Supporting Information

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SI Materials and Methods

Current Stocks and Fluxes. Live tree biomass and dead tree biomass were calculated using ecoregion- and species-specific allometric equations that use both height and diameter (DBH) in the equations for predicting bole and coarse root volume as well as bark, branch, and foliage biomass. Fine root biomass was calculated from coarse root biomass (1). In cases where an ecoregion- and or species-specific equation was not available, substitutions were made by genus or like form (e.g., pines with tap roots). Ecoregion-specific wood density data were used to convert bole and coarse root volume to biomass with substitutions made by genus, like form, etc. Dead tree branch, bark, and foliage biomass were adjusted based on decay class (e.g., a decay class of "0" indicates many branches and some foliage are still present versus higher decay classes indicating more to complete branch, bark, or foliage loss). Downed dead wood biomass was calculated by FIADB v.4.0 methods (line transect method for piece volume by size class), and species- and size-specific wood densities were reduced by decay class. Stump abundance was estimated from a relationship between stand age and the number of tree records on the plot recorded as "cut or removed." Stump volume was calculated as a cylinder 1 ft in height with an average DBH by species and age class, and was converted to biomass using decay class-adjusted, species-specific wood densities as for downed wood. Understory biomass (seedlings and shrubs) was calculated from shrub volume (percent cover and height), combined with an allometric equation database developed from harvested shrubs in previous studies (2–4) and from the shrub extension to BIOPAK (5). Again, substitution for species not represented in the database was applied by genus, family, like form, etc. Litter and duff biomass estimates were the product of plot average depth and material carbon density provided for each forest type in the FIA database tables. Conversions to carbon were calculated based on a carbon density of 0.5 for all live pools (Tables S1 and S2).

For NPP and NEP, we used a mass-balance approach with data from FIA and >200 regional study plots. NPP of woody components (branches and stems) was computed from the difference in biomass at two points in time divided by the measurement interval. Previous diameter and height for each tree were used to calculate the previous biomass. Previous diameter was derived from current diameter and radial increment. Previous height was recorded on remeasured trees or modeled for unmeasured trees in the previous inventory using diameter-height equations (3). Woody shrub, foliage, and fine root NPP were calculated from the additional regional plot data (2).

NEP was computed from NPP minus Rh using a mass balance approach (6):

$$\text{NEP} = \text{aboveground NPP} - \text{dead wood decomposition} - \text{litterfall} + \Delta\ \text{root} + \Delta\ \text{soil C}.$$

We estimated NEP from aboveground NPP minus dead wood decomposition minus litterfall plus the change in coarse and fine root carbon and the change in soil carbon (4). We assumed that annual soil respiration is in balance with litterfall, belowground carbon allocation, and change in carbon in roots and soils. Deadwood decomposition was estimated using a global dataset of wood decomposition rates for tree species modified by response to temperature, precipitation, diameter, and position [standing or downed wood (7)]. Foliage NPP was estimated from foliage biomass divided by leaf retention time. Litterfall was estimated from foliage NPP and 20% mass loss on abscission. We assumed litterfall turns over annually (losses equal additions to litter pool). Change in coarse root carbon was calculated as the difference between coarse root NPP and decomposition of dead tree and stump coarse roots. Change in soil C was estimated from an observed relationship with stand age calculated from a synthesis of chronosequence plot data in Oregon (8), where stand ages <50 y are losing soil carbon at the rate of 0.05–1.0 Mg C $ha^{-1} \cdot y^{-1}$, and then increased at rates of 0.01–0.05 Mg C $ha^{-1} \cdot y^{-1}$ until no net change at ∼200 y. We assumed no change in fine root carbon.

NECB is NEP minus losses due to fire or harvest, and it determines whether a forest is a net source or sink of atmospheric carbon dioxide (9). Harvest histories were constructed using Oregon Department of Forestry historical datasets. Harvest volumes were converted to biomass removals using wood density data (10) (Tables S3 and S4). Fire emissions were computed using annual burn area estimates for each severity class (low, moderate, and high; Monitoring Trends in Burn Severity database), biomass data, and region-specific combustion factors for each pool [large stems, small stems, downed dead wood, understory vegetation, standing dead wood, and litter pools (11, 12)]. Monitoring Trends in Burn Severity dataset burn areas are at least 404 ha in size (1,000 acres), which accounts for 92% of the total burn area of forests in the western United States (13). The Monitoring Trends in Burn Severity data on burn area are consistently correlated with field measurements in conifer forests of the western United States.

