nature climate change

LETTERS

| DOI: 10.1038/NCLIMATE1264

Regional carbon dioxide implications of forest bioenergy production

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Strategies for reducing carbon dioxide emissions include substitution of fossil fuel with bioenergy from forests[1], where carbon emitted is expected to be recaptured in the growth of new biomass to achieve zero net emissions[2], and forest thinning to reduce wildfire emissions[3]. Here, we use forest inventory data to show that fire prevention measures and large-scale bioenergy harvest in US West Coast forests lead to 2–14% (46–405 Tg C) higher emissions compared with current management practices over the next 20 years. We studied 80 forest types in 19 ecoregions, and found that the current carbon sink in 16 of these ecoregions is sufficiently strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy. If the sink in these ecoregions weakens below its current level by 30–60 g C m^{-2} yr^{-1} owing to insect infestations, increased fire emissions or reduced primary production, management schemes including bioenergy production may succeed in jointly reducing fire risk and carbon emissions. In the remaining three ecoregions, immediate implementation of fire prevention and biofuel policies may yield net emission savings. Hence, forest policy should consider current forest carbon balance, local forest conditions and ecosystem sustainability in establishing how to decrease emissions.

Policies are being developed worldwide to increase bioenergy production as a substitution for fossil fuel to mitigate fossil fuel-derived carbon dioxide emissions, the main cause of anthropogenic global climate change[4,5]. However, the capacity for forest sector bioenergy production to offset carbon dioxide emissions is limited by fossil fuel emissions from this activity (harvest, transport, and manufacturing of wood products) and the lower energy output per unit carbon emitted compared with fossil fuels[6]. Furthermore, forest carbon sequestration can take from decades to centuries to return to pre-harvest levels, depending on the initial conditions and amount of wood removed[7]. The effects of changes in management on CO$_2$ emissions need to be evaluated against this baseline. Consequently, energy policy implemented without full carbon accounting and an understanding of the underlying processes risks increasing rather than decreasing emissions[4,8].

In North America, there is increasing interest in partially meeting energy demands through large-scale forest thinning[5], with the added benefit of preventing catastrophic wildfire and concurrent carbon loss[3]. Although forest thinning can be economically feasible, sustainable, and an effective strategy for preventing wildfire where risk is high[9,10], it remains unresolved whether this type of forest treatment can satisfy both the aims of preventing wildfire and reducing regional greenhouse gas emissions.

For both aims to be satisfied, it needs to be shown that: (1) reduction in carbon stocks due to thinning and the associated emissions are offset by avoiding fire emissions and substituting fossil fuel emissions with forest bioenergy, (2) the change in management results in less CO$_2$ emissions than the current or 'baseline' emissions, and (3) short-term emission changes are sustained in the long term. Determination of baseline forest sector carbon emissions can be accomplished by combining forest inventory data and life-cycle assessment (LCA[6]) that includes full carbon accounting of net biome production (NBP) on the land in addition to carbon emissions from bioenergy production and storage in wood products. NBP is the annual net change of land-based forest carbon after accounting for harvest removals and fire emissions.

Our study focused on the US West Coast (Washington, Oregon and California), a diverse region owing to the strong climatic gradient from the coast inland (300–2,500 mm precipitation per year) and a total of 80 associated forest types, ranging from temperate rainforests to semi-arid woodlands (Supplementary Table S1). The region is divided into 19 distinct ecoregions[11] on the basis of climate, soil and species characteristics, and includes a broad range of productivity, age structures, fire regimes and topography. Mean net primary production of the forest types range from 100–900 g C m^{-2} yr^{-1} (this study), falling within the global range of 100 to 1,600 g C m^{-2} yr^{-1} reported for temperate and boreal forests[12]. Forest land ownership is divided fairly evenly between public and private sectors having different management histories and objectives that affect forest carbon dynamics[13].

