Regional Carbon Dioxide Implications of Forest Bioenergy Production

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Title: Regional CO_2 implications of forest bioenergy production

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Summary: Mitigation strategies for reducing CO_2 emissions include substitution of fossil fuel with bioenergy from forests [1], where carbon emitted is expected to be re-captured 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 to 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} due 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.

Main text: 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]. In addition, forest carbon sequestration can take decades to centuries to return to pre-harvest levels, depending on 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 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) 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 (LCA; [6]). NBP is the annual net change of land-based forest carbon (NEP; photosynthesis minus respiration) after accounting for harvest removals and fire emissions.

Our study focused on the US West Coast (Washington, Oregon, and California), a diverse region due to the strong climatic gradient from the coast inland (300 – 2500 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] based on climate, soil, and species characteristics, and includes a broad range of productivity, age structures, fire regimes and topography. Mean net primary production (NPP) of the forest types range from 100 to 900 g C m^{-2} yr^{-1} (this study), falling within the global range of 100 to 1600 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 NEP ranging from -85 g C m^{-2} yr^{-1} in the dry Northern Basin to over 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 that 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 due 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 ('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 twenty 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 longer term predictions. Extending our study beyond a 20-year timeframe would over-stretch 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 (i.e. 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 Supplementary 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 scenario 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 -10 to 28% of 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 (e.g. 100% energy efficiency). Nevertheless, if fire frequency and intensity increase in the future [19], emissions savings via 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 product carbon stock [21]. However, these studies were limited to a handful of sites, relied primarily on modeled 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 to BAU, we applied the same assumptions 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 translate 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 does 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 utilized, 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 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 9 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 to 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]. Finally, large areas in the Northern Rockies (i.e. Colorado and Wyoming) are currently 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). Also, 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 due to 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 (i.e. increased for the Fire Prevention scenario).

Our study is one of the first to provide a full carbon accounting, including all of the sinks and sources of carbon emissions from the 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 likely apply to other temperate regions globally (Supplementary Table S1) where forests are currently a strong net carbon-sink (i.e. 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 aging 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 Summary

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 over 6000 FIA plots (see Supplementary Online Methods; Supplementary 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), net ecosystem production (NEP, the balance of photosynthesis and respiration), and net biome production (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 meter 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 [31], 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 modeling studies [30] in the region, we included 30% as the upper-end combustion factor in our sensitivity analysis (Supplemental Table S9).

In addition to the spatially explicit estimates of stocks and fluxes under current management or Business-As-Usual (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 U.S. 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 (i.e. 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.

Lastly, we studied the net effects of the thinning treatments on atmospheric CO_2 by a life cycle assessment (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 Supplementary Table S4 and S5).

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Supplementary Information is linked to the online version of the paper at www.nature.com/ncclimate.

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Author Contributions

T.H. designed and implemented the study with guidance from B.L and S.L.. T.H., S.L, and B.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.

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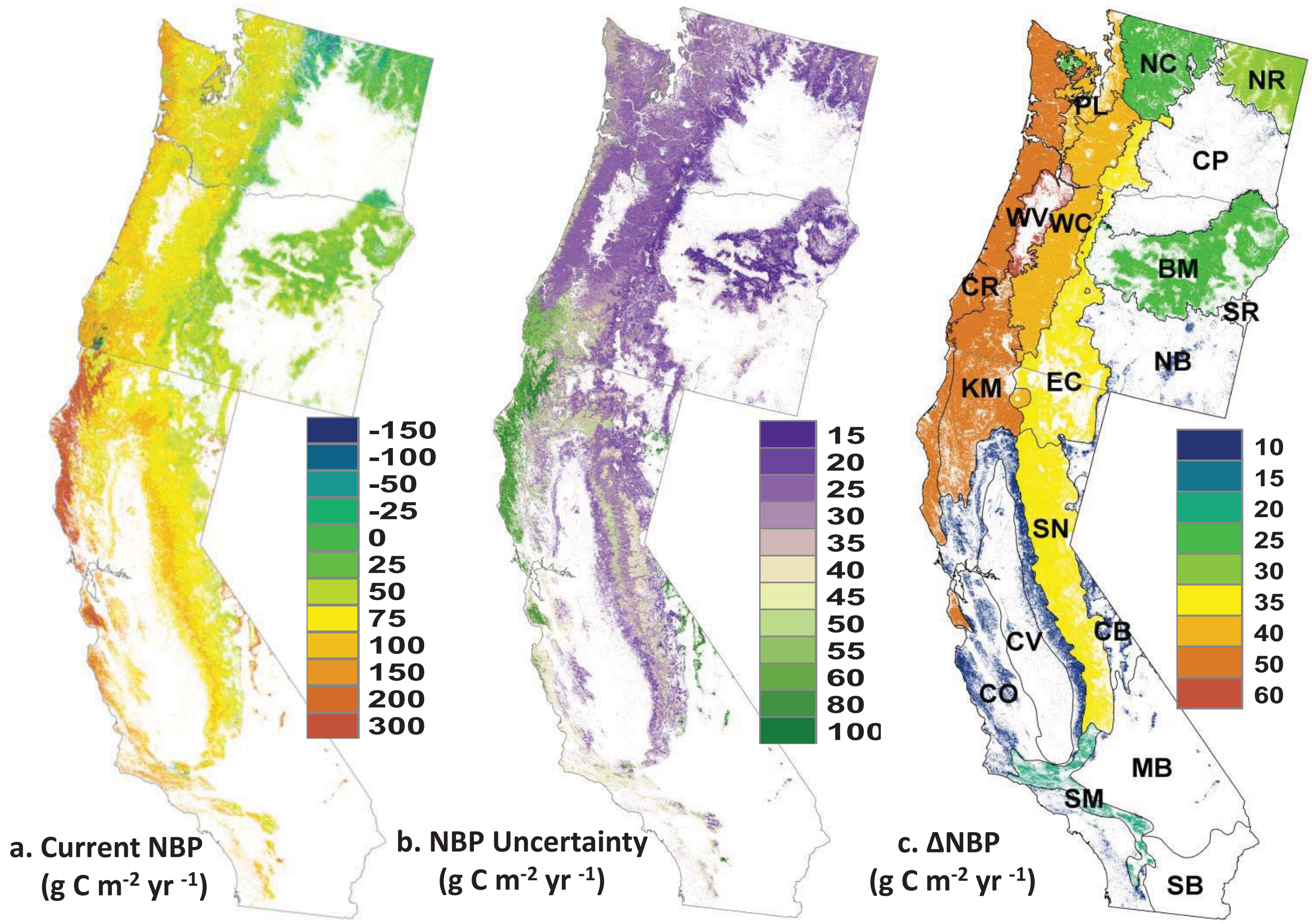
Figure Captions

