Core Model Proposal #:370
Break out global pulp and paper industry

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

Authors: Molly Charles**,** Kanishka B. Narayan, Sha Yu & Jae Edmonds

Reviewers: Ellie Lochner, Pralit Patel

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Related sector: Energy, Forest

Type of development: Data system, Input Data

Purpose: This CMP adds to global detailed industry by breaking out the pulp and paper sector from aggregate industry.

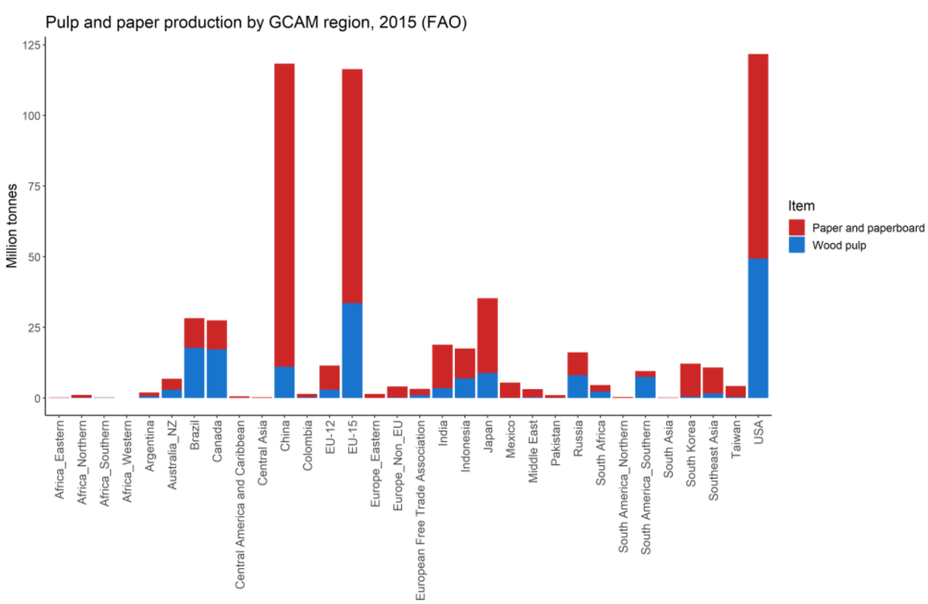
Description of Changes

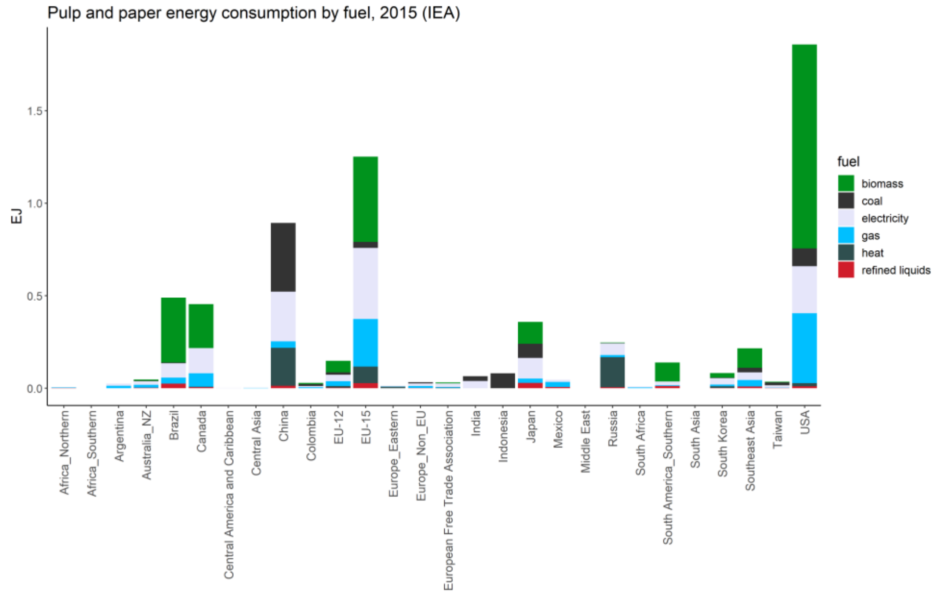
Overview

This core model proposal adds to the representation of detailed industrial sectors in GCAM (326 Global Detailed Industry: 2020-08-14) by breaking out the global pulp and paper industry from the aggregate industry sector. Historical energy use is calibrated to IEA energy use in the pulp and paper sector, and paper output is calibrated to FAO data. Further, this sector is linked to the forest sector and builds on the forest breakout model developments (369 Add detail to forest sectors), with the wood pulp commodity represented as an energy input in the paper industry.

