THE STATE OF MAINE'S CARBON BUDGET

Version 2, 2017-2021

Daniel Hayes[1,3,5], Angela Brewer[2], Adam Daigneault[1,3], Claire Enterline[4], Ivan Fernandez[1,3,5], Jereme Frank[6], Beverly Johnson[7], Stacy Knapp[8], Kasey Legaard[3], Nichole Price[9], Kristen Puryear[10], Erin Simons-Legaard[1,3], Abigail Stevens[1,11], Xinyuan Wei[1,3], Aaron Weiskittel[1,3]

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[1]School of Forest Resources, University of Maine
[2] Maine Department of Environmental Protection
[3] Center for Research on Sustainable Forests, University of Maine
[4] Gulf of Maine Research Institute
[5] Climate Change Institute, University of Maine
[6] Maine Forest Service
[7] Earth and Climate Sciences, Bates College
[8] Maine Department of Environmental Protection
[9] Bigelow Laboratories
[10] Maine Natural Areas Program
[11] Ecology and Environmental Sciences, University of Maine

Abstract

This report examines Maine's carbon budget, focusing on greenhouse gas emissions and carbon sequestration from 2017 to 2021. The study makes it clear that Maine's forests play a crucial role in mitigating climate change, absorbing nearly 91% of the state's greenhouse gas emissions during this period. Transportation remains the largest source of emissions, accounting for approximately 48% of the total. Encouragingly, Maine's overall emissions have been declining over time. Notably, the state's ability to offset its emissions has significantly improved, from 51% in 2007-2011 to 91% in 2017-2021. While forests are the primary carbon sink, coastal wetlands like salt marshes and eelgrass beds also contribute to carbon storage, albeit on a smaller scale. Additionally, carbon stored in wood products helps offset some emissions.

Introduction

The state of Maine is increasingly experiencing the impacts of climate change through warming temperatures, more frequent and severe storms, periods of drought, flooding, and sea-level rise (see Maine's Climate Future reports 2009, 2015, 2020; Maine Climate Council's Scientific and Technical Subcommittee reports 2020, 2021, 2024). These impacts are having dramatic effects on Maine's landscapes and ecosystems, its infrastructure and economy, and human health. In response, in 2019 Maine established statutory mitigation targets requiring a 45% reduction in greenhouse gas (GHG) emissions below 1990 levels by 2030, and at least 80% reduction by 2050. A critical part of this process is the tracking and biennial reporting of progress toward these goals by the Maine Department of Environmental Protection (DEP). These reports include detailed accounting of the *gross* emission of GHGs across the state from sources in the energy (transportation, residential, commercial, industrial, and electric power), agricultural, industrial processes, and waste categories. The most recent Tenth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals (June 2024) found annual CO_2 emissions from fossil fuel combustion in the electric power sector have decreased by 79% since they peaked in 2002, and current emissions trends are projected to be on track to meet the gross greenhouse gas reduction targets in 2030 and 2050 if emissions reductions continue or accelerate.

The data in the *Ninth Report* in part predate the release of the State's climate action plan (Maine Won't Wait, December 2020), which laid out strategies to ensure Maine meets the targets for reductions in gross GHG emissions when fully implemented. These goals were expanded by an executive order and later in statute (effective 2022) adding a target for achieving carbon neutrality in the state by 2045. ***Carbon neutrality*** is defined as the state of net zero carbon emissions, which is achieved by balancing anthropogenic emissions with the sequestration of carbon in the environment. Monitoring progress toward carbon neutrality now requires the DEP, in addition to reporting gross GHG emissions, to also quantify *net* emissions by accounting for carbon sequestration. The DEP Rules Chapter 167 establishes the methods at each reporting period for the calculation of annual gross and net GHG emissions to measure progress toward the reduction goals of the state's climate action plan.

Maine's ***net*** GHG emissions estimate was reported for the first time in the DEP's 9th Biennial Greenhouse Gas Report (7/25/2022). The net emissions calculation was based on comparing the gross GHG emissions data with a comprehensive accounting of carbon emissions and removals estimates for the major carbon pools and fluxes in the state's natural and working lands and waters. The State of Maine's Carbon Budget (version 1.0) was developed and led by researchers at the University of Maine's Center for Research on Sustainable Forests (CRSF) and other partners and released in 2022. The analysis compiled, synthesized, and reconciled the best available data at the time from various sources estimating the changes in stocks of live biomass and dead organic matter pools within and among the wood products, forest, agriculture, urban, wetland, and inland and coastal waters components of the state's carbon budget approximately representing the ten-year period from 2007 to 2016. The analysis suggested that, circa 2016 and using the methodology defined at that time, approximately 75% of Maine's gross GHG emissions were being offset by overall sequestration in land- and water-based carbon pools.