Carbon sequestration rates vary greatly across the region, with mean net ecosystem production (NEP; photosynthesis minus respiration) ranging from -85 g C m^{-2} yr^{-1} in the dry Northern Basin to more than 400 g C m^{-2} yr^{-1} in the mesic Coast Range. After accounting for fire emissions and substantial harvest removals, regional NBP remains a significant sink of 26 ± 3 Tg C yr^{-1} or 76 ± 9 g C m^{2} yr^{-1}, similar to the US average[14] and estimates for the member states of the European Union[15]. Sixteen of the 19 ecoregions, representing 98% of the forest area in the region are estimated to be carbon sinks (Fig. 1a; exceptions are drier ecoregions where annual productivity is low and fire emissions are relatively high). Thus, the observed regional sink is not solely due to the region's highly productive rainforests, which occupy 15% of the area. Within the region, California's NBP is higher than that of Oregon and Washington (107 versus 53–61 g C m^{-2} yr^{-1}), primarily owing to differences in NEP (Supplementary Table S2) and harvest between similar forest types within the same ecoregions that cross state boundaries (Supplementary Discussion and Table S3).

In addition to current management or business as usual (BAU, characterized by current preventive thinning and harvest levels), we designed three treatments (Supplementary Fig. S1a) to reflect the varying objectives of potential forest management systems: forest fire prevention by emphasizing removal of fuel ladders

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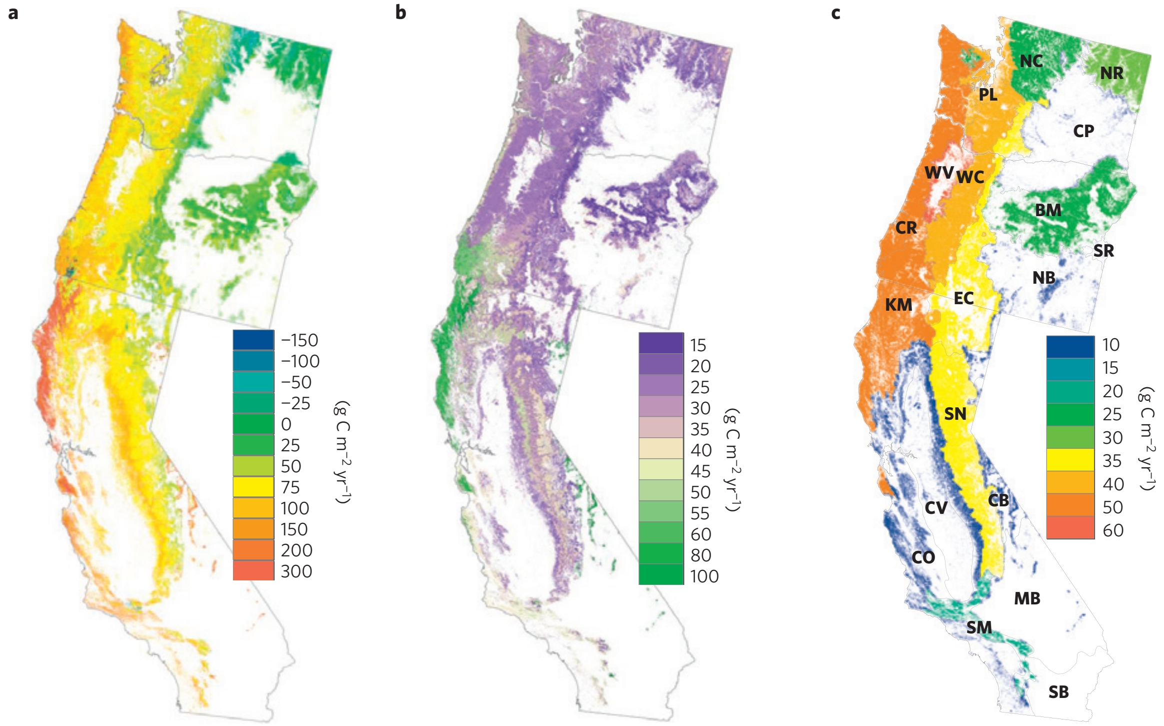