Background

The pulp and paper industry makes up about 6% of global industrial energy consumption. Pulp can be produced through chemical, mechanical, or recycled pulping processes. Compared to heavy industrial sectors, the pulp and paper industry is generally among the less challenging industries to decarbonize, due to its existing reliance on waste biomass energy, cogeneration, and use of low-temperature industrial heat. In addition, the pulp and paper sector can theoretically provide opportunities for negative emissions by adding CCS to existing biomass combustion. At the same time, the pulp and paper industry could be impacted by land use competition and growing demand for biomass feedstock in a decarbonization scenarios. We link the paper industry to the forest sector to better capture interactions between transition pathways for the paper industry and land use impacts.

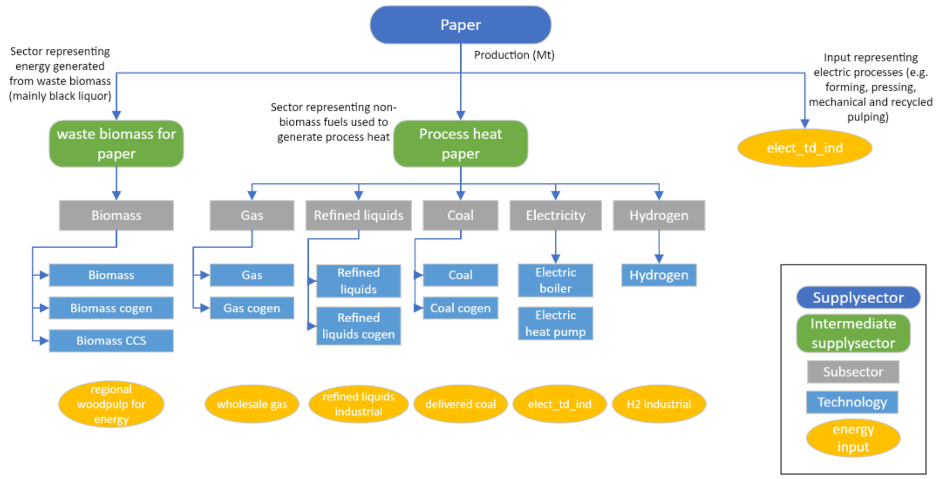




Modeling structure

Much of the energy used in the pulp and paper sector is biomass residue, primarily black liquor from the chemical pulping process. Biomass residue availability varies by region, with high usage in regions with high forested area and chemical pulp production. Other fuels are used for processes that require process heat, such as wood digestion, lime kiln for chemical recovery, and paper drying. Separate processes in paper production rely largely on electricity, such as wood chipping, mechanical pulping, recycled pulping, and paper forming.

To reflect the different uses of these energy sources and prevent unrealistic fuel substitution, we model two intermediate supply sectors. The waste biomass for paper sector reflects the use of biomass residue, mainly consisting of black liquor as well as debarking residues. The supply of waste biomass is related to the total raw material used in paper production. The process heat sector contains all other fuels used for heat generation. Electricity is a direct input into the paper supply sector, representing use in electric-based processes like machine drives and pumps.



Calibration

Energy use in the paper sector is calibrated to IEA energy balances (PAPERPRO sector). Paper physical output is calibrated to production by region, in tons, from the FAO forest statistics (using paper and paperboard only, excluding intermediate pulp production).

Energy and physical output are used to calculate sector-level input-output coefficients by GCAM region. Coefficients are calculated separately for electricity use, process heat, and waste biomass energy, since these inputs are separated in the modeling structure. All non-electricity and non-biomass fuels are assumed to be used for process heat production.

Biomass cogeneration is common in this industry. To reflect this, we reassign a portion of biomass cogeneration from GCAM aggregate industry to the paper sector. The share of biomass cogeneration assumed to be consumed in paper is based on the ratio of total final energy in the pulp and paper sector (PAPERPRO in IEA) and food production sector (FOODPRO), since these are the two main industrial sectors where biomass cogeneration is common. (Note- for now there is an input file with the ratio of paper industry energy to food production in IEA energy balances, but once the food processing industry breakout is merged this can be done within the data system.)

China reports zero biomass consumption in the pulp and paper sector in the IEA energy balances (and no industrial biomass use in general). However, other sources indicate that there is biomass use in the pulp and paper industry in China. For historical biomass use in China, we add in values from Man et al. (2022).

Technology costs

Technology costs for gas boilers, gas CHP, electric boilers, and electric heat pumps are based on costs from this Rissman 2022 report (via this tool). Levelized costs ($/GJ) are calculated assuming a 47% capacity utilization factor (average capacity U.S. factor for industrial boilers), 20 year capital cost amortization, and 10% discount rate. Based on GCAM-USA detailed industry assumptions, we assume the same costs for refined liquids and coal (with and without cogen) as for gas technologies. For electric heat pump costs, we assume a higher-temperature heat pump is required.

