Supporting Information

Interactive effects of environmental change and management strategies on regional forest carbon emissions

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Supporting Methods

Methods for formatting regional downscaled climate forcing dataset for use by CLM: The regional downscaled datasets includes daily precipitation, minimum and maximum temperature, and wind speed. To format the datasets for use by CLM4, the required shortwave radiation and relative humidity were calculated incorporating algorithms from DAYMET[1], and methods for sub-daily calculations as described by[2]. We created hourly atmospheric forcing data files to be used in offline CLM4 simulations. Source data files are from the climate impacts group (Salathe, 2008) and are downscaled historical and future ECHAM5 SRES A2 (middle of the road scenario) and IPSL_CM4 A2 (highest warming scenario) files specifically designed for use in the Pacific Northwest http://www.cses.washington.edu/data/ipccar4/.

The specific variable calculations are as follows:

1. Air temperature: The regional input files provide daily minimum and maximum temperature. Daylength was used to apply a diurnal pattern to the minimum and maximum temperatures.
2. Wind speed: The regional input files provide daily estimates of wind in m/s. Wind speed was assumed to be constant for sub-daily time steps.
3. Relative humidity: Percent relative humidity was calculated using the hourly mean temperatures calculated above and vapor pressure.
    a. DAYMET and MTClim algorithms were used to calculate vapor pressure from temperature, precipitation, and solar radiation. Vapor pressure was then used to calculate relative humidity (RH):
        i. RH = 100 * (VP/SVP); where VP = the average daily vapor pressure in Pascals and SVP = the saturation vapor pressure. SVP varies with temperature.
        ii. SVP = 610.78 * exp(T/(T+238.3)*17.2694); where T is the current temperature in degrees C.
4. Precipitation: The input files provide daily sums of precipitation. This needed to be distributed over the day, but not evenly. CLM will evaporate off the water too quickly and none of it will reach the plant roots. The precipitation was split into 3 equal amounts of precipitation and dropped at 8 hour intervals similar to the NCEP dataset where it is dropped at 6 hour intervals. We recognize more sophisticated diurnal precipitation algorithms using

site observations could be developed, but more locations with sub-daily patterns of rainfall would be necessary for the region.

6. FSDS (Incoming shortwave radiation or incident solar): FSDS is not provided in the input files. Again, DAYMET algorithms were used. The inputs required are daily T_{min}, T_{max}, precipitation, latitude, longitude, and elevation all of which are available from the downscaled regional dataset and other topographical datasets.

Life-cycle assessment: 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). For each scenario, the net flux of carbon from or to the atmosphere (net carbon emissions; Net C_e) over 90 years (2010-2100) was calculated as the difference between the sources and the sinks following this process:

Net carbon emissions (Net C_e) = NBP + Total Harvest – WD1 – WD2 – Wood Industry FFE – Bioenergy Emissions + Bioenergy Substitution + FF Well-To-Tank Emissions displacement + Wood Substitution (Eq. 1)

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. Total harvest is added back to NBP to represent the theoretical amount of wood that could be stored in a wood product or converted to bioenergy if the process was 100% efficient. The WD1 variable accounts for the wood losses because wood product conversion is not 100% efficient although up to 25% of harvest and mill residues are used internally at some processing facilities for bioenergy offsetting a portion of the losses[3]. We incorporated potential mill use of current harvest residues as part of the BAU scenario. This is different from the LCA described in[4] where current use of forest residues for bioenergy was not included as part of the BAU net emissions calculations. This does not reduce the WD1 term in the equation (the wood is still combusted and emissions still occur), but it increases the bioenergy substitution for fossil fuel emissions. Net C_e (net emissions from LCA equation) values are positive for carbon sinks and negative for carbon sources. In the figures and tables, 'delta Net C_e' refers to the difference between the management scenario Net C_e values and the BAU value. Net C_e can be positive in both cases, but negative 'delta Net C_e' values indicate

increased emissions (or decreased uptake) compared to BAU. In other words, the sink strength is weakened.

