Regionalized Life Cycle Greenhouse Gas Emissions of Forest Biomass Use for Electricity Generation in the United States

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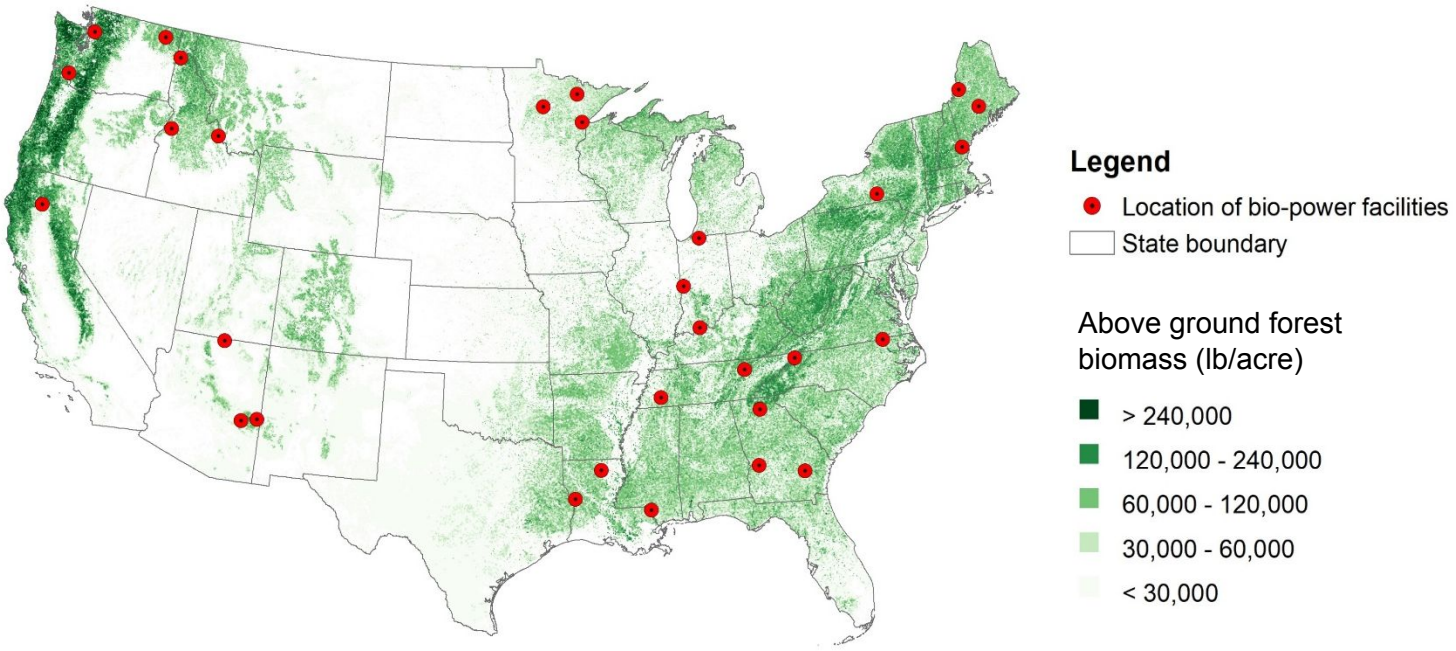

