 (2009).
3. Wirth, C. et al. (Max Planc Institute for Biogeochemistry, 2010).
4. Campbell, J., Alberti, G., Martin, J. & Law, B. E. Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada. Forest Ecology and Management 257, 453-463 (2009).
5. Giardina, C. P. & Ryan, M. G. Total belowground carbon allocation in a fast-growing eucalyptus plantation estimated using a carbon balance approach. Ecosystems 5, 487-499 (2002).

6. Law, B. E., Sun, O. J., Campbell, J., Van Tuyl, S. & Thornton, P. E. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biology 9, 510-524 (2003).
7. Chapin, F. et al. Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems 9, 1041-1050 (2006).
8. Turner, D. P. et al. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. Biogeosciences 4, 597-612 (2007).
9. Eidenshink, J. et al. A project for monitoring trends in burn severity. Fire ecology 3, 3-20 (2007).
10. Campbell, J., Donato, D., Azuma, D. & Law, B. Pyrogenic carbon emission from a large wildfire in Oregon, United States. J. Geophys. Res. 112 (2007).
11. Meigs, G., Donato, D., Campbell, J., Martin, J. & Law, B. Forest fire impacts on carbon uptake, storage, and emission: the role of burn severity in the Eastern Cascades, Oregon. Ecosystems 12, 1246-1267 (2009).
12. Ottmar, R. D., Pritchard, S. J., Vihnanek, R. E. & Sandberg, D. V. 14 pp (Final Report JFSP Project 98-1-9-06, 2006).
13. Wiedinmyer, C. & Hurteau, M. D. Prescribed fire as a means of reducing forest carbon emissions in the western United States. Environmental Science & Technology 44, 1926-1932 (2010).
14. Wiedinmyer, C. et al. Estimating emissions from fires in North America for air quality modeling. Atmospheric Environment 40, 3419-3432 (2006).
15. Stephens, S. L. et al. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19, 305-320 (2009).
16. Skog, K. E., Ince, P. J., Spelter, H., Kramp, A. & Barbour, R. J. Woody biomass supply from thinnings to reduce fire hazard in the U.S. West and its potential impact on regional wood markets (Forest Products Society, Madison, WI, 2008).
17. Perlack, R. et al. in US Department of Energy, US Department of Agriculture, Oak Ridge, TN (US Department of Energy, US Department of Agriculture, Oak Ridge, TN, 2005).
18. USDA. (USDA Forest Service Pacific Southwest Region, Vallejo, CA 94592, 2010).
19. Evans, A. & Finkral, A. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. GCB Bioenergy 1, 211-219 (2009).
20. Harrod, R. J., Peterson, D. W., Povak, N. A. & Dodson, E. K. Thinning and prescribed fire effects on overstory tree and snag structure in dry coniferous forests of the interior Pacific Northwest. Forest Ecology and Management 258, 712-721 (2009).
21. Finkral, A. J. & Evans, A. M. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. Forest Ecology and Management 255, 2743-2750 (2008).
22. Stephens, S. L., Moghaddas, J. J., Hartsough, B. R., Moghaddas, E. E. Y. & Clinton, N. E. Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. Canadian Journal of Forest Research 39, 1538-1547 (2009).
23. OFRI. Oregon Biofuels and Biomass: Woody Biomass in Oregon - Current Uses, Barriers and Opportunities for Increased Utilization and Research Needs. OSU Chemical Engineering Department, Institute for Natural Resources, and Oregon Wood Innovation Center, p.37 (2006).

24. Agee, J. K. & Skinner, C. N. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211, 83-96 (2005).
25. Huggett Jr, R. J., Abt, K. L. & Shepperd, W. Efficacy of mechanical fuel treatments for reducing wildfire hazard. Forest Policy and Economics 10, 408-414 (2008).
26. ORSenate. (73rd OREGON LEGISLATIVE ASSEMBLY--2005 Regular Session, Salem, OR, 2005).
27. Bowyer, J. (ed. Bowyer, J.) (Oregon Forest Resources Institute, Corvallis, OR, 2006).
28. Raymond, C. L. & Peterson, D. L. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research 35, 2981-2995 (2005).
29. Littell, J. S., McKenzie, D., Peterson, D. L. & Westerling, A. L. Climate and wildfire area burned in western U.S. ecoprovinces, 1916â€“2003. Ecological Applications 19, 1003-1021 (2009).
30. Westerling, A. L., Hidalgo, H. G., Cayan, D. R. & Swetnam, T. W. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science 313, 940-943 (2006).
31. Shinozaki, K. & Kira, T. Intraspecific competition among higher plants. VII. Logistic theory of the C - D effect. J Inst Polytech Osaka City Univ (1956).
32. Rogers, B. et al. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. J. Geophys. Res. doi:10.1029/2011JG001695 (In press).
33. Turner, D. et al. Decadal trends in net ecosystem production and net ecosystem carbon balance for a regional socioecological system. Forest Ecology and Management (In press).
34. Law, B. E. & Harmon, M. E. Forest sector carbon management, measurement and verification, and discussion of policy related to climate change. Carbon Management 2, 73-84 (2011).
35. Sonne, E. Greenhouse Gas Emissions from Forestry Operations. J. Environ. Qual. 35, 1439-1450 (2006).
36. Heath, L. S. et al. Greenhouse Gas and Carbon Profile of the U.S. Forest Products Industry Value Chain. Environmental Science & Technology 44, 3999-4005 (2010).
37. Jaeger, W. K., Cross, R. & Egelkraut, T. M. in OSU Extension (Oregon State University, Corvallis, OR, 2007).
38. Whitaker, J., Ludley, K. E., Rowe, R., Taylor, G. & Howard, D. C. Sources of variability in greenhouse gas and energy balances for biofuel production: a systematic review. GCB Bioenergy 2, 99-112 (2010).
39. Smith, J. E., Heath, L., Skog, K. E. & Birdsey, R. 216 (U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA, 2006).
40. Harmon, M. E., Harmon, J. M., Ferrell, W. K. & Brooks, D. Modeling carbon stores in Oregon and Washington forest products: 1900–1992. Climatic Change 33, 521-550 (1996).
41. Lippke, B., Wilson, J., Meil, J. & Taylor, A. Characterizing the importance of carbon stored in wood products. Wood and Fiber Science 42, 5-14 (2010).
42. Wright, L., Boundy, B., Perlack, R., Davis, S. C. & Saulsbury, B. Biomass energy data book: edition 1 (Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, 2006).
43. Mitchell, S. R., Harmon, M. E. & O'Connel, K. E. B. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19 (2009).