Figure 1 | Maps of US West Coast NBP and uncertainty for current and threshold conditions. a, Current NBP or BAU; positive values (warm colours) indicate forest sinks whereas negative values (cool colours) are carbon sources to the atmosphere. **b**, The current NBP uncertainty estimates that were calculated using Monte Carlo simulations of mean forest type values for the components of NBP (net ecosystem productivity, fire and harvest) combined with the uncertainty associated with remote sensing land cover estimates. **c**, The amount NBP would need to decrease to reach a threshold NBP where bioenergy management may result in emission decreases to the atmosphere. 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.

(‘fire prevention’) in fire-prone areas, making fuel ladder removal economically feasible by emphasizing removal of additional marketable wood in fire-prone areas (‘economically feasible’), or thinning all forestland regardless of fire risk to support energy production while contributing to fire prevention (‘bioenergy production’). Removals are in addition to current harvest levels and are performed over a 20-year period such that 5% of the landscape is treated each year. Our reliance on a data-driven approach versus model simulations strengthens our analysis in the short term, but limits our ability to make long-term predictions. Extending our study beyond a 20-year timeframe would overstretch data use because current forest growth is unlikely to represent future growth due to changes in climate, climate-related disturbance, and land use[16,17].

In our study region, we found that thinning reduced NBP under all three treatment scenarios for 13 of the 19 ecoregions, representing 90% of the region’s forest area. The exceptions where NBP was not reduced were primarily due to high initial fire emissions compared to NEP (for example, Northern Basin and North Cascades; Supplementary Fig. S2). The dominant trend at the ecoregion level was mirrored at the regional level, with the bioenergy production scenario (highest thinning level) resulting in the region becoming a net carbon source (Supplementary Table S2 and discussion of state-level estimates). Regionally, forest biomass removals exceeded the potential losses from forest fires, reducing the *in situ* forest carbon sink even after accounting for regrowth, as found in previous studies with different approaches or areas of inference[8,18]. Because we have assumed high reductions in fire emissions for the areas treated in each scenario, it is unlikely we are underestimating the benefit of preventive thinning on NBP.

It is important to recognize that even if the land-based flux is positive (a source) or zero (carbon neutral), decreases in NBP from BAU can increase CO_2 emissions to the atmosphere. LCA was used to estimate the net emissions of carbon to the atmosphere in each treatment scenario (Supplementary Fig. S1b and Tables S4 and S5). LCA at the ecoregion level revealed that emissions are increased for 10 out of 19 of the ecoregions (Fig. 2), representing 80% of the forest area in the region. The combination of *in situ* and wood-use carbon sinks and sources emit an additional 46, 181 and 405 Tg C to the atmosphere over a 20-year period (2–14% increase) above that of the BAU forest management scenarios for the fire prevention, economically feasible, and bioenergy production treatments, respectively (Fig. 3).

Sensitivity analysis of our results to a range of fire emission reductions, energy conversion efficiencies, wood product decomposition rates and inclusion of wood substitution showed that carbon emissions varied by −10 to 28% from the optimum values across the scenarios, depending on the combination of assumptions (Supplementary Discussion and Table S6). The analysis revealed that an increase in estimated current fire emissions (which effectively reduces the baseline sink) may decrease total atmospheric C emissions in the fire prevention scenario, but only given optimum conditions for all of the other parameters (for example 100% energy efficiency). Nevertheless, if fire frequency and intensity increase in the future[19], emissions savings through forest bioenergy production may become possible, especially in ecoregions where the sink is already weak.