For waste biomass energy technologies (conventional, cogen, and CCS), costs are based on IEA - Techno-economic assessment of retrofitting CCS in a market pulp mill and integrated pulp and board mill (2016). (Conventional biomass tech cost is based on cost of Kraft recovery boiler + black liquor evaporation + recausticizing plant, then levelized using a 10% discount rate; cogen technology includes added cost of steam turbine; CCS technology includes added cost of retrofitting CCS). CCS technology cost improvement is assumed based on the cost improvement of biomass CCS in the electricity sector.

See attached spreadsheet for levelized tech cost calculations.

Costs for the general paper technology ("paper" technology below, which takes inputs of process heat paper, waste biomass, and elect_td_ind) are estimated by subtracting non-energy and energy costs of the inputs per kg of paper produced from the average market price of paper. Market prices are calculated from FAO trade quantities and volumes, non-energy equipment costs are from GCAM technology cost assumptions, and energy costs are from GCAM fuel prices.

For hydrogen, a cost adder was included due to unrealistically large shares of hydrogen use in process heat, as literature generally indicates that hydrogen will not be an economic option to decarbonize this sector.

supplysector	subsector	technology	minicam.non.energy.input	1971	2010	2050	2100
paper	paper	paper	non-energy	0.09	0.09	0.09	0.09
waste biomass for paper	biomass	biomass	non-energy	1.28	1.28	1.28	1.28
waste biomass for paper	biomass	biomass cogen	non-energy	1.69	1.69	1.69	1.69
waste biomass for paper	biomass	biomass CCS	non-energy	3.31	3.31	2.74	2.04
process heat paper	gas	gas	non-energy	0.92	0.92	0.92	0.92
process heat paper	gas	gas cogen	non-energy	2.09	2.09	2.09	2.09
process heat paper	refined liquids	refined liquids	non-energy	0.92	0.92	0.92	0.92

process heat paper	refined liquids	refined liquids cogen	non-energy	2.09	2.09	2.09	2.09
process heat paper	heat	heat	non-energy	1.5	1.5	1.5	1.5
process heat paper	coal	coal	non-energy	0.92	0.92	0.92	0.92
process heat paper	coal	coal cogen	non-energy	2.09	2.09	2.09	2.09
process heat paper	electricity	electric boiler	non-energy	0.58	0.58	0.58	0.58
process heat paper	electricity	electric heat pump	non-energy	2.03	2.03	2.03	2.03
process heat paper	hydrogen	hydrogen	non-energy	10	10	10	10

Coefficients

Coefficients for most technologies are based on GCAM-USA industrial boiler assumptions. For biomass with CCS, efficiency is calculated based on the assumption that the heat requirement for CO2 capture is 3700 kJ / kgCO2 (Karlsson et al, 2021). Electric technologies are from Rissman, 2022.

supplysector	**subsector**	**technology**	**minicam.energy.input**	**secondary.output**	**1975**	**2100**
waste biomass for paper	biomass	biomass	regional wood pulp for energy		1.43	1.43
waste biomass for paper	biomass	biomass cogen	regional wood pulp for energy	electricity	1.82	1.82
waste biomass for paper	biomass	biomass CCS	regional wood pulp for energy		1.93	1.93
process heat paper	gas	gas	wholesale gas		1.25	1.25
process heat paper	gas	gas cogen	wholesale gas	electricity	1.67	1.67

process heat paper	refined liquids	refined liquids	refined liquids industrial		1.25	1.25
process heat paper	refined liquids	refined liquids cogen	refined liquids industrial	electricity	1.67	1.67
process heat paper	heat	heat	district heat		1	1
process heat paper	coal	coal	delivered coal		1.25	1.25
process heat paper	coal	coal cogen	delivered coal	electricity	1.67	1.67
process heat paper	electricity	electric boiler	elect_td_ind		1	1
process heat paper	electricity	electric heat pump	elect_td_ind		0.45	0.45
process heat paper	hydrogen	hydrogen	H2 industrial		1.18	1.18

Technology choice and shareweights

Like other detailed industry sectors, we use the Modified Logit model as discrete choice function, with subsector logit exponents set to -6. The overall paper sector logit exponent is set to 1 to reflect less flexibility in switching between electric-based and heat-based processes.

Existing technologies are assumed to maintain their share weight from the base year into the future. Future technology share weights are included below and are based on our understanding and literature on each technology's relative maturity and technological development. For hydrogen, we included the technology option but set default share weights to 0, as literature review indicated that hydrogen is not expected to play a major role in the pulp and paper industry.