44. Galbe, M. & Zacchi, G. A review of the production of ethanol from softwood. Applied Microbiology and Biotechnology 59, 618-628 (2002).
45. ICCT. p1-20 (International Council on Clean Transportation, Washington D.C., 2010).
46. Upton, B., Miner, R., Spinney, M. & Heath, L. S. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy 32, 1-10 (2008).
47. Jenkins, J. C., Chojnacky, D. C., Heath, L. S. & Birdsey, R. A. National-Scale Biomass Estimators for United States Tree Species. Forest Science 49, 12-35 (2003).
48. Heath, L. S. & Smith, J. E. An assessment of uncertainty in forest carbon budget projections. Environmental Science and Policy 3, 73-82 (2000).
49. NRC. Verifying Greenhouse Gas Emissions (ed. Pacala, S. W.) (National Academies Press, Washington, D.C., 2010).
50. Luyssaert, S. et al. Old-growth forests as global carbon sinks. Nature 455, 213-215 (2008).
51. Potter, C. The carbon budget of California. Environmental Science & Policy 13, 373-383 (2010).
52. Strittholt, J. R. & Tutak, J. (Conservation Biology Institute, Corvallis, OR, 2009).
53. Williams, R. B. 61-64 (California Biomass Collaborative, California Energy Commission, Davis, CA, 2007).
54. Van Tuyl, S., Law, B. E., Turner, D. P. & Gitelman, A. I. Variability in net primary production and carbon storage in biomass across Oregon forests--an assessment integrating data from forest inventories, intensive sites, and remote sensing. Forest Ecology and Management 209, 273-291 (2005).
55. Harmon, M. E. & Sexton, J. in Publication No. 20. US LTER Network Office, University of Washington, Seattle, WA 93pp. (Publication No. 20. US LTER Network Office, University of Washington, Seattle, WA, 1996).
56. Van Wagner, C. E. The line-intersect method in furest fuel sampling. Forest Science 14, 20-26 (1968).
57. Waddell, K. L. Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators 1, 139-153 (2002).
58. Campbell, J. L., Sun, O. J. & Law, B. E. Supply-side controls on soil respiration among Oregon forests. Global Change Biology 10, 1857-1869 (2004a).
59. Keyes, M. R. & Grier, C. C. Above- and belowground net production in 40-year-old Douglas-fir stands on low and high productivity sites Canadian Journal of Forest Research 11, 599-605 (1981).
60. van Heerwaarden, L. M., Toet, S. & Aerts, R. Current measures of nutrient resorption efficiency lead to a substantial underestimation of real resorption efficiency: facts and solutions. Oikos 101, 664-669 (2003).
61. Maeglin, R. R. & Wahlgren, H. E. (USDA Forest Service Research Paper FPL-183, 1972).
62. Wood Handbook, p. 72 (Forest Products Laboratory, Madison, WI, 1974).

Supplementary Table S1. Ecoregion characteristics including dominant forest types, mean annual temperature (MAT), mean annual precipitation (MAP), and area weighted mean fire return interval (MFRI).