Figure 1. **Maps of US west coast net biome productivity (NBP) and uncertainty for current and threshold conditions**. Map (a) shows current NBP or Business-as-Usual (BAU); positive values (warm colors) indicate forest sinks while negative values (cool colors) are carbon sources to the atmosphere. Map (b) show the current NBP uncertainty estimates and 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. Map (c) represents the amount NBP would need to decrease to reach a threshold NPB where bioenergy management may result in emission decreases to the atmosphere.

Figure 2. **Life Cycle Assessment carbon emission trends by ecoregion under varying 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. Colored circles represent each scenario (Green = BAU, Yellow = Fire Prevention, Orange = Economically Feasible, and Red = Bioenergy Production). Grey circles are the values for each sensitivity analysis set of parameters and the

error bars represent the estimate uncertainty. For most ecoregions, the treatments increase emissions to the atmosphere.

Figure 3. **Total US west coast forest sector carbon sinks, sources, and added emissions relative to BAU under varying 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.



-150
-100
-50
-25
0
25
50
75
100
150
200
300
a. Current NBP
(g C m-2 yr -1)
15
20
25
30
35
40
45
50
55
60
80
100
b. NBP Uncertainty
(g C m-2 yr -1)
NC
NR
PL
CP
WV
WC
BM
CR
SR
NB
KM
EC
SN
CB
CV
CO
MB
SM
SB
10
15
20
25
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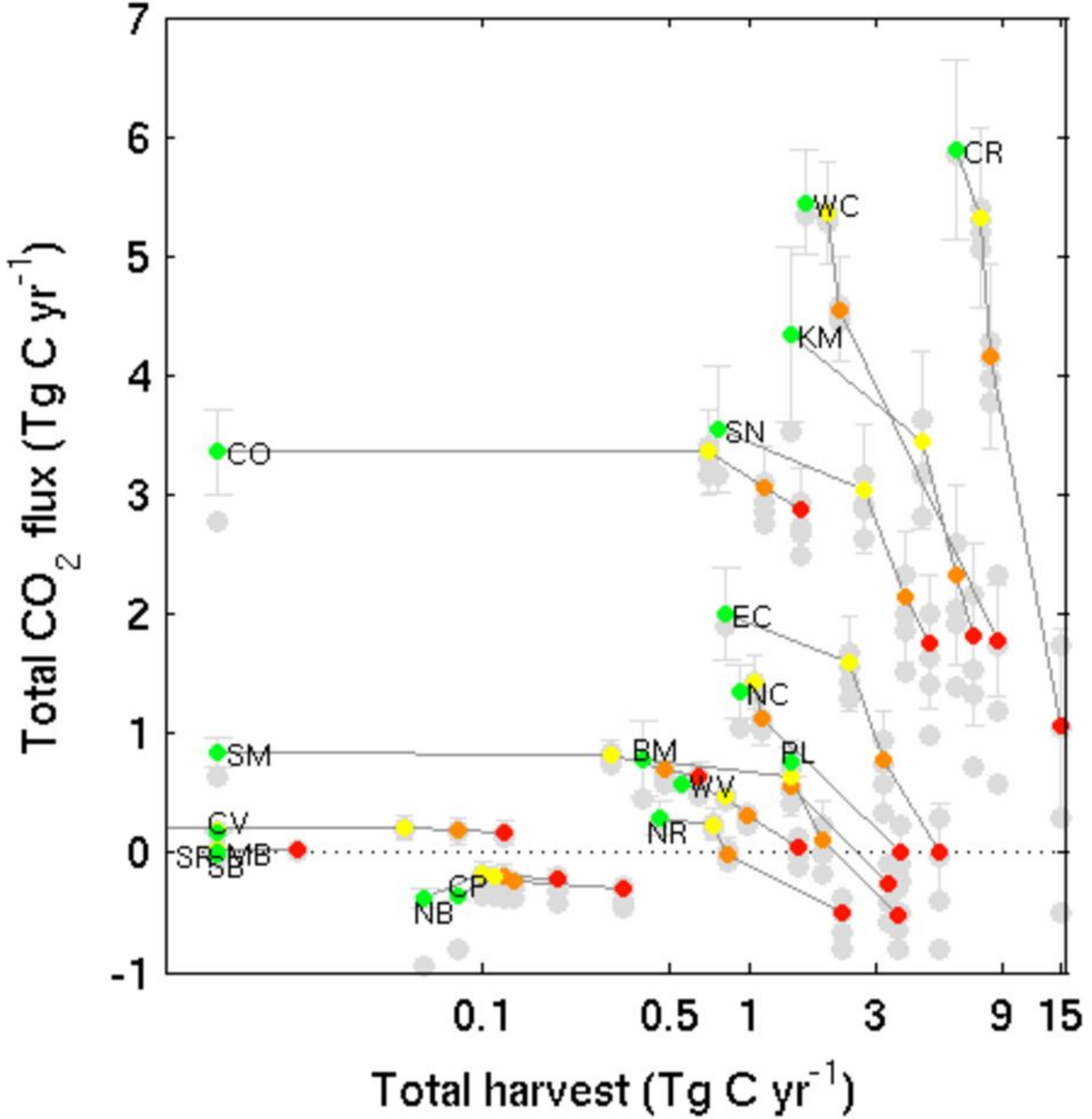
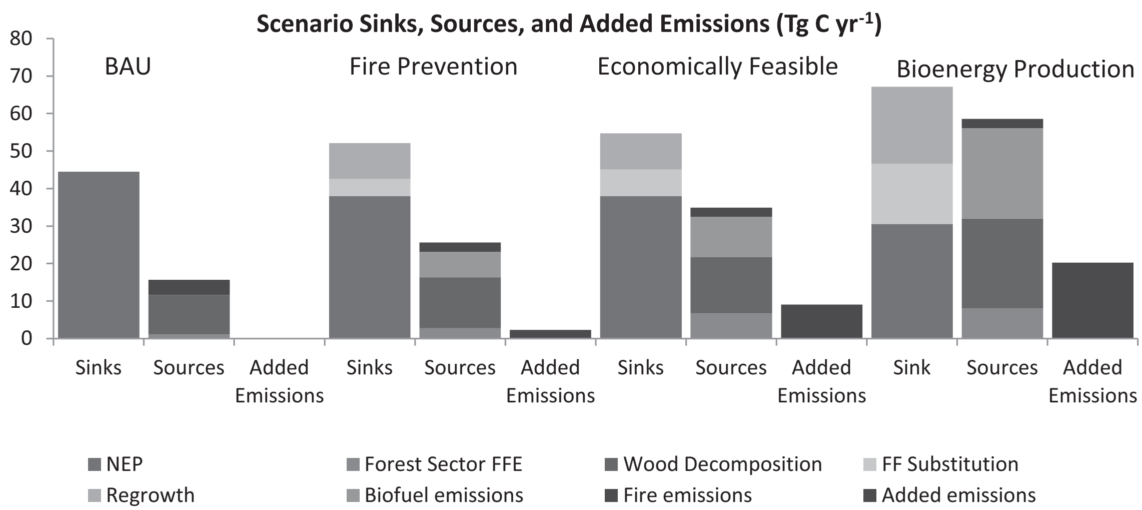
35
40
50
60
c. ΔNBP
(g C m-2 yr -1)



Total CO_2 flux (Tg C yr^{-1})
Total harvest (Tg C yr^{-1})
7
6
5
4
3
2
1
0
-1
0.1
0.5
1
3
9
15
CR
WC
KM
SN
CO
EC
NC
SM
BM
PL
WV
CV
NR
SR
MB
SB
CP
NB


Scenario Sinks, Sources, and Added Emissions (Tg C yr-1)
80
70
60
50
40
30
20
10
0
BAU
Fire Prevention
Economically Feasible
Bioenergy Production
Sinks
Sources
Added Emissions
Sinks
Sources
Added Emissions
Sinks
Sources
Added Emissions
Sink
Sources
Added Emissions
NEP
Forest Sector FFE
Wood Decomposition
FF Substitution
Regrowth
Biofuel emissions
Fire emissions
Added emissions