Technology	Share weight and interpolation rule
biomass CCS	0 in base year; linear interpolation to 0.5 in 2035 and 1 in 2050
electric boiler	0 in base year; linear interpolation to 1 in 2035
electric heat pump	0 in base year; linear interpolation to 0.5 in 2050 and 1 in 2100

Subsector share weights are fixed for most regions. For regions with only electricity use reported (or only estimated biomass use) and no other fuels, we modify future share weights to allow other fuels to be used in future years.

Note on CCS implementation.

In this CMP, we only implement CCS for the wood pulp for energy. There is no CCS implemented for the process heat generated from fossil fuels. The literature suggests that gas or coal with CCS is likely not economic compared to electrifying process heat, whereas biomass with CCS makes more sense because it utilizes the existing waste wood product.

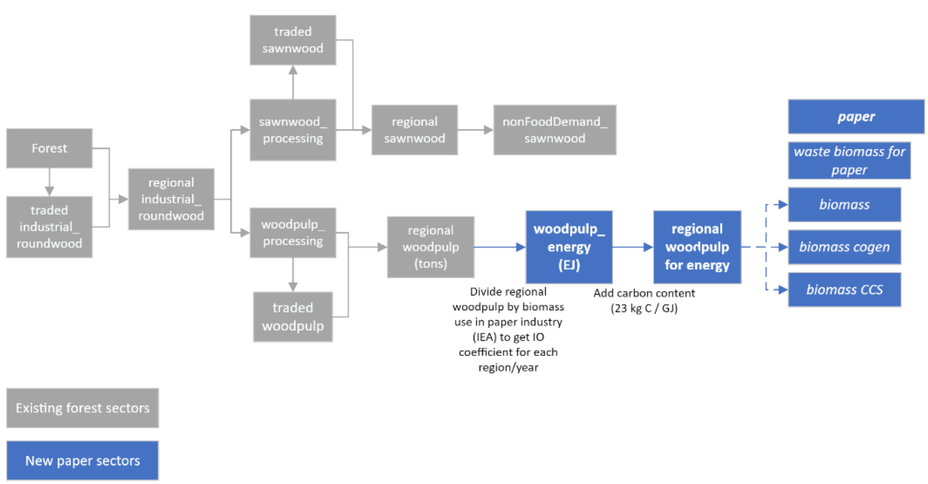
Vintage and retirement

We base capital stock retirement assumptions on values used in other detailed industry sectors. The below assumptions are used for all paper technologies (except heat pumps, which have a shorter lifetime assumption based on Obrist et al.).

technology	lifetime	shutdown.rate	half.life	steepness	median.shutdown.point	profit.shutdown.steepness
all boilers	40		20	0.3	-0.5	6
heat pump	25		13	0.3	-0.5	6

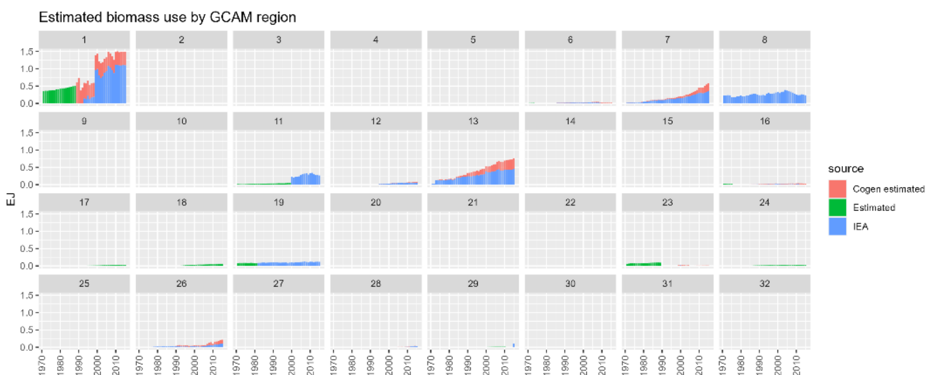
Linkage to forest sector

The paper industry is linked to the forest sector. The minicam.energy.input for the technologies in the waste biomass supplysector (biomass, biomass cogen, and biomass CCS) comes from the regional woodpulp commodity from the forest sector. A pass-through sector, "regional woodpulp for energy," is added to assign a carbon content to the woodpulp commodity where it enters the energy system. The diagram below shows the flow between sectors from the forest product to paper input.



Input-output coefficients from woodpulp to biomass energy in the paper sector are calculated for each region and year. These IO values are calculated as woodpulp (Mt, from FAO) divided by biomass use in the paper industry (EJ, from IEA). This results in a wide range of coefficients, since woodpulp and bimoass use varies widely based on the amount of primary and chemical pulp produced in each region. In future years, outlier values are adjusted to fit within the interquartile range of IO coefficients (this avoids an unrealistically large increase in biomass CCS use in regions with low woodpulp-to-energy IO coefficients under a policy scenario).