Ecoregion[1]	Forest (ha)	Dominant Forest Types	MAT	MAP	MFRI
BM	3312268	Mixed Conifer, Ponderosa Pine, Juniper, Spruce-Fir	7.3	552	41 to 45
CB	352650	Pinyon-Juniper, Jeffrey-Ponderosa Pine, Limber-Bristlecone Pine	6.0	445	51 to 60
CO	2688165	Blue Oak-Foothill Pine, Mixed Evergreen, Mixed Conifer, Redwood, Oak Woodland and Savanna, Black Oak-Conifer	14.8	652	26 to 30
CP	253667	Mixed Conifer, Ponderosa Pine, Riparian	9.7	330	51 to 60
CR	4812627	Douglas-fir-Western Hemlock, Sitka Spruce, Redwood, Mixed Evergreen, Riparian, Western Red Cedar, Western Hemlock-Silver Fir	11.0	1742	91 to 100
CV	170243	Blue Oak-Foothill Pine, Riparian, Salt Desert Scrub, Mixed Oak Savanna	17.2	412	36 to 40
EC	3545116	Ponderosa Pine, Mixed Conifer, Montane Riparian, Juniper, Jeffrey Pine-Ponderosa Pine, Lodgepole Pine, Red Fir, Mountain Hemlock	9.1	630	36 to 40
KM	3748465	Mixed Conifer, Mixed Evergreen, Red Fir, Douglas-fir-Western Hemlock, Riparian, Black Oak-Conifer, Redwood, Mixed Oak Woodland	11.5	1549	16 to 20
MB	93889	Pinyon-Juniper, Montane Riparian, Mixed Oak Woodland	18.4	185	41 to 45
NB	478106	Juniper, Aspen, Pinyon-Juniper, Montane Riparian, Jeffrey-Ponderosa Pine, Mountain Mahogany	9.7	304	51 to 60
NC	2311424	Western Hemlock-Silver Fir, Mixed Conifer, Mountain Hemlock, Spruce-Fir, Western Red Cedar, Riparian, Subalpine Woodland	5.6	1548	101 to 125
NR	1514359	Mixed conifer, Riparian, Spruce-Fir, Ponderosa Pine	7.5	613	51 to 60
PL	1102015	Douglas-fir-Western Hemlock, Riparian, Western Red Cedar, Sitka Spruce	10.6	1304	151 to 200
SB	2175	Pinyon-Juniper	22.0	110	41 to 45
SM	730051	Mixed Evergreen, Mixed Conifer, Mixed Oak, Blue Oak-Foothill Pine, Oak Woodland, Riparian	12.3	1064	26 to 30
SN	1022645	Mixed Conifer, Red Fir, Jeffrey-Ponderosa Pine, Riparian, Mixed Oak, Subalpine Woodland, Blue Oak-Foothill Pine, Black Oak-Conifer, Lodgepole Pine	8.2	915	21 to 25
SR	8613	Montane Riparian	9.7	303	101 to 125
WC	4329871	Douglas-fir-Western Hemlock, Silver Fir-Western Hemlock, Mountain Hemlock, Mixed Conifer, Red Fir, Riparian, Western Red Cedar	8.8	1688	101 to 125
WV	538681	Douglas-fir-Western Hemlock, Riparian	11.0	1280	46 to 50

[1]BM, Blue Mountains; CB, Central Basin; CO, California Chaparral and Oak Woodlands; CP, Columbia Plateau; CR, Coast Range; CV, Central California Valley; EC, East Cascades; KM, Klamath Mountains; MB, Mohave Basin; NB, North Basin and Range; NC, North Cascades; NR, Northern Rockies; PL, Puget Lowlands; SB, Sonoran Basin; SM, Southern California Mountains; SN, Sierra Nevada; SR, Snake River; WC, West Cascades; WV, Willamette Valley.

Supplementary Table S2. State total and mean carbon fluxes for Business-As-Usual (BAU) and treatments. Net biome production (NBP) calculated for 75% treatment efficiency (possible fire emission reductions). Uncertainty is noted by the '±' symbol.

State (forested hectares)	**Washington 9.0×10^6**	**Oregon 12.2×10^6**	**California 12.8×10^6**
Annual Fossil Fuel Emissions (Tg C yr^{-1})	21	15	105
Carbon density (Mg C ha^{-1})	172 ± 25	150 ± 22	130 ± 18
Net Primary Production (NPP) (Tg C yr^{-1}) (g C m^{-2} yr^{-1})	 46.7 ± 4.7 518 ± 52	 60.0 ± 6.0 488 ± 49	 61.0 ± 6.2 477 ± 48
Net Ecosystem Production (NEP) (Tg C yr^{-1}) (g C m^{-2} yr^{-1})	11.3 ± 1.2 125 ± 13	15.2 ± 1.6 125 ± 13	18.1 ± 2.1 142 ± 16
Harvest emissions (Tg C yr^{-1})	5.5 ± 0.4	6.4 ± 0.5	2.7 ± 0.2
Fire emissions (Tg C yr^{-1})	0.9 ± 0.1	1.3 ± 0.2	1.8 ± 0.3
Net Biome Production (NBP) (Tg C yr^{-1}) (g C 2^{-2} yr^{-1})	 4.8 ± 1.3 53 ± 14	 7.5 ± 1.7 61 ± 14	 13.6 ± 2.1 107 ± 16
Area Treated (hectares) • Fire Prevention • Economically Feasible • Bioenergy Production	 0.8×10^6 0.8×10^6 7.2×10^6	 4.0×10^6 4.0×10^6 9.8×10^6	 6.8×10^6 6.8×10^6 7.9×10^6
Additional Removals (Tg C yr^{-1}) • Fire Prevention • Economically Feasible • Bioenergy Production	0.6 ± 0.02 0.9 ± 0.04 13.2 ± 0.4	3.8 ± 0.2 5.7 ± 0.3 17.2 ± 0.7	6.7 ± 0.4 10.5 ± 0.7 13.4 ± 0.9
Scenario NBP (Tg C yr^{-1}) • Fire Prevention • Economically Feasible • Bioenergy Production	 4.8 ± 1.3 4.5 ± 1.3 -6.1 ± 1.3	 5.2 ± 1.7 3.3 ± 1.7 -6.6 ± 1.9	 9.4 ± 2.1 5.6 ± 2.2 2.9 ± 2.3

Supplementary Table S3. Forest types that contribute more than 1 g C m^{-2} y^{-1} to the observed area-weighted difference of 46.4 g C m^{-2} y^{-1} (see also Supplementary Table 2) in net biome production (NBP) between California and Oregon for shared forest types. For example, this difference in NBP is partially due to an area-weighted difference in net ecosystem production (NEP) and harvest of 19.2 and 2.7 g C m^{-2} y^{-1} for the California Coastal Redwood forest type (see example calculation in footnote). Units are in g C m^{-2} y^{-1} unless otherwise noted.