In The State of Maine's Carbon Budget (Version 2.0), we present the updated and revised estimates included in the net emissions calculation for the DEP's Tenth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals (2024). This version 2.0 budget updates the estimates (ca. 2021) along with five-year intervals to report three recent time periods (2007-2011, 2012-2016, and 2017-2021) using the same data sources and consistent methodology as outlined in the DEP Rules Chapter 167. Compared to version 1.0, this new budget analysis uses the same component pools, fluxes, and transfers but the updated estimates for these incorporate several new data sources and improved calculation approaches, as we describe in this report.

Assembling the State Carbon Budget, v 2.0

We calculated the state-level carbon budget by assembling various estimates of the major components of the carbon cycle, either as the change in carbon stock of a given pool between two dates, or as the average annual flux or transfer of carbon from one pool to another over that same time period. We modeled our approach after previous carbon budget assessments done at global and regional scales, the Global Carbon Budget (Friedlingstein et al. 2023) and the Second State of the Carbon Cycle Report for North America (Hayes et al. 2018) being prominent examples. First, we identified the major categories of Maine's carbon-containing natural and working lands and waters, or what we might call our "buckets": forests and wood products, agriculture, urban, interior wetlands, inland waters, coastal wetlands, and coastal waters. These categories are represented on the map in **Figure 1**, from which we can estimate the area of the state covered by each (**Table 1**). To construct Figure 2, we added a box for each of these categories, assembled together with boxes representing gross emissions and what ultimately ends up being added to the atmosphere as "the atmosphere," including arrows to represent the fluxes and transfers of carbon among the components of the carbon cycle. This resulted in the template for the budget diagram that we used here to illustrate the flows of carbon through the system (**Figure 2**).

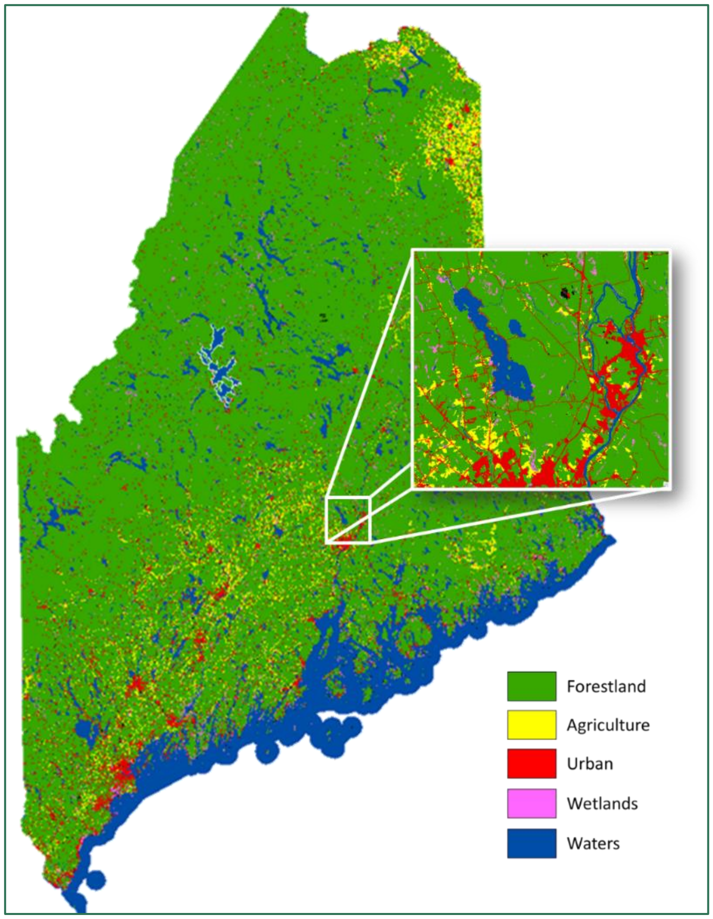

Figure 1. This map combines categories from the USGS National Land Cover Database (NLCD) for 2021 to show the general distribution of the major natural and working lands and waters sectors across Maine, with an inset map shown in greater spatial detail.