For most regions, energy in the woodpulp_energy sector is equal to reported biomass consumption in the paper sector from IEA. This then gets treated as biomass and subtracted from remaining industrial biomass. However, a number of regions also report pulp production but no biomass use in the industry. Since waste biomass from pulping is produced and used onsite, the lack of biomass may be a data reporting issue. For calculating woodpulp-to-energy IO coefficients for these regions, we take the global median value across GCAM regions and scale it by the share of pulp that is domestically produced, since pulping activity generally determines waste biomass availability. We then use these assumed IO coefficients to estimate biomass use. As shown in the figure below, this is mainly applicable in historical years, and the amount of biomass assumed is small in most regions (with the exception of the US before 1989).

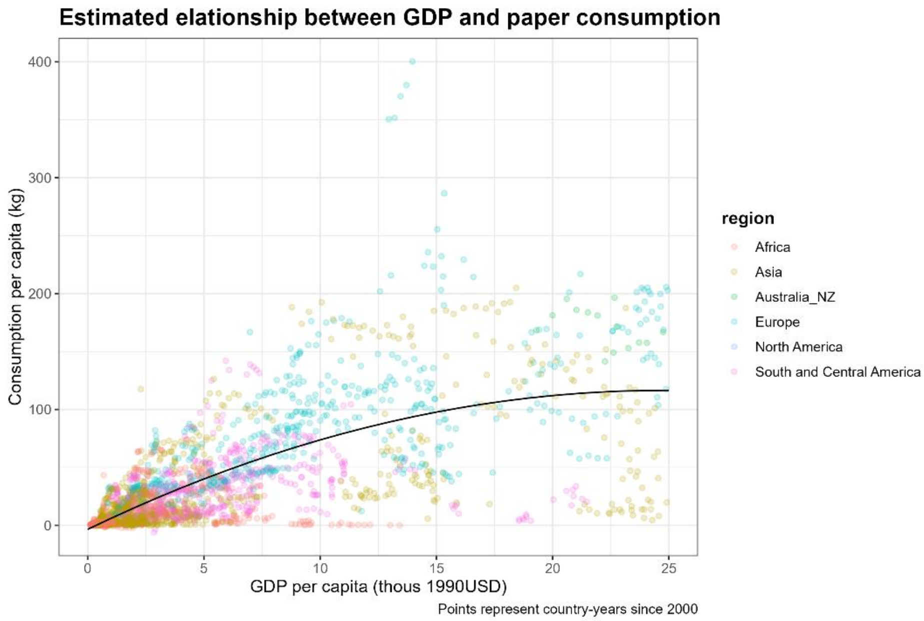


Water use

Global average water consumption and withdrawal coefficients (from [Vassolo and Doll, 2005]) are used to estimate water use in each region based on annual paper production. Water withdrawals and consumption in the paper industry are subtracted from total industrial water.

Demand growth

Income elasticities at each per-capita income level were estimated based on historical data on paper consumption (from FAO) and GDP per capita. We fit a linear model for historical data (all countries since 2000), shown below, then estimate the increase in per-capita consumption at each per-capita income level. Region groupings are shown for reference.



pcgdp_90thousUSD	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
inc_elas	1.25	1.17	1.09	1.01	0.97	0.93	0.89	0.86	0.83	0.8	0.76	0.73	0.69	0.66	0.62	0.58	0.54	0.5	0.45	0.4	0.35	0.29	0.23	0.17	0.1	0.05

Emissions

As with most other detailed industrial sectors, we map CEDS combustion-related emissions from this sector (1A2d_Ind-Comb-Pulp-paper) to the paper industry by type of fuel. Note that we don't include any process emissions and only combustion emissions as a part of this proposal. This can be improved upon in the future.

Description of Code Changes

This table details the code chunks and input files that were modified or added.

Chunk	Input files	Notes

zchunk_LA1327.paper.R (added)	aglu/FAO/FAO_Paper_Prod_t_FORESTAT.csv (added) energy/A327.globaltech_coef.csv (added) energy/paper_food_TFE.csv (added) energy/A327.china_biomass.csv (added)	
zchunk_L2327.paper.R (added)	energy/calibrated_techs.csv (modified) energy/A327.sector.csv (added) energy/A327.subsector_interp.csv (added) energy/A327.subsector_logit.csv (added) energy/A327.subsector_shrwt.csv (added) energy/A327.globaltech_coef.csv (added) energy/A327.globaltech_co2capture.csv (added) energy/A327.globaltech_cost.csv (added) energy/A327.globaltech_shrwt.csv (added) energy/A327.globaltech_retirement.csv (added) energy/A327.demand.csv (added) energy/A327.subsector_interp_adj_future_years.csv (added) energy/A327.subsector_shrwt_adj_future_years.csv (added)	