Forest Type	State	NEP	Fire	Harvest	Area (ha)	ΔNEP	ΔFire	ΔHarvest	Weighted NBP	ΔNBP
North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest	CA	189	4	0	3488	-44.9	-0.1	-24.9	0.1	-19.9
	OR	205	0	113	2684324				19.9	
California Coastal Redwood Forest	CA	296	1	41	832912	19.2	0.1	2.7	16.6	16.5
	OR	238	0	26	2983				0.1	
California Lower Montane Blue Oak-Foothill Pine Woodland and Savanna	CA	120	7	17	1636673	15.4	0.9	2.2	12.3	12.3
	OR	0	0	0	0				0.0	
Mediterranean California Mesic Mixed Conifer Forest and Woodland	CA	111	13	27	2748963	17.6	1.9	4.1	15.4	11.6
	OR	107	14	29	721488				3.8	
Central and Southern California Mixed Evergreen Woodland	CA	186	28	2	643670	9.4	1.4	0.1	7.9	7.9
	OR	0	0	0	0				0.0	
California Montane Riparian Systems	CA	165	14	0	667775	8.1	0.7	0.0	7.9	7.4
	OR	163	18	0	42589				0.5	
Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland	CA	153	20	27	1559888	10.1	2.0	1.2	13.0	6.8
	OR	158	8	37	671005				6.2	
Mediterranean California Mixed Evergreen Forest	CA	308	11	62	581798	3.6	-3.0	1.1	10.7	5.5
	OR	228	76	38	562982				5.2	
North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest	CA	166	0	0	3184	-11.1	-0.7	-5.4	0.0	-5.0
	OR	163	11	78	838685				5.1	
Great Basin Pinyon-Juniper	CA	208	23	0	343308	5.4	0.6	0.0	5.0	4.8

Woodland	OR	221	16	0	8570				0.1	
Mediterranean California Mixed Oak Woodland	CA	155	27	0	455384	5.4	1.0	0.0	4.5	4.4
	OR	151	7	0	9823				0.1	

Forest Type	State	NEP	Fire	Harvest	Area (ha)	ΔNEP	ΔFire	ΔHarvest	Weighted NBP	ΔNBP
Mediterranean California Red Fir Forest	CA	91	13	20	1087841	6.7	1.1	1.3	4.9	4.3
	OR	90	2	38	147570				0.6	
North Pacific Hypermaritime Sitka Spruce Forest	CA	0	0	0	0	-7.2	0.0	-3.8	0.0	-3.4
	OR	275	0	145	321231				3.4	
Northern Rocky Mountain Ponderosa Pine Woodland and Savanna	CA	59	3	21	104182	-5.8	-0.9	-1.9	0.3	-3.0
	OR	63	10	20	1225805				3.3	
North Pacific Montane Riparian Woodland and Shrubland	CA	178	3	0	2846	-2.7	-0.1	0.0	0.0	-2.7
	OR	175	3	0	192321				2.7	
Mediterranean California Lower Montane Black Oak-Conifer Forest	CA	158	13	27	320462	3.6	0.3	0.6	2.9	2.6
	OR	159	9	23	28108				0.3	
Southern California Oak Woodland and Savanna	CA	158	51	0	261241	3.2	1.0	0.0	2.2	2.2
	OR	0	0	0	0				0.0	
Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest	CA	41	4	20	4468	-5.6	-1.0	-2.4	0.0	-2.2
	OR	40	7	17	1737309				2.2	
California Montane Jeffrey Pine(-Ponderosa Pine) Woodland	CA	71	11	22	601572	3.3	0.4	1.0	1.8	1.9
	OR	71	89	22	13831				0.0	
North Pacific Dry-Mesic Silver Fir-Western Hemlock-Douglas-fir Forest	CA	122	0	0	9	-4.1	-0.2	-2.1	0.0	-1.8
	OR	142	7	73	350817				1.8	
North Pacific Swamp Systems	CA	190	0	0	71	-1.7	0.0	0.0	0.0	-1.7
	OR	190	5	0	112087				1.7	
North Pacific Mountain Hemlock Forest	CA	105	2	33	9232	-2.9	-0.4	-1.4	0.1	-1.1
	OR	99	14	48	372207				1.1	

[1] Weighted NBP = ((NEP – Fire – Harvest) * Forest Type Area) / Total Forest Area of State; Total forest areas are 12.2 and 12.8 million hectares for Oregon and California, respectively (Supplementary Table 2)

Supplementary Table S4. Life Cycle Assessment coefficients. Each coefficient is multiplied by a biomass pool (Tg C yr^{-1}). Processing efficiencies vary by state (PNW = Pacific Northwest or Oregon and Washington; CA = California)