To quantify the change in Net C_e for each scenario, we calculate the difference between each scenario and the BAU Net C_e. 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). 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/). FFE and 'Emissions' variables in the equation include release of carbon from woody biomass combustion and FFE associated with harvest[5, 6], transport of both harvested material and end-use products[7, 8], and processing and manufacturing of wood products[8] and bioenergy[9]. We assumed a transport distance of 75km for the harvested wood and 150km for the wood products[5]. 'Decomposition' includes loss of material through decomposition or combustion during the manufacturing of wood products and the percentage of wood products that are expected to no longer be in-use at the end of the treatment period[10].

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[11] and decay at a net rate of 1% per year[10, 12] after accounting for the portion stored in landfills. Using values provided by[10], 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 using the net decay rate. The remaining non-merchantable wood from harvest was used for combined heat and power (CHP) bioenergy. We also accounted for the associated emissions for both conversion to wood chips and the combustion emissions.

Fossil fuel substitution with bioenergy was calculated as biomass combustion for CHP compared to fossil fuel sources. 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 35.5 GJ per ton in coal and 58 GJ per ton in natural gas) because fossil fuels have a lower heating value[13]. The conversion efficiency of biomass to CHP compared to the reference fossil fuel source ranges

from 20-80% depending on the power plant and the fossil fuel source being replaced[14]. The US average conversion efficiency is 51% given a combination of low to highly efficient plants and the US mix of fossil fuel CHP production (coal, natural gas and petroleum/oil). State annual fossil fuel emissions, energy sources, and consumption were acquired from the Oregon Department of Energy (http://www.oregon.gov/energy/pages/oregons_electric_power_mix.aspx). The Oregon average conversion efficiency given the state energy mix is very close to the US average at 50%. This was also an improvement over the LCA used in[4] where the fossil fuel source replaced was petroleum/oil only.

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 carbon emitted per unit of fossil fuel energy varies widely by source fuel, but average WTT emissions are approximately 15% of total emissions (WTW)[15], or 12 g CO_2 per MJ of energy. We have included these emissions in the Wood Industry FFE and we have added a WTT displacement benefit along with the bioenergy substitution benefit.

Finally, we add potential wood product substitution benefits for replacement of fossil fuel derived products. 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[16] and 26% for concrete[17]. We assumed these rates will continue into the future for new residential housing and applied a 36% wood substitution benefit of the final structural wood product pool to represent optimal substitution rates.

Sensitivity Analysis: Many of the factors in the LCA are associated with a range of values depending on assumptions made regarding transport distance, fossil fuel replaced, wood substitution rates, energy conversion efficiency, wood use efficiency, etc. To account for the variation, we varied the coefficients over the range of reported values, resulting in 20 LCA estimates of net C emissions. The parameters varied are reported in Supporting Table 3. We use the standard errors of the sensitivity analysis in our overall measure of uncertainty (see below).

Uncertainty: We use the propagation of error approach to combine the standard errors or uncertainty estimates of each flux component as a measure of uncertainty. We use the following equations as advised by the 2006 IPCC good practice guidelines report and used by[18]:

(1) Combining Uncertainties (percentages)

$$U_{total} = \sqrt{U_1^2 + U_2^2 + \cdots + U_n^2}$$

Where, U_{total} = the percentage uncertainty in the product of the quantities (half the 95 percent confidence interval divided by the total and expressed as a percentage); and U_n = the percentage uncertainties associated with each of the quantities.

(2) Combining Uncertainties (individual associated uncertainties)

$$U_{total} = \frac{\sqrt{(U_1 * x_1)^2 + (U_2 * x_2)^2 + \cdots + (U_n * x_n)^2}}{|x_1 + x_2 + \cdots + x_n|}$$

Where, U_{total} = the percentage uncertainty in the sum of the quantities (half the 95 percent confidence interval divided by the total (i.e., mean) and expressed as a percentage); and x_n and U_n = the uncertain quantities and the percentage uncertainties associated with them, respectively.