zchunk_batch_paper_xml.R (added)		
zchunk_L2327.paper_Inc_Elas_scenarios.R (added)	socioeconomics/A327.inc_elas (added)	
zchunk_batch_paper_SSP_xml.R (added)		
zchunk_L232.other_industry.R (modified)		Modified input of remaining "other industry" energy to come from paper industry chunk output
zchunk_L112.ceds_ghg_en_R_S_T_Y.R (modified)	emissions/CEDS/ceds_sector_map.csv (modified) emissions/CEDS/CEDS_sector_tech_combustion.csv (modified) emissions/CEDS/CEDS_sector_tech_combustion_revised.csv (modified) emissions/A51.max_reduction.csv (modified) emissions/A51.min_coeff.csv (modified) emissions/A51.steepness.csv (modified)	Modified input files to include pulp and paper heat technologies; modified R chunk to take an input of pulp and paper energy use
zchunk_L202.an_input.R (modified)		Modified to add woodpulp biomass energy used in pulp and paper sector
zchunk_batch_an_input_xml.R (modified)		

zchunk_L232.water_demand_ manufacturing.R (modified)	water/paper_mfg_intensity.csv (added)	Modified to estimate paper industry water use, as global average water intensity * paper production, and subtract from aggregate industry water use
zchunk_batch_water_demand_ industry_xml.R (modified)		
	energy/mappings/IEA_flow_sector.csv (modified)	Modified to include mapping for IEA food processing energy use to GCAM food processing sector
	emissions/A_PrimaryFuelCCoef.csv (modified)	Modified to add carbon coefficient for woodpulp biomass energy
	energy/A21.globaltech_coef.csv (modified) energy/A21.globaltech_cost.csv (modified) energy/A21.globaltech_shrwt.csv (modified) energy/A21.sector.csv (modified) energy/A21.subsector_interp.csv (modified) energy/A21.subsector_logit.csv (modified) energy/A21.subsector_shrwt.csv (modified)	Modified to create pass-through sector for assigning a carbon content to woodpulp biomass energy

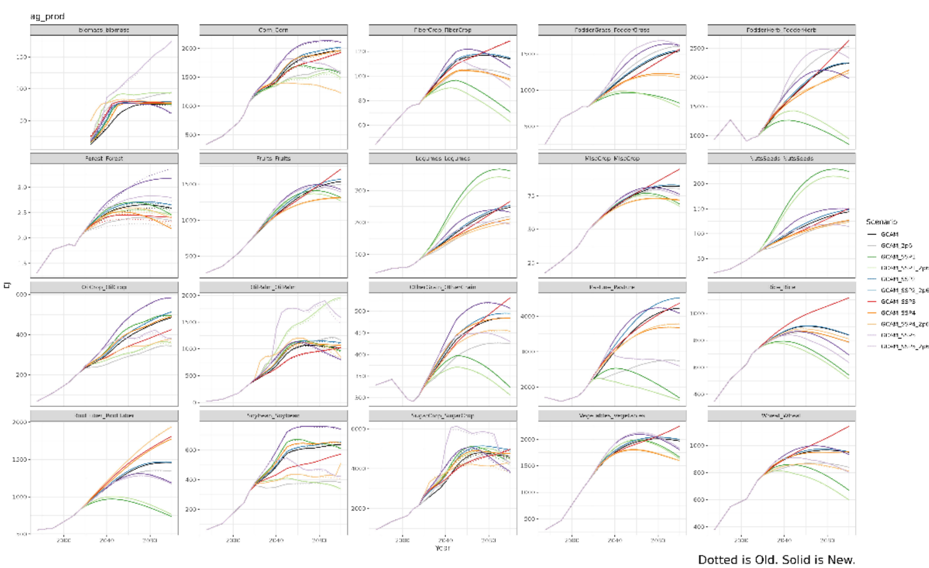
	aglu/A_an_input_subsector.csv (modified) aglu/A_an_input_supplysector.csv (modified) aglu/A_an_input_technology.csv (modified)	Modified to add assumptions for the woodpulp_energy supply sector
	aglu/A_demand_nesting_subsector.csv (modified) aglu/A_demand_subsector.csv (modified) aglu/A_demand_supplysector.csv (modified) aglu/A_demand_technology.csv (modified)	Modified to remove NonFoodDemand_woodpulp as the final demand for woodpulp
	exe/batch_SSP_REF.xml (modified) exe/batch_SSP_SPA1.xml (modified) exe/batch_SSP_SPA23.xml (modified) exe/batch_SSP_SPA4.xml (modified) exe/batch_SSP_SPA5.xml (modified) exe/configuration_policy.xml (modified) exe/configuration_ref.xml (modified) exe/configuration_usa.xml (modified)	Modified to include paper.xml
constants.R		Modified to add forest final demand sectors to be deleted and replaced with paper industry