Life-Cycle Factor	**Coefficient**	**Biomass Pool**	**Description and source**
Sawlog (SL)	0.80	Merchantable wood	Sawlog fraction of merchantable portion of harvest[39]
Pulpwood (PW)	0.11	Merchantable wood	Pulpwood fraction of merchantable portion of harvest[39]
WD1a	0.09	Merchantable Wood	Portion of wood lost in initial manufacturing process[39]
Sawlog Wood (PNW) Sawlog Wood (CA)	0.56 0.53	Sawlog (SL)	Wood product fraction of sawlog [39]
Sawlog Paper (PNW) Sawlog Paper (CA)	0.25 0.145	Sawlog (SL)	Paper product fraction of sawlog [39]
Pulpwood Paper (PNW) Pulpwood Paper (CA)	0.50 0.145	Pulpwood (PW)	Paper product fraction of pulpwood [39]
WD1b	na	(SL+PW)- (Wood + Paper)	Portion of wood lost in conversion to products [39]
WD2	0.46	(Wood + Paper)	10yr Decomposition (no longer in use or in a landfill) [39]
Wood Industry FFE[2] Harvest Harvest Transport Manufacturing Wood Paper Product Transport FF WTT[3]	 .009 .003 0.004 0.57 0.009 0.1675	 Merchantable Wood Merchantable Wood Wood Paper (Wood + Paper) Wood Industry FFE	 Harvest FFE [35] Transport FFE [36] for average 75 km distance[19] Wood FFE [36] Paper FFE [36] Transport FFE [36] for average 250 km distance[19] Fossil Fuel extraction and production [45]
Bioenergy FFE Combustion (CHP) Cellulosic Ethanol (CE)	 0.05 0.35	 Non-Merchantable Wood Non-Merchantable Wood	 Harvest, Transport, Chip manufacturing[36] Harvest, Transport, Conversion to Ethanol[37, 38]
Bioenergy Substitution Combustion (CHP) Cellulosic Ethanol (CE)	 0.78 0.36	 Non-Merchantable Wood Non-Merchantable Wood	 FFE reduction for the energy potential of wood energy compared to fossil fuel [43]
FF WTT Displacement	0.1675	Bioenergy Substitution	Displaced FF emissions from crude oil extraction

Bioenergy Emissions	1.00	Non-Merchantable Wood	C released from bioenergy use
Wood Substitution	0.36	Sawlog Wood	FFE reduction with 50:50 mix of aluminum/steel substitution[46]

[1] LCA = FCO_2 = NBP + Total Harvest – WD1a – WD1b – WD2 – Wood Industry FFE - Bioenergy Emissions + Bioenergy Substitution + FF WTT displacement + (Wood Substitution); WTT = Well to tank emissions; WD = Wood decomposition; Wood Substitution is dependent on increase in wood use

[2]FFE = Fossil Fuel Emissions

[3] WTT = Well to Tank emissions from crude oil extraction are approximately 15% of total well to wheels (extraction plus use) emissions.

Supplementary Table S5. Life cycle assessment of forest derived bioenergy for the West Coast region assuming a 50:50 mix of combustion for combined heat and power (CHP) and conversion to cellulosic ethanol (CE). All values are in Tg C yr^{-1} unless otherwise noted. Numbers in bold represent optimum conditions, biomass pool specific combustion factors, and no wood substitution.

Total Region				
LCA Parameter	**Business-as-Usual (BAU) Opt | Alt | Low[1]**	**Fire Prevention Opt | Alt | Low**	**Economically Feasible Opt | Alt | Low**	**Bioenergy Production Opt | Alt | Low**
NEP	44.5	38.0	38.0	30.5
Regrowth [2]	0.00	9.6	9.6	20.6
Fire emissions	4.1 | 8.1 | na	2.5 | 3.9 | 3.0	2.5 | 3.9 | 3.0	2.5 | 3.9 | 3.0
Total harvest [3]				
Current	14.6	14.6	14.6	14.6
Additional	0.00	11.1	17.1	43.8
NBP [4]	**25.8** | 21.8 | na	**19.4** | 18.0 | 18.9	**13.4** | 12.0 | 12.9	**-9.7** | -11.1 | -10.3
Wood Product FFE (fossil fuel emissions)	1.06	2.74	6.69	8.07
Wood Decomposition (WD1)	7.08	9.34	10.46	16.82
Wood Decomposition (WD2)	3.47	4.25 | 4.25 | 4.68	4.64 | 4.64 | 4.96	7.12 | 7.12 | 9.16
Bioenergy emissions	0.00	6.80	10.65	24.12
FF Substitution	0.00	3.9 | 3.9 | 2.5	6.1 | 6.1 | 3.9	13.7 | 13.7 | 8.9
FF WTT Displaced[5]	0.00	0.65 | 0.65 | 0.42	1.01 | 1.01 | 0.67	2.30 | 2.30 | 1.49
Wood Substitution	0.00	0.7	1.0	3.1
FCO_2 [6]				
No Wood Sub	**28.9** | 24.8 | na	**26.6** | 25.1 | 24.0	**19.8** | 18.4 | 16.1	**8.6** | 7.2 | 0.4
With Wood Sub	na	27.2	20.8	11.6
Uncertainty	**3.0**	**3.1**	**3.3**	**3.5**
Σ Tg C added to atmosphere (20 yrs)				
No Wood Sub	**0.00**	**46.0** | -7.0 | 97.3	**174.6** | 127.7 | 254.4	**420.7** | 352.0 | 569.1
With Wood Sub	0.00	32.9	161.1	344.5

[1] Opt = Optimum efficiency parameters, Alt = Alternative combustion coefficients, not pool specific, Low = Low efficiency parameters

[2] Thinned plot total NEP is the sum of the NEP and Regrowth rows

[3] Total harvest includes the continued harvest for wood products plus an additional harvest for bioenergy resulting in harvest increases compared to BAU for each scenario

[4] NBP = Scenario NEP + Scenario Regrowth – Scenario Total harvest – Scenario Fire emissions

[5] FF WTT = Fossil fuel well-to-tank emissions from extraction and refining of crude oil

[6] FCO_2 = NEP + Regrowth – Fire –Wood Product FFE (includes associated FF WTT) – WD1 – WD2 – Bioenergy Emissions + FF Substitution + FF WTT displacement + (Wood Substitution)

Supplementary Table S6. Sensitivity Analysis parameters and relative impact on results (CHP = biomass used as combined heat and power; FP = Fire Prevention scenario; EC = Economically Feasible scenario; BP = Bioenergy Production scenario).