The total uncertainty of our carbon flux estimates is calculated as a combination of the calibration dataset (observation) uncertainty and the standard error (expressed as a percentage) from the four forcing scenarios using equation 1 and 2. Equation 2 was used to calculate an overall uncertainty percentage for NBP by combining the calibration dataset uncertainties in NPP and R_h and NEP. We were unable to quantify the uncertainty associated with model structure which would be part of this term, but because we spent considerable effort in developing the model for use in the region we feel most of the uncertainty lies in the observations used to both calibrate and evaluate the model (see[19]). Finally, we combine uncertainty from our carbon flux estimates and the LCA to calculate an overall uncertainty for the final net carbon emissions using equation 1.

There is very little uncertainty in our parameter values as we have over 300 field plots in the region with observed values for the majority of the tree species (e.g specific leaf area, foliar carbon nitrogen ratios, litter carbon nitrogen ratios, and leaf longevity). We modified the PFTs to be ecoregion and forest type specific so that the parameter values were not a broad characterization of the evergreen needleleaf PFT, but rather a subclass with regional variation.

Supporting Table 1. Ecoregion characteristics including forested area, mean stand ages by ownership, dominant forest types, mean annual precipitation (MAP), mean annual temperature (MAT), and proposed bioenergy management scenarios. Ecoregions are listed from high to low MAP. Statistics are reported using the Federal Forest Inventory Database (http://www.fia.fs.fed.us/) and calculated from climate forcing datasets. NPP was calculated in[4].

Ecoregion	**Forest Hectares (% total)**	**Stand Age Private/Public**	**Dominant Forest Types**	**MAP (mm yr^{-1})**	**MAT (C°)**	**NPP (g C m^{-1} yr^{-1})**
Coast Range (CR)	2,043,332 (17)	34 / 75	Douglas-fir, Sitka Spruce, Redwood, Western Red Cedar, Fir-hemlock	1742	11.0	750
West Cascades (WC)	2,693,263 (22)	50 / 140	Douglas-fir, Hemlock, Mixed Conifer, Red Fir, Western Red Cedar	1688	8.8	550
Klamath Mountains (KM)	1,302,111 (11)	59 / 106	Mixed Conifer, Mixed Evergreen, Red Fir, Douglas-fir, Riparian, Oak	1549	11.5	616
Willamette Valley (WV)	501,793 (4)	43 / 61	Douglas-fir, Hemlock, Riparian	1280	11.0	500
East Cascades (EC)	2,099,866 (17)	64 / 94	Ponderosa Pine, Mixed Conifer, Juniper, Pine, Red Fir	630	9.1	300
Blue Mountains (BM)	3,364,151 (27)	71 /100	Mixed Conifer, Ponderosa Pine, Juniper, Spruce-Fir	552	7.3	265
Columbia Plateau (CP)	88,922 (<1)	80 / 47	Mixed Conifer, Ponderosa Pine, Riparian	330	9.7	260
Northern Basin (NB)	253,690 (2)	80 / 130	Juniper, Aspen, Pinyon-Juniper, Ponderosa Pine, Mountain Mahogany	304	9.7	130

Supporting Table 2. CLM4 future simulations for control, baseline, and bioenergy management scenarios. Transient CO_2, nitrogen deposition (Ndep), and land cover files are annual files covering the period from 2010-2100.