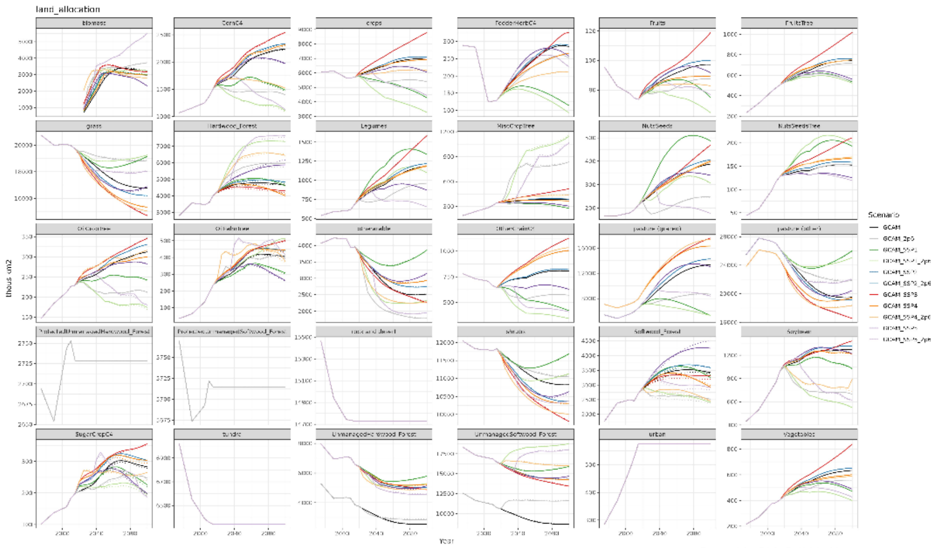
	output/queries/Main_queries.xml (modified)	Added paper-specific queries. Modified some existing queries to exclude intermediate supplysectors (similar to process heat) and include regional woodpulp for energy.

Validation

Validation figures are presented below..

We observe that there are no significant changes in trends with the introduction of the paper industry in GCAM. There is a small increase in roundwood production driven by increase in demand for paper products. This also leads to more forest conversion from unmanaged to managed   resulting in small increases in LUC emissions across scenarios.





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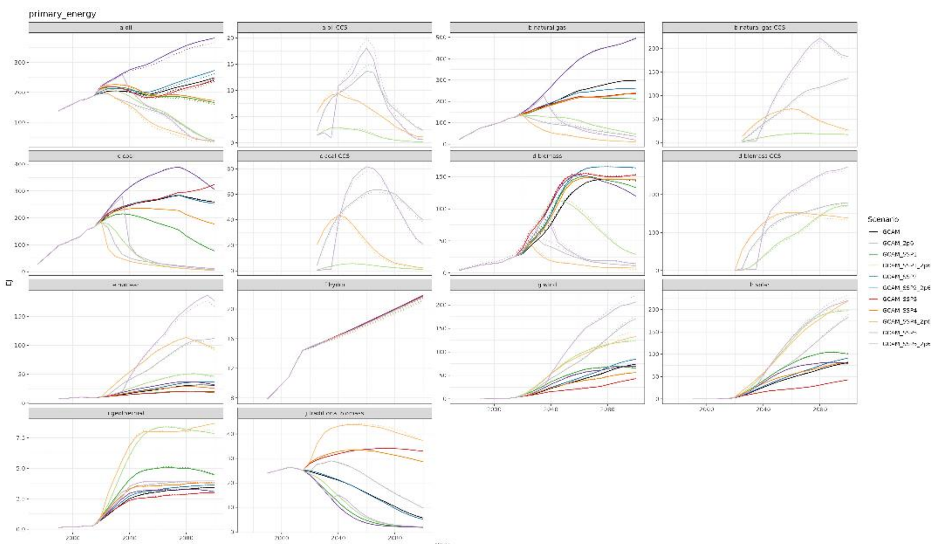