Efficiency	**Parameters evaluated**	**Value**	**Impact on result (%)**
Optimum	CHP substitution efficiency Ethanol substitution efficiency Percentage wood products still in use or in landfill Fire emissions reductions	0.78 0.36 0.64 75%	These are the optimum or best case scenario conditions and were used for the results. The other sets of parameter values are compared to the FCO_2 value obtained for this parameter set. Negative values indicate emissions savings.
Moderate	CHP substitution efficiency Ethanol substitution efficiency Percentage wood products still in use or in landfill Fire emissions reductions	0.68 0.26 0.54 75%	FP +3% EC +5% BP +13%
Low	CHP substitution efficiency Ethanol substitution efficiency Percentage wood products still in use or in landfill Fire emissions reductions	0.58 0.16 0.44 50%	FP +9% EC +12% BP +28%
Combustion	Woody biomass combustion coefficients	30% combustion of all aboveground woody biomass	FP -9% EC -6% BP +1%
Wood Substitution	Included wood substitution in LCA	36% substitution benefit of structural wood products pool	FP -2% EC -3% BF -10%

Supplementary Table S7. Forest Inventory Analysis plot information for the study region.

Ecoregion[1]	Number of Plots	With Increment Data	With Phase 3 measurements	Percentage excluded
BM	885	857	672	22
CB	129	126	101	20
CO	672	633	509	20
CP	75	66	48	27
CR	1057	1036	819	21
CV	13	11	10	9
EC	1097	1069	855	20
KM	1154	1137	878	23
MB	57	53	42	21
NB	115	106	76	28
NC	482	477	359	25
NR	338	334	258	23
PL	174	169	122	28
SM	204	192	167	15
SN	1275	1258	1035	18
WC	1019	998	801	20
WV	115	109	91	17

[1]BM, Blue Mountains; CB, Central Basin; CO, California Chaparral and Oak Woodlands; CP, Columbia Plateau; CR, Coast Range; CV, Central California Valley; EC, East Cascades; KM, Klamath Mountains; MB, Mohave Basin; NB, North Basin and Range; NC, North Cascades; NR, Northern Rockies; PL, Puget Lowlands; SB, Sonoran Basin; SM, Southern California Mountains; SN, Sierra Nevada; SR, Snake River; WC, West Cascades; WV, Willamette Valley.

Supplementary Table S8. Equations and factors used to calculate carbon stocks, fluxes, and life-cycle assessment.

Component	Code	Equation	Notes
Bole Biomass [1]	$Biomass_b$	Bole Volume Equation*Wood Density	Bole volume derived from allometric equation using DBH (diameter at breast height) and height; [2, 47]
Branch biomass	$Biomass_{br}$	Allometric Equation	Derived from DBH and/or height;[2, 47]
Bark biomass	$Biomass_{ba}$	Allometric Equation	Derived from DBH and/or height; [2, 47]
Foliage biomass	$Biomass_f$	Allometric Equation	Derived (allometry) from DBH and/or height; [2, 47]
Coarse root biomass	$Biomass_{cr}$	Allometric Equation	Derived from a volume equation developed for Douglas-fir and species-specific wood densities; [2, 47]
Leaf Area Index [2]	LAI	$Biomass_f$/ LMA	Calculated from $Biomass_f$ and leaf mass per unit leaf area (LMA)
Fine root biomass	$Biomass_{fr}$	$(\exp(4.4179+(.3256*LAI)-(.0237*LAI^2))$	[54], Supplemental plot data ($p<0.001$, $R^2 = 0.41$, $n=36$)
Understory shrub biomass [3]	$Biomass_s$	a*(1-(exp(-b*Shrub Volume)))	Shrub volume calculated as the product of the recorded fraction plot cover, plot area, and height
Coarse woody debris Volume	$Volume_{cwd}$	$(9.869/(8*L))*(D^2)$[5]	Where, L is the transect length in meters and D is the diameter of the piece in centimeters [55-57]
Coarse woody debris biomass	$Biomass_{cwd}$	$Volume_{cwd}$ * Adjusted Density	Derived by multiplying $Volume_{cwd}$ by a decay class adjusted species-specific density
Component	**Code**	**Equation**	**Notes**
Wood NPP (Bole, Branch, Bark, and Coarse Roots)	NPP_w	$Biomass_{w2} – Biomass_{w1}$	Difference between biomass of woody components at current and previous time steps
Foliage NPP[4]	NPP_f	$Biomass_f$/ Foliage Retention time	Biomass of foliage divided by the average number of years of foliage a stand carries[5]