Using this box and arrow diagram as a framework for the key components that support a statewide carbon budget calculation, we populated the main budget components with estimates of stock changes and fluxes based on the best available data using established accounting methods for estimates. Estimates in the boxes were typically derived from inventory-based data where the annual average rate of change could be calculated from stocks measured in carbon pools between two points over a given period of time. The flux estimates represented by the arrows often come from modeled estimates and research that has studied land-atmosphere carbon exchange and other fluxes from representative ecosystems or managed environments. Taken together, **the budget diagram assembled in this way allowed us to quantify and interpret the state-level carbon budget from two perspectives: (1) the storage (sequestration) of carbon within the major pools, or "buckets," and (2) the emissions or removals of carbon in these pools to/from the atmosphere**. Here we can report net emissions by the proportion (%) of gross GHG emissions that are offset by storage in the major pools of the natural and working lands and waters in Maine, as evaluated in units of average annual mass of CO_2 equivalent gas added to (or removed from) the atmosphere. The carbon neutrality target will be achieved when Maine's net emissions offset reaches or exceeds 100% of gross emissions at a given point in time as defined by the approved methodology for that analysis.

Table 1. ***The area (shown in acres and proportion of the total) represented by each natural and working lands and waters sector in Maine, ca. 2021. The Forestland area is the U.S. Forest Service Forest Inventory and Analysis estimate for the 2021 inventory year. The Coastal Wetlands area is the sum of eelgrass, farmed seaweed, and saltmarsh coverage based on mapping by Maine Natural Areas Program, Maine Department of Environmental Protection, and recent research (see text below). The other categories are calculated from the USGS National Land Cover Database for 2021.***

Sector	Area (acres)	% of Total
Forestland	17,518,847	84.4%
Agriculture	744,031	3.6%
Urban	956,477	4.6%
Inland Wetlands	264,642	1.3%
Other	285,636	1.4%
Inland Water	951,282	4.6%
Coastal Wetlands	39,853	0.2%
TOTAL	**20,760,767**	**100%**

The State of the State Carbon Budget, ca 2021

The diagram in Figure 2 illustrates the carbon budget of estimated stock changes and fluxes over the 2017 to 2021 time period for Maine's natural and working lands and waters relative to the state's gross GHG emissions. We used this full budget approach to estimate the state's net emissions during this time period to be approximately +1.4 MMTCO_2e/yr, or about 8.7% of the +16.1 MMTCO_2e/yr gross emissions remaining in the atmosphere (i.e., the "airborne fraction") after accounting for offsetting net emissions and removals from the state's natural and working lands and waters (**Table 2**). The **major source of atmospheric GHGs is gross emissions from the energy sector** (+15.4 MMTCO_2e/yr), with smaller additional contributions from agricultural emissions of nitrous oxide (Ag. N_2O) and waste. **In the energy sector, transportation** (+7.8 MMTCO_2e/yr) **is the largest contributor** (48.4%) to gross GHG emissions, followed by residential (+3.0 MMTCO_2e/yr; 18.6%), industrial, electric power, and commercial sources. On the net emissions side, **Forestland represents the largest GHG removals category with an estimated net uptake of -22.2 MMTCO_2e/yr from 2017 to 2021**. Not all of this carbon is stored in the forest ecosystem pools, however, with portions removed in harvest (-6.0 MMTCO_2e/yr) or transferred to the aquatic system (-1.4 MMTCO_2e/yr). In addition to Forestland, **Coastal Wetland soils** (saltmarshes, eelgrass, and farmed seaweed) **represent a small net sink for atmospheric GHGs** (-0.07 MMTCO_2e/yr) in the statewide carbon budget; however, **these are some of the most effective ecosystems in the state for long-term carbon burial on a per square meter basis** (Mcleod et al. 2011). The remaining categories act as net sources, including +4.4 MMTCO_2e/yr from Wood Products decay and a combined +1.8 MMTCO_2e/yr from Agriculture, Urban, and Interior Wetlands. An additional +1.4 MMTCO_2e/yr is added to the atmosphere as emissions from the state's inland and coastal waters. Summarizing across all of the natural and working lands and waters categories in Maine, we estimate a net sink of -14.7 MMTCO_2e/yr, which represents a 91.3% offset of gross GHG emissions in the state over the 2017 to 2021 time period.

Guide to Reading the Maine Carbon Budget (Version 2)

The carbon budget assessment shown in Figure 2 is the second iteration of an estimate of the major flows of carbon among the various component pools of The State of Maine's Carbon Budget (Version 2). Fluxes are estimated as either stock changes (differences in stocks between two years divided by the number of years) or direct fluxes (typically estimated by factors derived from the literature and/or as reported annually by the U.S.