Name	Description	Climate	CO_2 / Ndep	Land Cover	Harvest Rate	Insect Mortality	Fire
			Baseline				
BAU_E4.5	Business-as-Usual	ECHAM	RCP 4.5	BAU	BAU	Yes	Yes
BAU_E8.5	Business-as-Usual	ECHAM	RCP 8.5	BAU	BAU	Yes	Yes
BAU_I4.5	Business-as-Usual	IPSL	RCP 4.5	BAU	BAU	Yes	Yes
BAU_I4.5	Business-as-Usual	IPSL	RCP 8.5	BAU	BAU	Yes	Yes
			Proposed Management				
Thin_E4.5	Thin at risk forests	ECHAM	RCP 4.5	transient	None	No	Yes
Thin_E8.5	Thin at risk forests	ECHAM	RCP 8.5	transient	None	No	Yes
Thin_I4.5	Thin at risk forests	IPSL	RCP 4.5	transient	None	No	Yes
Thin_I8.5	Thin at risk forests	IPSL	RCP 8.5	transient	None	No	Yes
CC_E4.5	Clearcut mesic forests	ECHAM	RCP 4.5	transient	None	Yes	Yes
CC_E8.5	Clearcut mesic forests	ECHAM	RCP 8.5	transient	None	Yes	Yes
CC_I4.5	Clearcut mesic forests	IPSL	RCP 4.5	transient	None	Yes	Yes
CC_I8.5	Clearcut mesic forests	IPSL	RCP 8.5	transient	None	Yes	Yes
TC_E4.5	Thin + clearcut	ECHAM	RCP 4.5	transient	50 or 95%	No	Yes
TC_E8.5	Thin + clearcut	ECHAM	RCP 8.5	transient	50 or 95%	No	Yes
TC_I4.5	Thin + clearcut	IPSL	RCP 4.5	transient	50 or 95%	No	Yes
TC_I8.5	Thin + clearcut	IPSL	RCP 8.5	transient	50 or 95%	No	Yes
			Control				
CLIM_E	Vary climate	ECHAM	constant[1]	constant	none	No	No
CLIM_E_4.5	Vary climate, CO_2, Ndep	ECHAM	RCP 4.5[2]	constant	none	No	No
CLIM_E_8.5	Vary climate, CO_2, Ndep	ECHAM	RCP 8.5[3]	constant	none	No	No
CLIM_I	Vary climate	IPSL	constant	constant	none	No	No
CLIM_I_4.5	Vary climate, CO_2, Ndep	IPSL	RCP 4.5	constant	none	No	No
CLIM_I_8.5	Vary climate, CO_2, Ndep	IPSL	RCP 8.5	constant	none	No	No

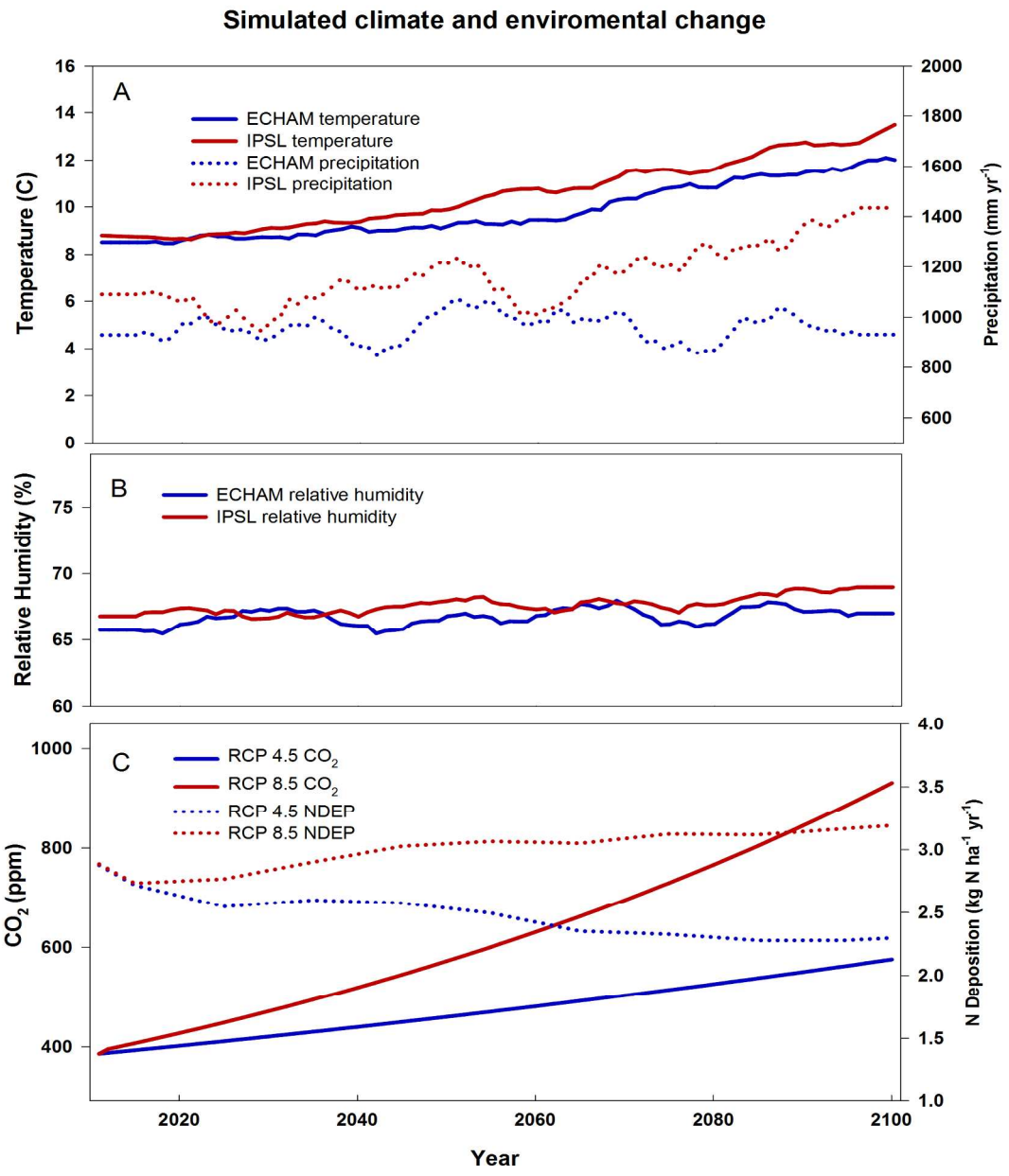
[1] constant level is based on the value from the year 2000