Fine root NPP	NPP_{fr}	$Biomass_{fr}$ * 1.2 $year^{-1}$	Average fine root turnover (1.2 year-1) obtained from the literature and supplemental plot data [58, 59]
NEP	NEP	ANPP – Rh_{wood} – litterfall + Δ root + Δ soil C	Where Δ fine root and Δ soil C are assumed to be zero over the time period[5]
Litterfall		NPP_f x 0.79	Average mass retention of 21%; [60]
Dead Wood Rh	Rh_{wood}	$Biomass_{cwd}$ - $Biomass_{cwd}$ *exp(-kt)	Where k value is calculated as a function of piece size, genus, precipitation, and mean annual temperature (http://www.bgc-jena.mpg.de/bgc-organisms/pmwiki.php/Research/FET)

[1]Species-specific wood densities were obtained from US Forest Service wood density survey for western Oregon [61], the Forest Products Laboratory wood handbook (1974) [62], and from wood cores obtained on our supplemental plots. Wood densities were reduced according to decay class for standing dead trees [57].
[2] Leaf specific mass (LMA) was obtained from a look-up Supplementary Table of species-specific values obtained from measurements on the supplemental plots in each of the ecoregions. In some cases, a species-specific value was not available and therefore a closely related species was used.
[3] The parameters 'a' and 'b' are regression coefficients that vary by species. Equations were developed from harvested shrubs at the supplemental field plots.
[4]Foliage (branch) samples from evergreen species were collected at all supplemental plots and the average number of years of growth retained on each branch was recorded to calculate retention time. Samples were also dried and weighed. New shoot growth was recorded for foliage NPP. This information was used to construct species and ecoregion specific lookup Supplementary Tables for the FIA plots.

Supplementary Table S9. Comparison of combustion factors by source and fuel category.

Source	Forest Types	Fuel Category	Combustion Factor (Fraction Combusted) by severity			
			High	**Moderate**	**Low**	**Unburned/Very Low**
Campbell et al., 2007	Mixed Conifer, Douglas-fir, Western Hemlock, Tanoak, Jeffrey Pine	Trees	0.08	0.07	0.03	0.00
		Snags	0.18	0.14	0.11	0.01
		Shrubs	0.86	0.66	0.42	0.00
		Foliage	1.00	0.76	0.75	0.70
		FWD	1.00	0.76	0.75	0.70
		CWD	0.78	0.58	0.61	0.62
		Litter	1.00	0.76	0.75	0.70
		Duff	0.99	0.51	0.54	0.44
Meigs et al., 2009[1]	Ponderosa Pine	Live Trees	0.03	0.014	.003	n.a.
Wiedinmyer and Hurteau (2010)[2], Wiedinmyer et al., 2006	n.a.	Aboveground woody mass	0.30	0.30	0.30	0.30
		Litter/Duff	0.90	0.90	0.90	0.90

1 From Consume 3.0 simulations [12] and field measurements of consumption

2 Combustion factors were not indicated to vary by severity in the reported citations

Supplementary Figure S1. **A**. Thinning treatment scenarios. Included are the percent basal area reductions, the maximum tree diameter (DBH) that can be harvested, and the land area where the proposed treatment would be implemented. The treatments remove enough live biomass in order to lower risk of wildfire and provide biomass for bioenergy. MFRI is the mean fire return interval. **B**. Boundary of the processes accounted for in the life-cycle assessment (LCA). The boundary was expanded to account for substitution of fossil fuels by bio-energy. Full lines show C flow and dotted lines show energy flow. Arrows show fluxes and lines show substitution. Carbon is exchanged between the forest and the atmosphere through photosynthesis (1) and respiration (2) and lost to the atmosphere via fire (2) or removed by harvest (3). The carbon removed is used for bioenergy or wood products. Transport of the biomass to either end use utilizes fossil fuels and contributes to the total fossil fuel emissions (FFE) (4). FFE are associated with both manufacturing of wood products and both forms of bioenergy production (energy is required to convert the biomass to a useable form of energy; (5)). Biomass utilized for wood products can end up in a long term storage product (structural wood), a short term product (paper), imported, or exported. Some wood product carbon reenters the atmosphere through slow (6; wood) or rapid (7; paper) decomposition or combustion while some of it is eventually disposed in landfills (8 and 9) where it is very slowly decomposed. Biomass utilized for bioenergy can be burned or converted to cellulosic ethanol, releasing carbon to the atmosphere (10). Wood products can be substituted for fossil fuel products (11) and bioenergy emissions can be substituted for fossil fuels emissions associated with use, extraction, and production (12).