Previous case studies showed that harvesting an old-growth forest in the Pacific Northwest[20] or increasing the thinning removals of temperate forests is likely to deteriorate the forest and wood

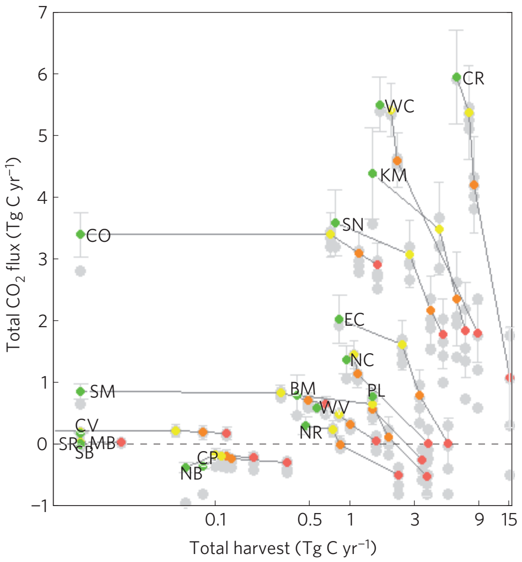

Figure 2 | Life-cycle assessment carbon emission trends by ecoregion under various management scenarios. The *x* axis is the total harvest (BAU + treatment) and the *y* axis is the total CO_2 flux in $Tg\,C\,yr^{-1}$ for each ecoregion. Coloured circles represent each scenario (green, BAU; yellow, fire prevention; orange, economically feasible; red, bioenergy production). Grey circles are the values for each sensitivity analysis set of parameters and the error bars represent the estimate uncertainty. The locations of the ecoregions indicated by labels are shown in Fig. 1a. For most ecoregions, the treatments increase emissions to the atmosphere.

product carbon stock[21]. However, these studies were limited to a handful of sites, relied primarily on modelled results[3,18] and did not account for the energy requirements of forest management and wood processing nor for the potential to substitute fossil fuels with bioenergy. We build on these results by including all ecoregions, all age classes (not just old-growth), three treatments including bioenergy production, and sector-based LCA. We found that even though forest sector emissions are compensated for by emission savings from bioenergy use, fewer forest fires, and wood product substitution, the end result is an increase in regional CO_2 emissions compared to BAU as long as the regional sink persists.

To determine a threshold NBP for which bioenergy management reduces atmospheric CO_2 emissions compared with BAU, we applied the same assumptions as used in the LCA. We found that if the NBP drops by 50–60 $g\,C\,m^{-2}\,yr^{-1}$ in currently productive ecoregions or 15–30 $g\,C\,m^{-2}\,yr^{-1}$ in currently less productive ecoregions, bioenergy management would come with CO_2 emissions savings compared to BAU (Fig 1c). Aggregating the ecoregion thresholds translates into a regional mean NBP of 45 $g\,C\,m^{-2}\,yr^{-1}$ or a 41% reduction on average. Reductions in NBP may occur due to increased mortality and/or decreased growth due to climate, fire, or insect outbreaks. However, reductions in NBP from increased harvest do not qualify because harvest increases emissions; wood carbon enters the products/bioenergy chain, where subsequent losses occur. We cannot predict from the data when the threshold NBP would occur because a high resolution process-based model with the ability to incorporate future climate, nitrogen deposition, age dynamics, disturbance and management would need to be used, which is beyond the scope of this study.