Uncertainty Analysis. For the observation-based analysis, Monte Carlo simulations were used to conduct an uncertainty analysis with the mean and SDs for NPP and Rh calculated using several approaches. For NPP, three 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 with a DBH-only national set and with 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 with decay constants that were allowed to vary by genus, precipitation, and temperature or by class, precipitation, and temperature. Finally, uncertainty in NECB was calculated as the combined uncertainty of NEP, fire emissions (10%), harvest emissions (7%), and land cover estimates (10%) using the propagation of error approach. Uncertainty in CLM4.5 model simulations and LCA was quantified by combining the uncertainty in the observations used to evaluate the model, the uncertainty in input datasets (e.g., remote sensing), and the uncertainty in the LCA coefficients (14).

Methods for Tables S3–S5 are provided in the main text.

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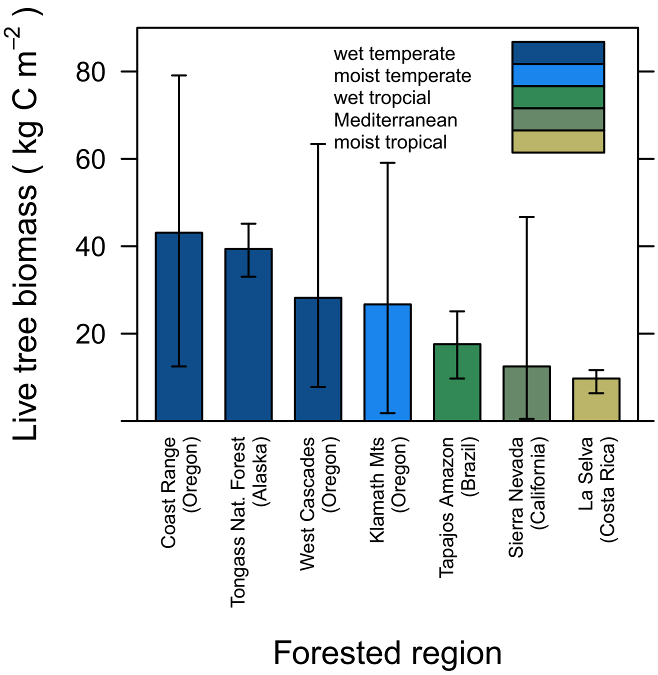

Fig. S1. Live tree biomass in primary forests from Oregon and other regions. Live tree biomass (kg C m^{-2}; aboveground + belowground) for primary forests in Oregon's mesic ecoregions relative to primary forests in other parts of the world. Each bar denotes median live tree biomass in a region, while whiskers denote minimum and maximum live tree biomass across a network of plots. Summaries for Oregon and California were derived using data from one of our earlier studies for stands >300 y old (1). Summaries from southern Alaska (2), Brazil (3), and Costa Rica (4) were drawn from the literature, with belowground biomass estimated using root/shoot ratios for each biome (5) and biomass assumed to be 50% carbon. Mts, Mountains.

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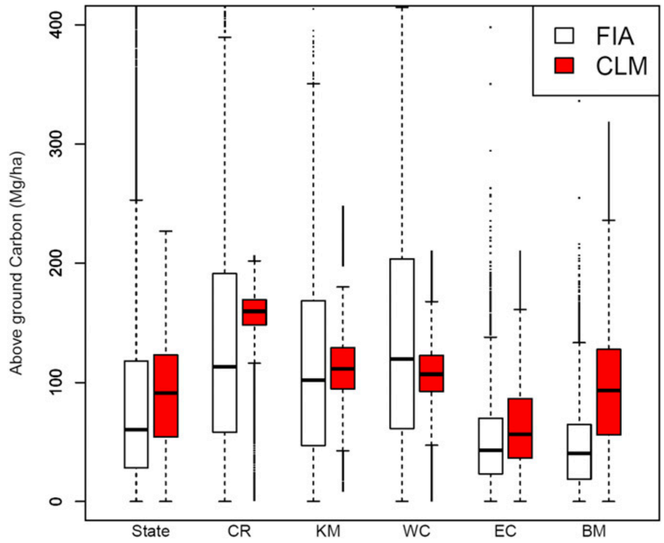

Fig. S2. Evaluation of simulated aboveground tree carbon. Comparison between observed aboveground tree carbon stocks derived from FIA surveys and simulated by CLM4.5. Estimates are provided for the state and by ecoregion. Ecoregions include the Coastal Range (CR), Klamath Mountains (KM), Western Cascades (WC), Eastern Cascades (EC), and Blue Mountains (BM). The intrabox line denotes median value, box edges denote the 25th and 75th percentiles, and whiskers extend the interquartile range 1.5-fold.