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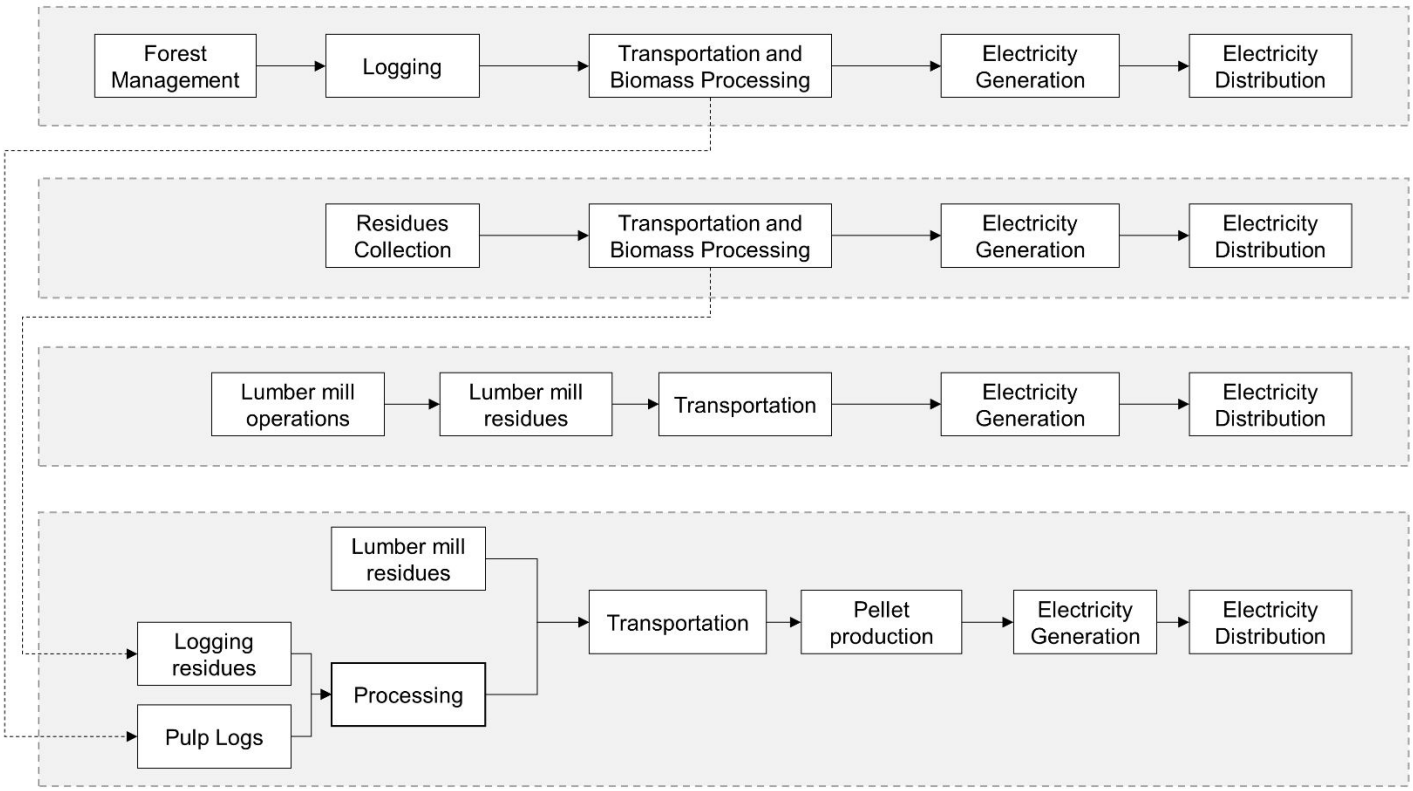