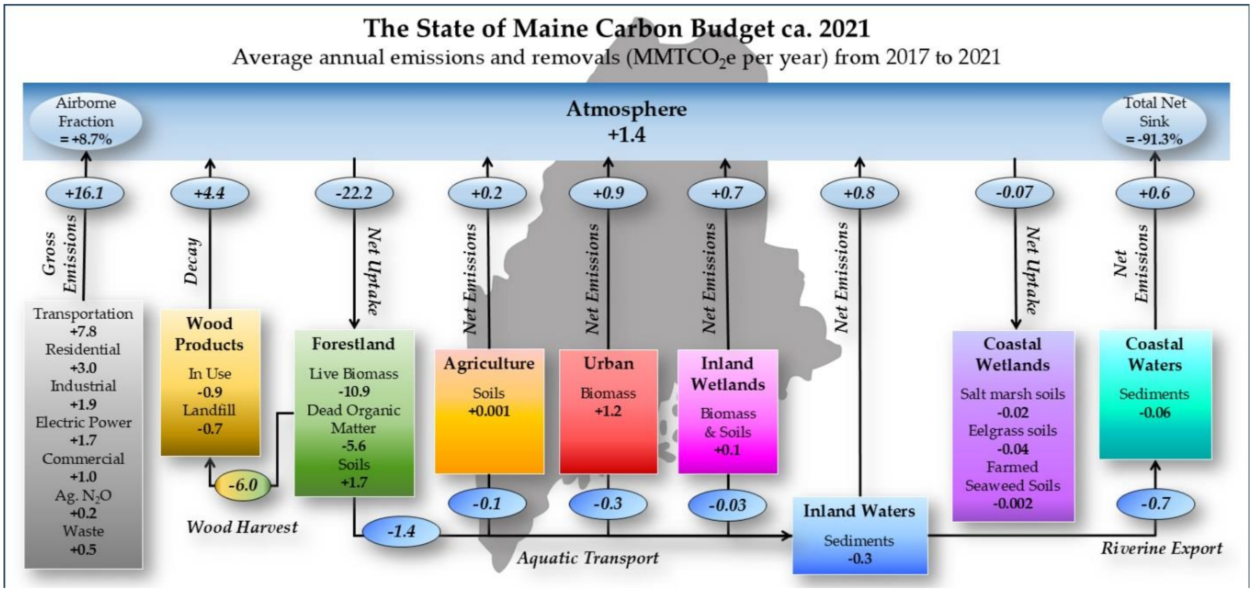

Figure 2. ***This budget diagram illustrates the contemporary state of the carbon cycle in the State of Maine, USA, with estimates of carbon stock change within and fluxes between the major component pools, or "buckets". The estimates are provided here as annual averages, in million metric tons of carbon dioxide equivalent per year (MMTCO$_2$e/yr), approximating the time period from 2017 to 2021. The estimates are given from the atmospheric perspective, where positive values represent net emissions and negative values are net removals. Visit the*** **Carbon webpage** ***for downloadable, high-resolution image.***

Environmental Protection Agency [EPA] in the Inventory of U.S. Greenhouse Gas Emissions and Sinks). The data shown here represent an approximate 5-year period of averaging to estimate an annual change or flux for most compartments in this budget, which are compared with an accounting of annual gross GHG emissions over the same time period, as required by Maine statutes.

Figure 2 is constructed to guide the viewer using the following conventions:

- Stock change and flux values in the diagram are provided in units of million metric tons of carbon dioxide equivalent per year (MMTCO$_2$e/yr). Carbon expressed as CO$_2$e is the mass of C multiplied by the molecular weight ratio of CO_2:C, i.e. 44/12. Carbon in methane (CH_4) gas expressed in units of CO$_2$e is the mass of C times the molecular weight ratio of CH_4:C, i.e. 16/12, and multiplied by the 100-year global warming potential (GWP) of CH_4, i.e. 27.9 according to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6).
- Because it is a carbon budget, only carbon in organic matter and carbon-containing GHGs (i.e., CO_2 and CH_4) are included in the natural and working lands and waters (NWLW) calculations in this figure. However, N_2O emissions sources (GWP 273) are

included in the gross emissions estimates. Including N_2O emissions from NWLW sources in future versions of the net emissions calculation will require additional data that are not currently available.