[2] RCP 4.5 refers to the IPCC representative concentration pathway where CO_2 rises to ~550 ppm by the end of the century

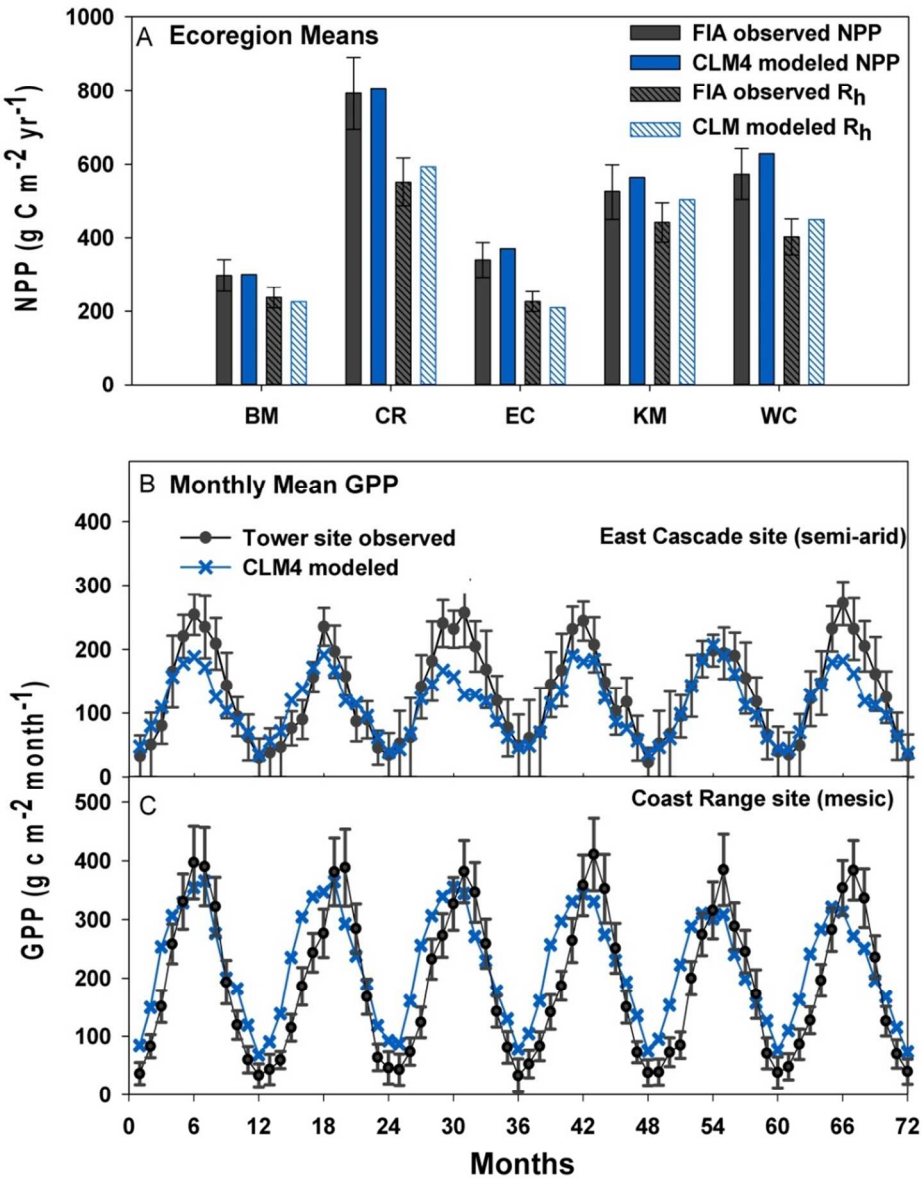
[3] RCP 8.5 refers to the IPCC representative concentration pathway where CO_2 rises to ~900 ppm by the end of the century