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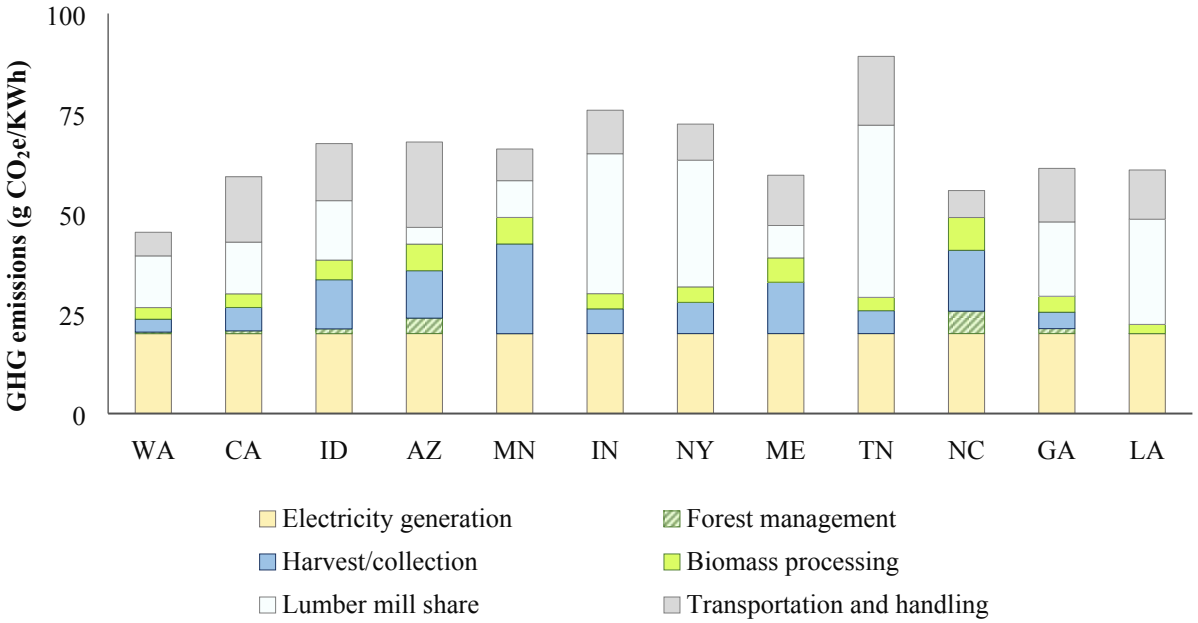
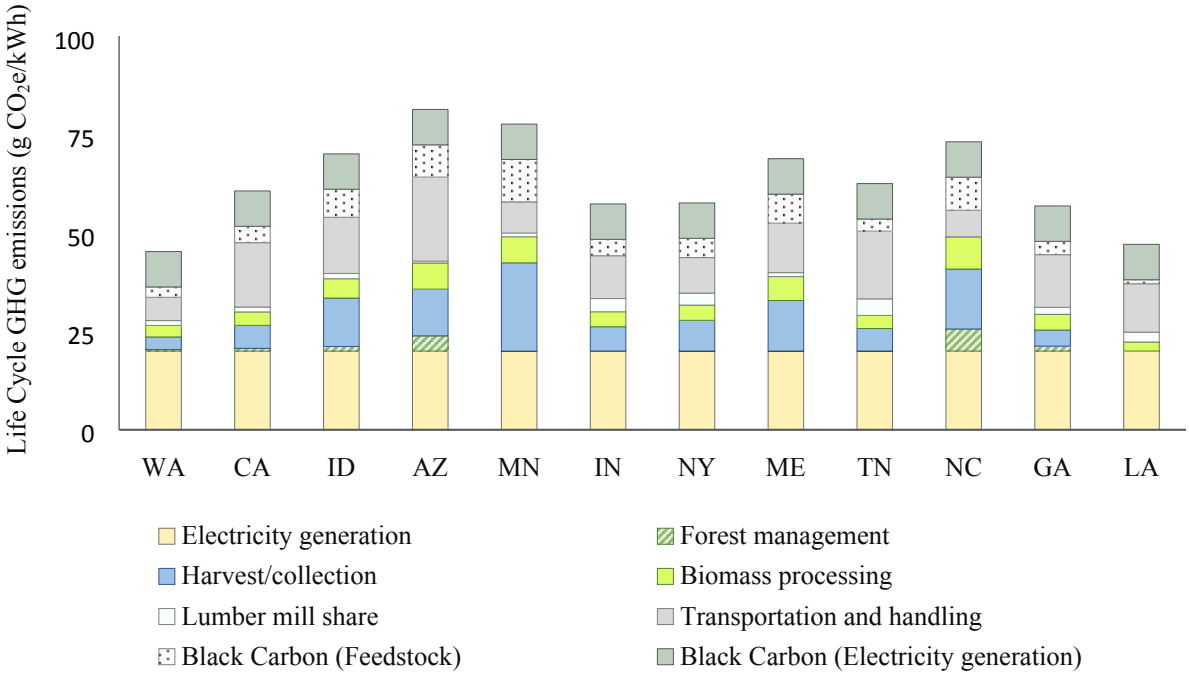


Figure S3. State-level life cycle GHG emissions of forest-residues-to-bioelectricity pathways (g CO_2e/kWh). Lumber mill share is based on mass-balance allocation.