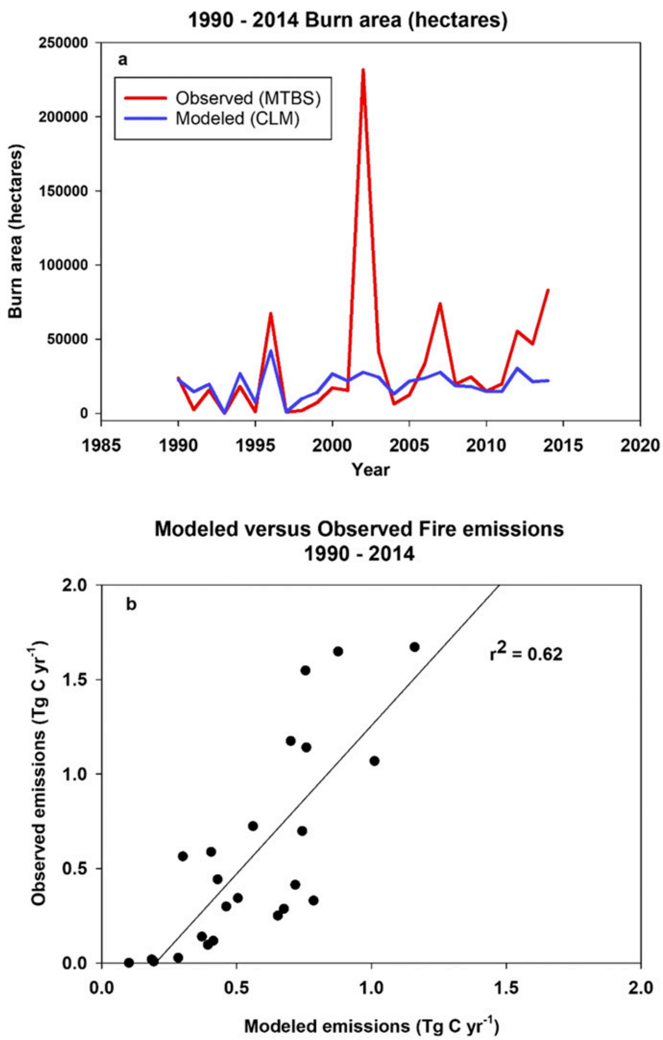

Fig. S3. Evaluation of simulated total burn area and emissions. Comparison of total area burned (*A*) and emissions (*B*) from 1990 to 2014 for Oregon as derived from the Monitoring Trends in Burn Severity (MTBS) dataset and as simulated by CLM 4.5. The Biscuit Fire emissions were removed for the comparison in *B* to assess the model's ability to predict average fire conditions rather than large anomalous fires. The MTBS dataset is based on Landsat satellite observations.

Table S1. State total carbon stocks by ecoregion (Tg·C)