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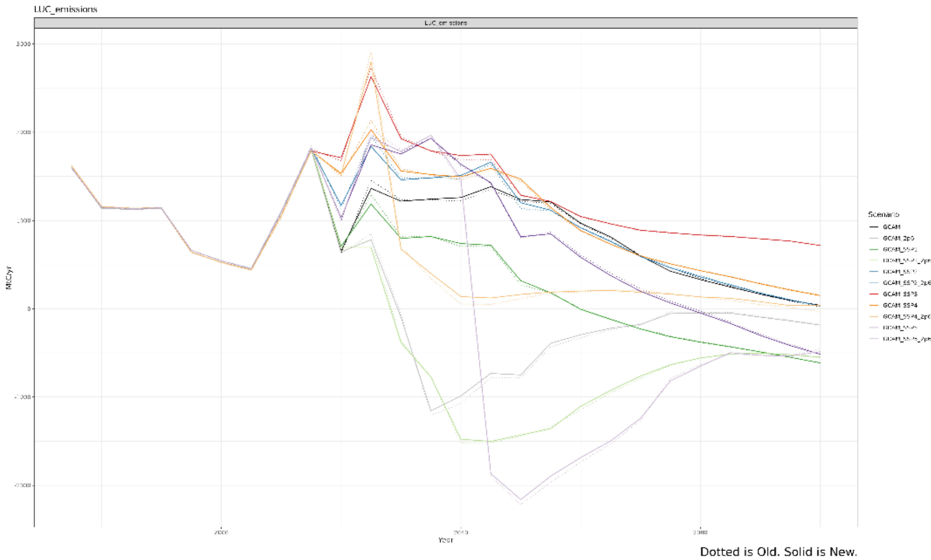
LUC_emissions
Scenario
GCAM
GCAM_2p6
GCAM_SSP2_2p6
GCAM_SSP3
GCAM_SSP4
GCAM_SSP4_2p6
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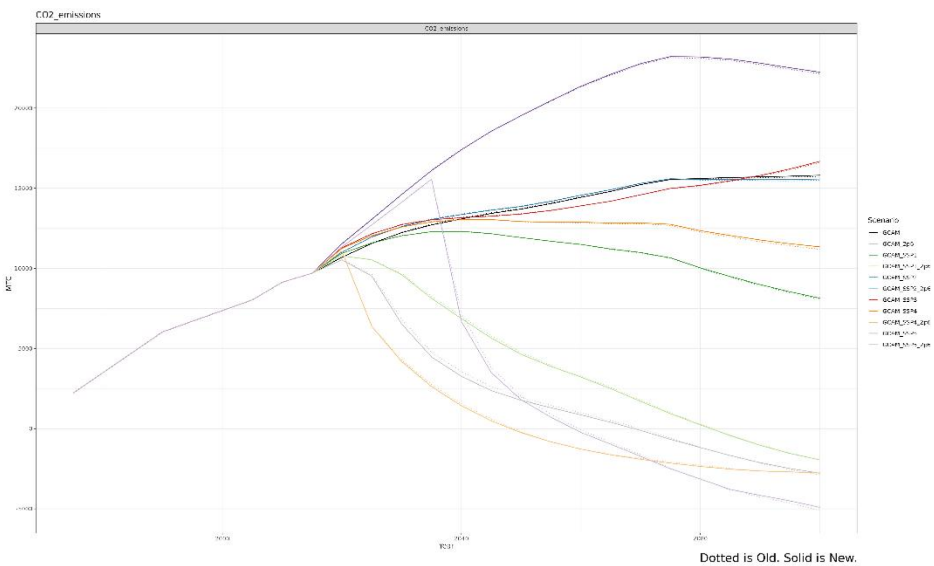
CO2_emissions
Scenario
GCAM
GCAM_2p6
GCAM_SSP2_2p6
GCAM_SSP3
GCAM_SSP4
GCAM_SSP4_2p6
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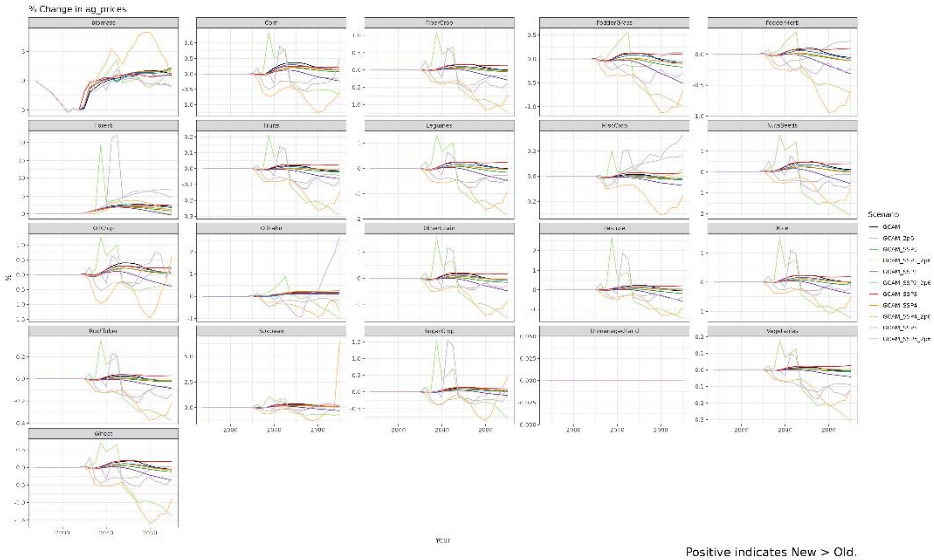

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