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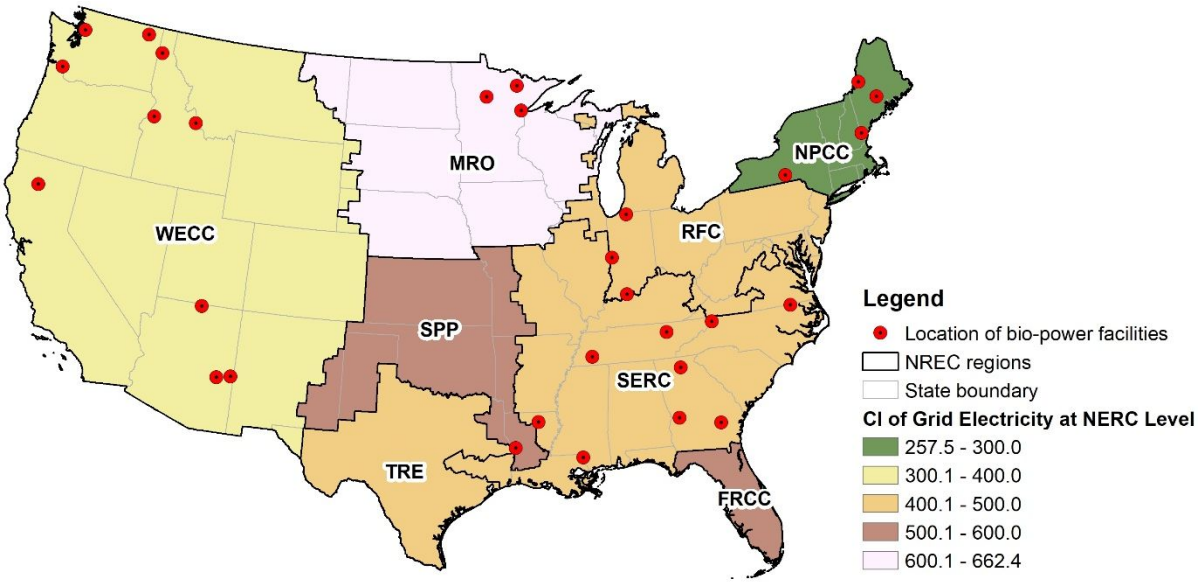

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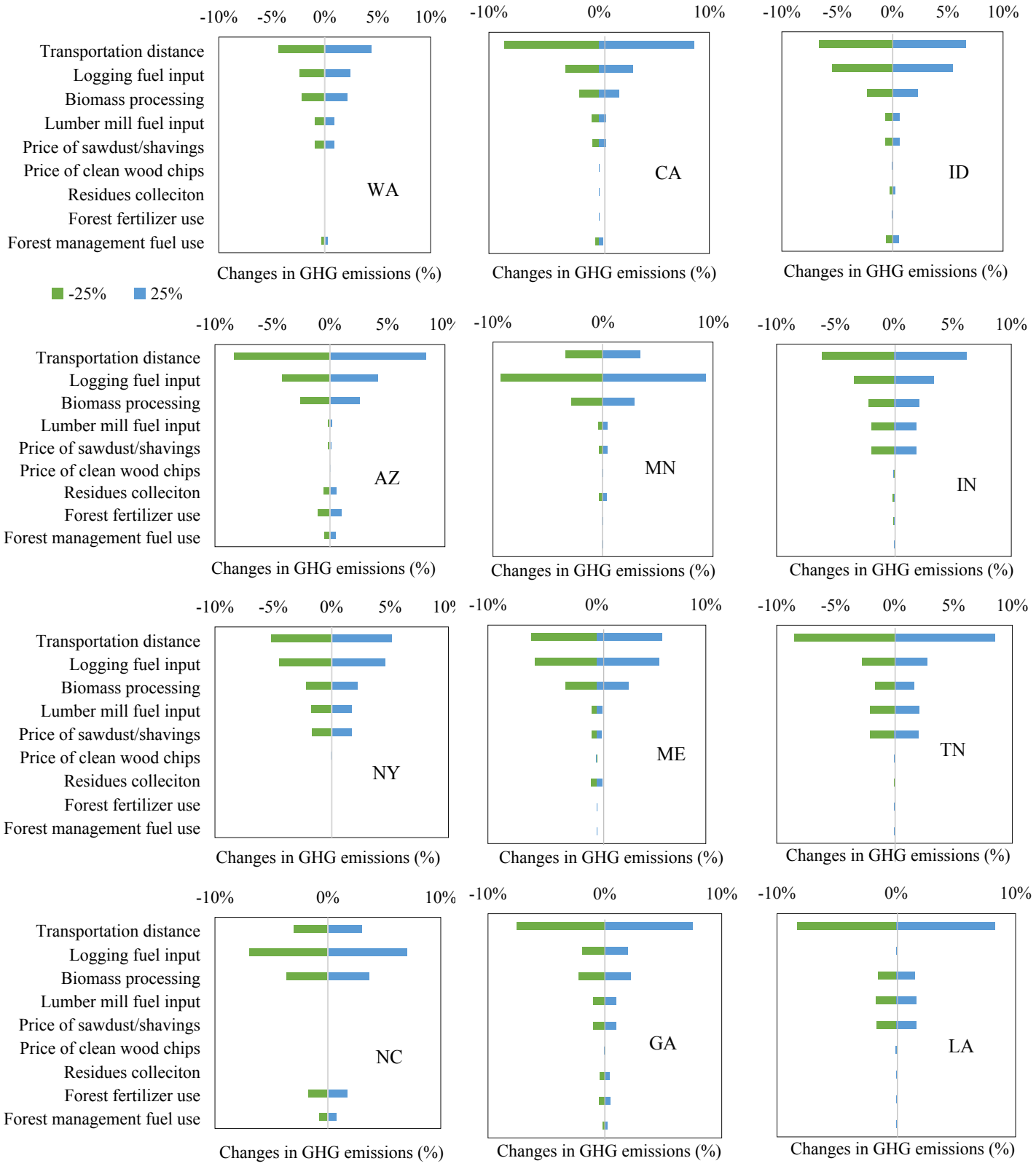