Ecoregion	Live trees	Dead trees	CWD*	FWD	Shrubs	Litter and duff	Soil C	Total C
2001–2005								
Blue Mountains	230.32	39.49	35.74	0.32	2.55	44.88	226.18	579
West Cascades	481.52	52.96	48.05	0.77	6.21	43.62	249.98	883
Coast Range	328.87	18.87	31.43	0.80	8.19	42.30	211.47	641
Columbia Plateau	2.03	0.32	0.31	0.00	0.02	0.39	1.95	5
East Cascades	137.16	21.62	22.44	0.19	1.78	31.72	129.93	345
Klamath Mountains	214.59	24.29	19.97	0.34	2.72	18.50	112.53	393
Northern Basin	11.16	2.17	1.55	0.02	0.10	2.27	10.95	28
Willamette Valley	48.91	5.31	4.87	0.08	0.62	4.44	25.57	90
State total	1,454.57	165.03	164.37	2.52	22.20	188.13	968.57	2,965
2006–2010								
Blue Mountains	235.71	37.13	35.68	0.31	2.70	40.74	224.01	576
West Cascades	481.45	53.38	47.77	0.78	6.31	43.00	249.83	883
Coast Range	334.77	22.74	32.17	0.87	8.44	38.91	213.40	651
Columbia Plateau	2.10	0.30	0.32	0.00	0.02	0.35	1.94	5
East Cascades	141.64	19.04	19.27	0.20	2.04	19.91	128.84	331
Klamath Mountains	215.64	24.67	20.31	0.35	2.76	18.65	113.46	396
Northern Basin	11.22	2.13	1.51	0.02	0.12	2.19	10.95	28
Willamette Valley	49.19	5.36	4.88	0.08	0.64	4.44	25.67	90
State total	1,471.71	164.75	161.89	2.62	23.04	168.20	968.10	2,960
2011–2015								
Blue Mountains	238.20	38.34	37.63	0.33	2.88	42.08	224.98	584
West Cascades	489.55	54.02	47.77	0.76	5.88	42.99	249.48	890
Coast Range	379.02	30.02	32.79	0.79	5.91	38.13	209.50	696
Columbia Plateau	2.09	0.31	0.34	0.00	0.03	0.37	1.94	5
East Cascades	140.54	26.38	18.57	0.18	2.05	25.42	130.37	344
Klamath Mountains	217.21	24.59	20.11	0.35	2.58	18.29	112.83	396
Willamette Valley	12.20	2.33	1.60	0.02	0.14	2.41	10.92	30
Northern Basin	49.89	5.44	4.90	0.08	0.60	4.40	25.57	91
State total	1,528.70	181.42	163.72	2.52	20.06	174.10	965.58	3,036

Values are derived from inventory (FIA) and >200 intensive plots. FWD, fine woody debris.
*Coarse woody debris (CWD) does not include stumps.

Table S2. State mean carbon stocks by ecoregion (Mg C ha^{-1})

Ecoregion	Live trees	Dead trees	CWD	FWD	Shrubs	Litter and duff	Soil C	Total C
2001–2005								
Blue Mountains	62.13	10.65	9.64	0.09	0.69	12.11	61.02	156.32
West Cascades	172.13	18.93	17.18	0.28	2.22	15.59	89.36	315.69
Coast Range	155.91	8.95	14.90	0.38	3.88	20.05	100.25	304.32
Columbia Plateau	54.13	8.49	8.28	0.07	0.62	10.41	51.86	133.87
East Cascades	61.37	9.67	10.04	0.09	0.80	14.19	58.13	154.29
Klamath Mountains	171.33	19.39	15.94	0.27	2.17	14.77	89.85	313.73
Northern Basin	60.13	11.68	8.35	0.09	0.53	12.22	59.01	152.01
Willamette Valley	168.49	18.30	16.77	0.27	2.15	15.31	88.08	309.38
State average	115.31	13.08	13.03	0.20	1.76	14.91	76.78	235.07
2006–2010								
Blue Mountains	63.58	10.02	9.63	0.08	0.73	10.99	60.43	155.46
West Cascades	172.10	19.08	17.07	0.28	2.26	15.37	89.31	315.47
Coast Range	158.70	10.78	15.25	0.41	4.00	18.45	101.17	308.76
Columbia Plateau	55.94	8.03	8.44	0.07	0.64	9.39	51.54	134.05
East Cascades	63.37	8.52	8.62	0.09	0.91	8.91	57.65	148.07
Klamath Mountains	172.17	19.70	16.21	0.28	2.20	14.89	90.59	316.05
Northern Basin	60.43	11.46	8.12	0.10	0.64	11.78	58.98	151.50
Willamette Valley	169.43	18.47	16.81	0.28	2.20	15.30	88.41	310.90
State average	116.66	13.06	12.83	0.21	1.83	13.33	76.74	234.67
2011–2015								
Blue Mountains	64.26	10.34	10.15	0.09	0.78	11.35	60.69	157.66
West Cascades	175.00	19.31	17.08	0.27	2.10	15.37	89.18	318.31
Coast Range	179.68	14.23	15.55	0.37	2.80	18.08	99.32	330.02
Columbia Plateau	55.63	8.38	9.11	0.08	0.69	9.97	51.69	135.55
East Cascades	62.88	11.80	8.31	0.08	0.92	11.38	58.33	153.69
Klamath Mountains	173.42	19.63	16.06	0.28	2.06	14.60	90.09	316.14
Willamette Valley	65.72	12.53	8.64	0.10	0.73	13.00	58.81	159.53
Northern Basin	171.86	18.73	16.88	0.27	2.05	15.15	88.06	313.01
State average	121.18	14.38	12.98	0.20	1.59	13.80	76.54	240.67

Values are derived from inventory (FIA) and >200 intensive plots. FWD, fine woody debris.
*Coarse woody debris (CWD) does not include stumps.