Ecoregion threshold NBP is dependent on the scenario treatment removals and area because the fire prevention treatment targets only those areas most likely to burn. For example, to reduce emissions in the Sierra Nevada, baseline NBP would have to decrease by as much as 84 $g\,C\,m^{-2}\,yr^{-1}$ for the bioenergy production scenario versus only 13 $g\,C\,m^{-2}\,yr^{-1}$ for the fire prevention scenario. In ecoregions where current sinks are marginal or weakened by climate, fire, or insect outbreaks there may be a combination of harvest intensity and bioenergy production that reduces forest sector emissions. In nine of the ecoregions where forests are carbon neutral or a source of CO_2 to the atmosphere and/or fire emissions are high for BAU, total CO_2 emissions under the fire prevention scenario could be reduced compared with BAU. They provide examples where management strategies for carbon emission reduction or sequestration should differ from the majority of the region; a one-size-fits-all approach will not work[22]. Also, large areas in the Northern Rockies (for example, Colorado and Wyoming) are at present experiencing increases in forest mortality due to beetle-kill, a trend which could continue in a warmer climate[23]. These areas may already be at or below the threshold NBP; if so, they could benefit from targeted bioenergy implementation. However, simply lowering current regional harvest intensities in areas where NBP is not weakened also reduces emissions (Supplemental Discussion and Fig. S3). Finally, as we have assumed large-scale implementation of these strategies in addition to BAU harvest, we may be overestimating future harvest even though harvest has declined significantly since 1990 because of restrictions placed on harvest on federal lands as part of the Northwest Forest Plan. If the strategies were used to substitute for BAU harvest, the outcome on NBP would be much different (that is, increased for the fire prevention scenario).

Our study is one of the first to provide full carbon accounting, including all of the sinks and sources of carbon emissions from the

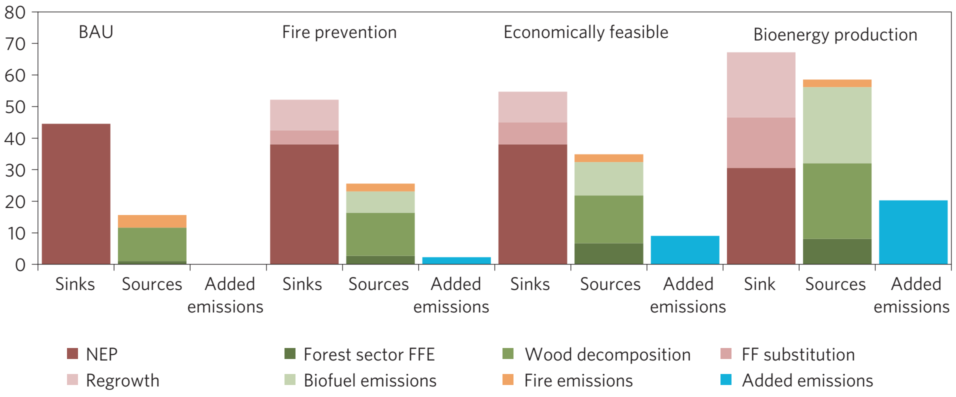

Figure 3 | Total US West Coast forest sector carbon sinks, sources and added emissions relative to BAU under various management scenarios. Units are in $Tg\,C\,yr^{-1}$. Life-cycle assessment estimates account for changes in carbon on land in addition to emissions associated with production, transport and usage of wood, and substitution and displacement of fossil fuel emissions associated with use and extraction. BAU results in the lowest anthropogenic emissions from the forest sector.

forestry sector and the current *in situ* sink, for such a large area. Given the diversity of woody ecosystems in the study region, ranging from highly productive temperate rainforests to less productive semi-arid woodlands, the trends in response probably apply to other temperate regions globally (Supplementary Table S1) where forests are at present a strong net carbon-sink (for example, Eastern US, China and Europe), although the extent of the effect remains to be established.

Greenhouse-gas reduction plans call for up to 10% reductions in emissions by 2020 and forest-derived fuels are being proposed as a carbon-neutral solution to reducing energy emissions. In all of our proposed scenarios, increases in harvest volume on the US West Coast will on average result in regional emission increases above current levels, although there are a few ecoregions where the tested scenarios could result in emission savings. As long as the current *in situ* NBP persists, increasing harvest volumes in support of bioenergy production is counterproductive for reducing CO_2 emissions. In this study region, the current *in situ* NBP in tree biomass, woody detritus and soil carbon is more beneficial in contributing to reduction of anthropogenic carbon dioxide emissions than increasing harvest to substitute fossil fuels with bioenergy from forests.