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Table S1. Assumptions for the hypothetical woody biomass power plant.

Variable	Value	Unit
Nameplate Capacity	20	MW/yr
Heat Rate	15.826	MJ/kWh
HHV	13.956	MJ/kg biomass (dry)
Capacity Factor	0.6	Fraction of production time
Annual Generation	105,120	MWh/yr
Feedstock Required	119,204	t /yr (dry basis)
Moisture content of pulpwood feedstock	45	% (at forest landing)
Moisture content of logging residues	30	% (at forest landing)
Moisture content of sawmill residues	30	% (at lumber mill)

Table S2. Fuel and material inputs for site preparation, planting, and stand management. Natural regeneration is assumed for Northeast/North Central, thus there are no energy/material inputs.

Inputs	Pacific Northwest	Inland Northwest	South East	Northeast/North-Central
Energy Use (L/ha)				
Diesel	19.5	88.0	123.1	
Gasoline	4.2	-	-	
Lubricants	0.4	1.8	2.5	
Kerosene/Jet Fuel	7.9	-	-	
Electricity	-	-	-	
Fertilizer Use (grams/ha)				
Nitrogen	71,734	37.0	103,100	
P_2O_5	0	62.0	12,800	
K_2O	-	152.0	-	
$CaCO_3$	-	-	-	
Pesticide Use (grams/ha)				
Herbicide	4,437	-	1,360	
Insecticide	-	-	-	

Table S3. Energy inputs for logging in the Pacific Northwest region. Data is adapted from Oneil et al. (2017).[1]

Steps	Equipment	Diesel Use (L/m3)	Lubricants (L/m3)
Felling	Large feller-buncher	0.77	0.01
Yarding	Shovel yarder	3.56	0.06
Sorting	Large loader	0.35	0.01
Processing	Processor	1.01	0.02
Loading	Large loader	0.71	0.01
Sub-total		**6.39**	**0.11**

Table S4. Energy inputs for logging in the Inland Pacific Northwest region. Data is adapted from Oneil et al. (2010).[2]

Steps	Equipment	Diesel Use (L/m3)	Lubricants (L/m3)
Felling	Large feller-buncher	0.37	0.01
Skidding	Large grapple skidder	1.13	0.02
Processing	Processor	0.29	0.01
Loading	Large loader	0.77	0.01
Sub-total		**2.55**	**0.05**

Table S5. Energy inputs for logging in the Northcentral region (except Tennesse). Data is adapted from Oneil et al. (2010).[2]

Steps	Equipment	Diesel Use (L/m3)		Lubricants (L/m3)	
		Softwood	Hardwood	Softwood	Hardwood
Felling	Large feller-buncher	1.02	0.07	0.02	0.00
Skidding	Large grapple skidder	1.66	2.73	0.03	0.05
Processing	Processor	0.02	0.02	0.00	0.00
Loading	Large loader	1.44	1.44	0.03	0.03
Sub-total		**4.14**	**4.27**	**0.07**	**0.08**

Table S6. Energy inputs for logging in Tennesse. Data is adapted from Abbas et al. (2018).[3]