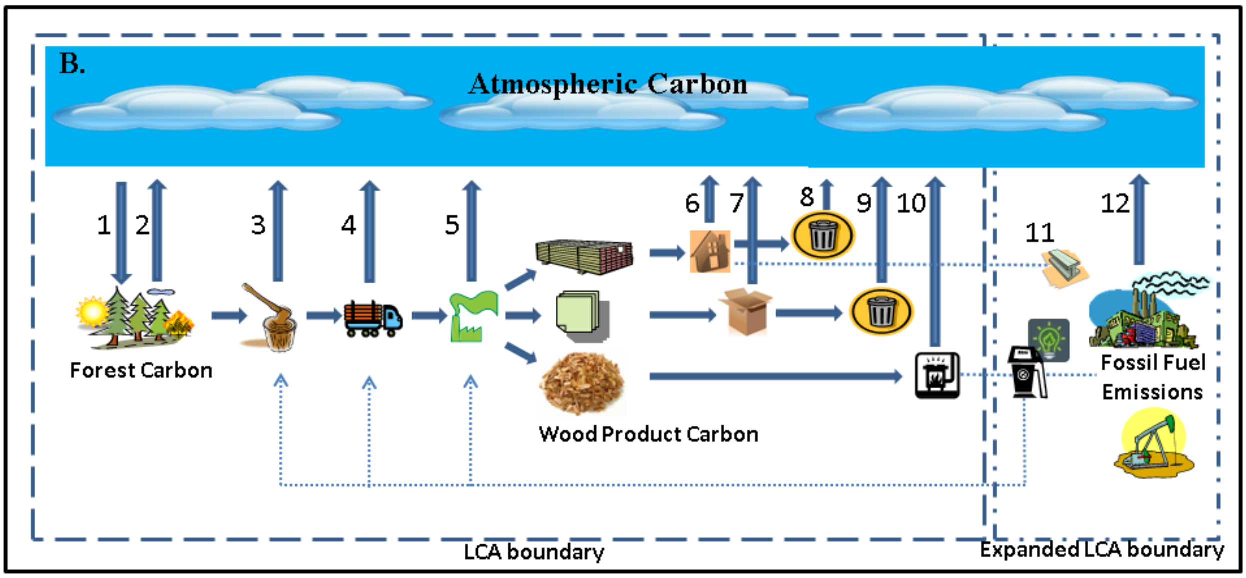
Supplementary Figure S2. (A) MFRI (Mean Fire Return Interval) verses delta CO_2 (Fire Prevention; FP – Business as Usual; BAU) and (B) initial emissions versus delta CO_2.

Supplementary Figure S3. Conceptual analysis of harvest to NEP ratio, product mix, and varying efficiencies of bioenergy production. The x-axis is the harvest to NEP ratio, the y-axis is the product to harvest ratio (a value of 1 indicates all harvest is in wood products, a 0 indicates all harvest is used for bioenergy). F_0 lines (black and grey) are the combinations for carbon-neutral flux and F_{BAU} (dark red and red) are the lines where the flux is equal to BAU. A) Energy mix is 50:50. B) Energy mix is varied. Dark red line = BAU and red line = where the energy mix ratio flux is equal to BAU. Black line = 100% biomass combustion and the grey line = 100% cellulosic ethanol conversion. Nearly all of the harvest must be used for bioenergy to realize a lower emission than BAU. C) Fossil fuel inputs are varied. Black line = fossil fuel inputs are equivalent to product biomass (least efficient) and grey line = No fossil fuel inputs required (most efficient). Even if no fossil fuel inputs are required, only a small increase in harvest decreases emissions compared to BAU. D) Amount of wood in short term pool is varied and used for bioenergy instead of going to landfill. Black line = 100% of wood product enters short term pool and then used for bioenergy and the grey line = 100% of wood product enters long term pool. With complete recycling of wood waste (no short term pool) for use as bioenergy, there is still very little emissions savings.

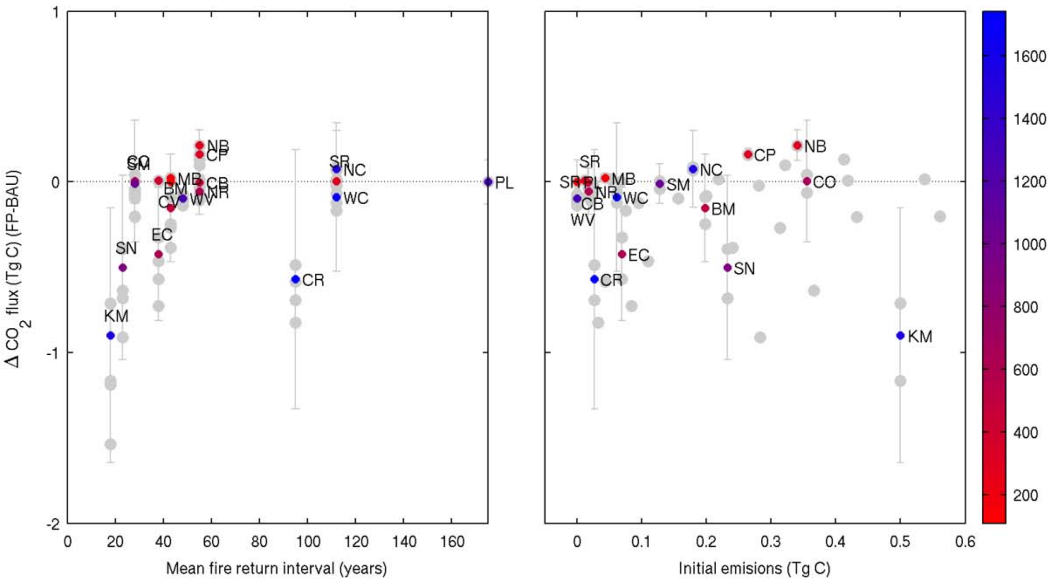
Supplementary Figure S1

A. **Treatment Scenarios**

Thinning Treatment	Basal Area % Reduction	DBH Limit (cm)	Land Area Treated	Tree emphasis
Fire Prevention	30	45	MFRI < 40 years	small to medium
Economically Feasible	40	60	MFRI < 40 years	merchantable
Bioenergy Production	50	60	All	no preference



Supplementary Figure



S2

Supplementary Figure S3