Table S3. Forest sector emissions (million $tCO_2e \cdot y^{-1}$) calculated from the LCA

Period	Utility fuel	WD1*	WD2†	Total wood product emissions‡	Wood substitution credits	Net wood product emissions
2001–2005	−1.18	−8.67	−51.85	−61.70	29.09	−32.61
2006–2010	−1.06	−7.84	−52.00	−60.91	26.30	−34.60
2011–2015	−1.18	−8.72	−53.79	−63.69	29.23	−34.45

Average emissions are calculated for each period.
*WD1 is emissions in manufacturing processes.
†WD2 is wood decomposed over time from product use.
‡Total wood product emissions are the sum of utility fuel, WD1, and WD2.

Table S4. Forest sector emissions averaged over each period (million $tCO_2e \cdot y^{-1}$)

Period	NECB*	Fire emissions	Net wood product emissions†	Forest sector emissions‡	Energy sector emissions§	Total emissions (forest + energy sectors)
2001–2005	62.41	−8.69	−32.61	−41.30	−64.65	−105.95
2006–2010	68.32	−6.56	−34.60	−41.16	−65.49	−106.65
2011–2015	68.98	−3.56	−34.45	−38.01	−59.85	−97.86

Energy sector emissions are shown separately for comparison, and the sum of forest and energy sector emissions is used to determine the role of the forest carbon sink (NECB) in reducing total emissions to the atmosphere. Net emissions to the atmosphere are shown as negative values (Fig. 1).

*NECB is calculated from NEP minus fire emissions and harvest removals.

†Net wood product emissions are from Table S3.

‡Forest sector emissions are the sum of utility fuels, fire, and net wood product emissions. The estimates include cradle-to-grave emissions calculated by the LCA.

§Energy sector emissions are those reported by the Oregon Global Warming Commission (1), and include transportation, residential/commercial, industrial, and agriculture emissions, subtracting forest utility fuel emissions to avoid double counting. The state estimates of energy sector emissions do not include cradle-to-grave emissions.

1. Oregon Global Warming Commission (2017) Biennial Report to the Legislature (Oregon Global Warming Commission, Salem, OR).

Table S5. Projected ecoregion percent change in NECB (Tg C) compared with BAU for the combined afforestation, reforestation, and reduced harvest scenarios for 2050 and 2100

Ecoregion	2050 change, %	2100 change, %
Blue Mountains	11	9
West Cascades	47	42
Coast Range	77	8
Columbia Plateau	0	1
East Cascades	98	60
Klamath Mountains	166	106
Willamette Valley	0	0
Northern Basin	0	0

Table S6. Increase in NECB (million tCO_2e) for each strategy compared with BAU management in each period

Strategy	2025	2050
BAU	3	4
Afforestation	4	4
Reforestation	4	4
Reduced harvest	5	6
Total	13	14
8% offset (energy sector GHG emissions)	0.9	3.6
8% offset (total GHG emissions)	2.1	8.4

Values are shown for periods with GHG targets. Offsets are 8% of target emission reductions, which are 20% of 1990 levels by 2025 and 80% below 1990 levels by 2050.

Table S7. Grass seed crop reduction in irrigation demand due to afforestation

Year	Grass crop area, ha	Irrigation demand total, billion $m^3 \cdot y^{-1}$	Irrigation demand per hectare,* $m^3 \cdot y^{-1}$	Reduced irrigation demand,† billion $m^3 \cdot y^{-1}$
2015	238,679	413	1,730,027	220
2050	235,600	412	1,748,277	222
2100	220,524	405	1,838,234	233

Grass crop area and irrigation demand are projected under future climate and management scenarios using hydrology and agricultural models (Willamette Water 2100, 2017) (1).

*Irrigation demand per hectare was computed from an agricultural water demand submodel, which estimates daily water demand for each crop type, where ET is a function of climate, crop type, crop growth state, and available soil water capacity. A crop decision submodel determines the crop type by calculating the probability of growing several crop categories and accounts for irrigation water rights.

†Reduced irrigation demand is due to afforestation of 127,000 ha of irrigated grass seed crop that can support native forests without irrigation under future climate conditions.

1. Hudiburg TW, Law BE, Thornton PE (2013) Evaluation and improvement of the community land model (CLM4) in Oregon forests. *Biogeosciences* 10:453–470.