Type	Softwood	Hardwood
Gasoline (L/dry ton)	1.32	1.50
Diesel (L/dry ton)	9.03	9.62
Lubricants (L/dry ton)	0.64	0.68

Table S7. Energy inputs for logging in the Northeast. Data is adapted from Quinn et al. (2020). [4]

Steps	Diesel fuel (L/dry ton)	Lubricants (L/dry ton)
Felling, skidding, and BMP	6.078	0.122
Processing pulpwood	0.615	0.012
Subtotal	**6.693**	**0.134**

Table S8. Energy inputs for logging in the Southeast region. Data is adapted from Lan et al. (in review).[5]

Steps	**Equipment**	**Diesel Use (L/m3)**	**Lubricant (L/m3)**
Logging	Not specified	1.98	0.04
Subtotal		**1.98**	**0.04**

Table S9. Energy inputs for logging residues recovery. Data is adapted from Han et al. (2018)[6] and Lan et al. (in review).[5]

Fuel Consumption	**Southeast**	**Pacific Northwest and Inland Pacific Northwest**	**Northeast/North Central**
Diesel (L/dry ton)	2.89	3.45	2.45
Gasoline (L/dry ton)	-	0.06	-
Lubricants (L/dry ton)	-	0.07	-

Table S10. Energy inputs for wood pellets production. Data for Southeast and Pacific Northwest regions are derived from Morrison and Gordon (2017)[7] and Brackely et al. (2017),[8] respectively.

Energy inputs	**Southeast Region**		**Pacific Northwest Region**	
	Drying	Pelletizing	Drying	Pelletizing
Diesel (L/dry ton)	-	2.5	-	-
Lubricants (L/dry ton)	-	0.3	-	-
Electricity (KWh/dry ton)	40.6	162.2	30.0	145.8
Natural Gas (L/dry ton)	-	0.01	-	0.2
Biomass (waste wood, MJ/dry ton)	589.0	-	3203.8	-

Table S11. Break-down of life cycle GHG emissions by state for the pulpwood (softwood) to electricity pathway. States with zero transportation emissions indicate that pulpwood is not included in biomass supply mix simulated by LURA; values for other stages are included here for reference.

Breakdown by stages	WA	CA	ID	AZ	MN	IN	NY	ME	TN	NC	GA	LA
Forest Management	2.5	2.5	2.5	5.6	0.0	0.0	0.0	0.0	0.0	5.6	5.6	5.6
Harvest/Collection	20.6	20.6	25.1	15.2	32.2	24.1	21.7	23.0	37.3	15.2	15.2	15.2
Biomass processing	6.3	6.3	6.5	6.3	6.7	6.3	6.3	6.7	6.3	6.3	6.3	6.3
Lumber mill operation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transportation	5.1	9.3	11.1	13.0	7.9	10.5	10.0	10.3	13.3	6.7	9.4	0.0
Electricity generation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sum	54.4	58.6	65.2	60.1	66.8	60.9	58.0	60.0	76.9	53.8	56.5	47.1

Table S12. Break-down of life cycle GHG emissions by state for the logging residues (softwood) to electricity pathway. States with zero transportation emissions indicate that logging residues are not included in biomass supply mix simulated by LURA; values for other stages are included here for reference.

Breakdown by stages	WA	CA	ID	AZ	MN	IN	NY	ME	TN	NC	GA	LA
Forest Management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Harvest/Collection	11.3	11.3	11.6	9.4	8.2	9.4	9.4	8.2	9.4	9.4	9.4	9.4
Biomass processing	12.4	12.4	12.8	12.5	13.3	12.5	12.5	13.3	12.5	12.5	12.5	12.5
Lumber mill operation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transportation	0.0	0.0	13.7	16.8	9.1	14.2	0.0	14.3	5.3	0.0	5.2	0.0
Electricity generation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sum	43.7	43.7	58.1	58.7	50.6	56.1	41.9	55.8	47.2	41.9	47.1	41.9

Table S13. Break-down of life cycle GHG emissions by state for the mill residues (sawdust and shavings, softwood) to electricity pathway. States with zero transportation emissions indicate that mill residues are not included in biomass supply mix simulated by LURA; values for other stages are included here for reference.