Supporting Table 3. LCA parameters varied for sensitivity analysis. We only included the parameters where there is a high level of variation and/or uncertainty in the estimate.

Parameter	Description	Lower Value	Upper Value	Source
Wood product decomposition	Both the short and long-term wood product pools vary in the rate of decomposition depending on end-use, eventual deposit in landfills, and recycling of used products	1% per year	2% per year	[3, 10, 11]
Wood industry fossil fuel WTT emissions	Fossil fuel emissions associated with acquisition and production of fossil fuels used by the industry (well-to-tank).	5% of industry fossil fuel usage	25% of industry fossil fuel usage	[15]
Conversion efficiency in CHP operations (fossil fuel substitution rate)	This value affects the substitution benefit of the fuel. Fossil fuels have higher energy contents than wood. The more efficient the conversion of wood to heat and/or power results in a better fossil fuel substitution. This depends on the power plant technology and fossil fuel energy source replaced; i.e. oil has a higher energy content than coal.	20% compared to fossil fuels	80% compared to fossil fuels	[14]
Fossil Fuel WTT emissions displacement by substitution	Varies with fossil fuel replaced; i.e. the carbon intensity of oil production is higher than natural gas resulting in a higher displacement benefit	5% of substituted fossil fuel emissions	25% of substituted fossil fuel emissions	[15]
Wood substitution	Wood product substitution depends on a variety of factors, but primarily on residential housing development	15% replacement benefit (reduction in emissions)	36% replacement benefit	[16]



Supporting Figure 1. Predicted regional climate and environmental change for the moderate (blue; ECHAM) and high impact (red; IPSL) climate scenarios for: (A) annual temperature (solid) and precipitation (dotted) from 2010 to 2100, (B) associated changes to relative humidity, and (C) annual CO2 concentrations (solid) for RCP 4.5 (blue) and RCP 8.5 (red) and associated changes to nitrogen deposition (Ndep; dotted). The y-axis varies in units for each variable.



Supporting Figure 2. Model evaluation of ecoregion mean annual NPP and R_h and simulated monthly GPP versus observed GPP at two FLUNET eddy-covariance tower sites in the study region using the modified version of the CLM model (figure adapted from Hudiburg et.al, 2013). A) Modeled NPP and R_h compared with observed NPP and R_h calculated from forest inventory data from 2001-2006. B) Monthly GPP for the years 2002 -2007 at the Metolius mature pine site in Oregon, USA. Solid black circles and bars represent tower observations, and blue crosses and bars are modeled GPP. C) Monthly GPP for 1998-2003 at the Campbell River fir site, British Columbia, Canada. Black error bars represent observed estimate uncertainty in all panels.

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