Although large uncertainty remains for regional forecasts to year 2050 or 2100, it is expected that forest carbon sinks will diminish over time because of ageing of the forests, saturation of the CO_2-fertilization and N-deposition effects, and increased mortality due to climate or insects[24,25]. This would require new assessments to identify management options appropriate for each situation. Carbon-management is not the sole criteria that should be considered when planning forest management. Our findings should thus also be evaluated against other ecosystem services, such as habitat, genetic and species diversity, watershed protection, and natural adaptation to climate change.

Methods

We quantified forest sequestration rates and test forest thinning scenarios across the region using a data-intensive approach which, for the first time, takes into account the diversity of forest characteristics and management. We combined Landsat remote sensing data with inventories and ancillary data to map current forest NEP, NBP, and changes in NBP with three thinning scenarios. The approach can be applied at multiple scales of analysis in other regions.

We combined spatially representative observational data from more than 6,000 federal Forest and Inventory Analysis plots (see Supplementary Methods and Table S7) with remote-sensing products on forest type, age and fire risk[26], a global data compilation of wood decomposition data and 200 supplementary plots[13] to provide new estimates of US West Coast (∼34 million hectares) forest biomass carbon stocks (Supplementary Table S8), NEP (the balance of photosynthesis and respiration) and NBP (the *in situ* net forest carbon-sink accounting for removals). We included all forestland in our analysis, across all age classes (20–800 years old) and management regimes. Plot values were aggregated by climatic region (ecoregion), age class and forest type, and this look-up table was used to assign a value to each associated 30 m pixel.

We use regional combustion coefficients to determine fire emissions. Only 3–8% of live tree biomass is actually combusted and emitted in high severity fire in the Pacific Northwest[28], contrary to other studies that report much higher emissions because they assume 30% of all aboveground woody biomass is consumed[27]. Although the latter contradicts extensive field observations[28,29] and modelling studies[30] in the region, we included 30% as the upper-end combustion factor in our sensitivity analysis (Supplementary Table S9).

In addition to the spatially explicit estimates of stocks and fluxes under current management or BAU (current forest harvest), three treatments were designed (fire prevention, economically feasible and bioenergy production; Supplementary Fig. S1a) to reflect the varying objectives of potential future forest management over the next 20 years; within the proposed time period for CO_2 reductions in the US. Areas were prioritized for treatment by fire risk and frequency. The proposed treatments result in additional harvest removals because we assume the current harvest rate for wood products will continue in the future. We limit our specific analysis to the short term because this is the timeframe suitable for policymakers, effectiveness of fire protection treatments, and an appropriate use of the data-driven approach. However, to investigate conditions (for example, sink saturation) that could invalidate our short-term results in the long term, we also calculated the *in situ* NBP at which the atmosphere may benefit from bioenergy removals.

Last, we studied the net effects of the thinning treatments on atmospheric CO_2 by LCA of carbon sources and sinks that includes the post-thinning NBP and wood use (harvest, transport, manufacturing, decomposition, wood product substitution, conversion and use of bioenergy, and displacement of fossil fuel extraction emissions; Supplementary Fig. S1b and Table S4,S5).

Received 19 July 2011; accepted 30 September 2011;

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Acknowledgements

This research was supported by the Office of Science (BER), US Department of Energy (DOE, Grant no. DE-FG02-07ER64361), for the North American Carbon Program study, 'Integrating Remote Sensing, Field Observations, and Models to Understand Disturbance and Climate Effects on the Carbon Balance of the West Coast US'. We further thank M. Harmon for discussions of wood product life-cycle assessment. T.W.H. is funded by a DOE global change education program PhD fellowship (GREF). S.L. is funded by ERC Starting Grant 242564.

Author contributions

T.W.H. designed and implemented the study with guidance from B.E.L. and S.L. T.W.H., S.L. and B.E.L. co-wrote the paper and S.L. contributed to parts of the analysis. C.W. provided essential data and methods for the analysis and valuable comments on the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.W.H.