Breakdown by stages	WA	CA	ID	AZ	MN	IN	NY	ME	TN	NC	GA	LA
Forest Management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Harvest/Collection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biomass processing	2.3	2.3	2.3	2.3	2.4	2.3	2.3	2.4	2.3	2.3	2.3	2.3
Lumber mill operation	1.5	1.5	2.7	2.3	2.5	2.3	2.3	2.5	2.3	2.3	2.3	2.3
Transportation	6.2	19.2	17.3	50.9	7.3	18.6	13.3	16.1	20.4	0.0	14.9	12.3
Electricity generation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sum	29.9	42.9	42.3	75.4	32.2	43.3	37.9	41.0	45.0	24.5	39.4	36.8

Table S14. Break-down of life cycle GHG emissions by state for the wood pellet (sourced from pulpwood, softwood) to electricity pathway. States with zero transportation emissions indicate that mill residues are not included in biomass supply mix simulated by LURA; values for other stages are included here for reference.

Breakdown by stages	WA	CA	ID	AZ	MN	IN	NY	ME	TN	NC	GA	LA
Forest Management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Harvest/Collection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biomass processing	89.8	89.8	92.7	92.5	95.7	93.3	95.9	95.7	95.6	92.5	92.5	92.5
Lumber mill operation	1.1	1.1	2.4	1.7	1.9	1.9	1.9	1.9	1.9	1.7	1.7	1.7
Transportation	0.0	0.0	31.0	33.2	4.3	7.6	0.0	4.7	16.3	10.0	0.0	0.0
Electricity generation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sum	110.8	110.8	146.0	147.4	122.0	122.8	117.9	122.4	133.8	124.2	114.2	114.2

Table S15. Break-down of life cycle GHG emissions by state for the wood pellet (sourced from pulpwood) to electricity pathway. States with zero transportation emissions indicate that mill residues are not included in biomass supply mix simulated by LURA; values for other stages are included here for reference.

Breakdown by stages	WA	CA	ID	AZ	MN	IN	NY	ME	TN	NC	GA	LA
Forest Management	2.5	2.5	2.5	5.6	0.0	5.8	0.0	0.0	0.0	5.6	5.6	5.6
Harvest/Collection	20.6	20.6	25.1	15.2	32.2	24.9	23.0	23.0	38.5	15.2	15.2	15.2
Biomass processing	89.8	89.8	92.7	92.5	95.7	93.3	95.9	95.7	95.6	92.5	92.5	92.5
Lumber mill operation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transportation	0.0	0.0	31.0	33.2	4.3	7.6	0.0	4.7	16.3	10.0	0.0	0.0
Electricity generation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sum	132.8	132.8	171.2	166.5	152.2	151.6	138.9	143.4	170.4	143.4	133.4	133.4

Table S16. Comparison of economic value versus mass based allocation factors used for the sawing process (log to rough green lumber) at lumber mill. States within the same region share the same allocation factors.

	Mass-based allocation					Economic Allocation				
Products (green)	PNW	INW	SE	NE/NC (SW)	NE/NC (HW)	PNW	INW	SE	NE/NC (SW)	NE/NC (HW)
lumber	50.1%	52.0%	52.2%	34.0%	59.4%	91.8%	92.0%	91.4%	85.1%	95.1%
chips	24.4%	32.0%	30.7%	37.0%	15.5%	5.7%	7.2%	6.9%	11.8%	3.2%
Sawdust/shavings	5.6%	4.0%	9.7%	11.0%	13.6%	0.7%	0.5%	1.1%	1.8%	1.4%
hogfuel	13.8%	1.0%	4.8%	5.0%	0.2%	1.7%	0.1%	0.6%	0.8%	0.0%
bark	6.1%	9.0%	2.6%	13.0%	11.2%	0.2%	0.2%	0.1%	0.5%	0.3%

Table S17. Comparison of economic value versus mass based allocation factors used for the planning process (rough saw lumber to planned lumber) at lumber mill. States within the same region share the same allocation factors.

	Mass-based allocation					Economic Allocation				
Products	PNW	INW	SE	NE/NC (SW)	NE/NC (HW)	PNW	INW	SE	NE/NC (SW)	NE/NC (HW)
Sawn lumber	88.7%	82.0%	90.1%	90.0%	80.2%	99.1%	98.6%	99.3%	99.2%	98.4%
Chips	1.3%	0.0%	0.2%	1.0%	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%
Sawdust/shavings	10.1%	18.0%	9.6%	9.0%	19.8%	0.7%	1.4%	0.7%	0.7%	1.6%