- ❖ Stock change labels and values are shown in the boxes in regular text. Each box represents a major component ("bucket") storing carbon. The values are given from the atmospheric perspective, where positive values represent net emissions reflecting a loss of carbon from NWLW pools while net uptake (removals from the atmosphere) by, storage in, and lateral transfers among NWLW components are given as negative values.
- ❖ Flux labels and values are shown in italics in the ovals. Flux values are estimates of the average annual rate of carbon transfer between two pools over the 2017 to 2021 period. The arrows show the direction of the net flux estimates.
- ❖ For each box, the sum of all fluxes into the pool minus those out of the pool equals the net change in carbon stock for that component. All of the data in the budget 'add up' to maintain the mass balance of all carbon stock changes and fluxes over the whole statewide carbon budget system. Note that the mass balance is maintained in units of carbon, but will differ slightly as shown in this diagram as a result of the small amount of carbon as CH_4 gas that was converted to units of CO_2 equivalent and included in the net emissions estimates for Agriculture and Inland Wetlands (**Table 2**).
- ❖ As explained where appropriate in the sections below, some datasets used in this analysis – such as gross GHG emissions – have a temporal resolution allowing precise time periods to be summarized (i.e., annually). Other data, such as carbon burial in the soils of coastal wetland ecosystems, are average flux rates derived from research studies and used here to approximate the annual flux for the current time period. To calculate the change in carbon stocks in the Forestland pools, we used data from the U.S. Forest Service's Forest Inventory and Analysis (FIA) program. Since Forestland represents the largest component of Maine's statewide budget in terms of the magnitude of its stocks and fluxes, we chose to assemble this Version 2 budget for a 5-year time period to match the 5-year inventory cycle for FIA in Maine. As such, this diagram attempts to synthesize the various budget components in the state using reported estimates and datasets generally representative of the 2017 to 2021 time period. In addition, we retrospectively calculated the budget for the two preceding five-year periods (i.e., 2007-2011 and 2012-2016) using the same datasets and methods and we included these estimates in the data tables in the sections below for comparison.

Table 2. Estimated average annual emissions/removals of greenhouse gases (in $MMTCO_2eq$ per year) gross and net emissions sectors and pools in Maine over three 5-year time periods (2007-2011, 2012-2016, 2017-2021). The proportion offset or contributed (%) by each flux relative to the total gross emissions for that time period are included with each estimate.

Sector	Pool	2007-2011	%	2012-2016	%	2017-2021	%
Gross Emissions	***TOTAL***	**20.2**	**100.0%**	**17.9**	**100.0%**	**16.1**	**100.0%**
Energy	***Total***	**19.4**	**96.0%**	**17.2**	**96.1%**	**15.4**	**95.7%**
	Transportation	8.8	43.6%	9.0	50.3%	7.8	48.4%
	Residential	3.1	15.3%	2.7	15.1%	3.0	18.6%
	Industrial	3.1	15.3%	2.2	12.3%	1.9	11.8%
	Electric power	2.0	9.9%	1.7	9.5%	1.7	10.6%
	Commercial	2.4	11.9%	1.6	8.9%	1.0	6.2%
Agriculture	***N2O only***	**0.3**	**1.5%**	**0.2**	**1.1%**	**0.2**	**1.2%**
Waste	***Total***	**0.5**	**2.5%**	**0.5**	**2.8%**	**0.5**	**3.1%**
Net Emissions	***TOTAL***	**-10.3**	**-51.0%**	**-14.4**	**-80.4%**	**-14.7**	**-91.1%**
Wood Products	*CO_2 Emissions*	5.8	28.7%	5.4	30.2%	4.4	27.3%
Forestland	*CO_2 Emissions*	-19.1	-94.6%	-22.7	-126.8%	-22.2	-137.9%
Agriculture	*CH_4 Emissions*	0.3	1.5%	0.3	1.7%	0.3	1.9%
Agriculture	*CO_2 Emissions*	-0.1	-0.5%	-0.1	-0.6%	-0.1	-0.6%
Urban	*CO_2 Emissions*	0.8	4.0%	0.9	5.0%	0.9	5.6%
Inland Wetlands	*CH_4 Emissions*	0.6	3.0%	0.6	3.4%	0.6	3.7%
Inland Wetlands	*CO_2 Emissions*	0.1	0.5%	0.1	0.6%	0.1	0.6%
Inland Waters	*CO_2 Emissions*	0.7	3.5%	0.6	3.4%	0.8	5.0%
Coastal Wetlands	*CO_2 Emissions*	-0.1	-0.5%	-0.1	-0.6%	-0.07	-0.4%
Coastal Waters	*CO_2 Emissions*	0.7	3.5%	0.6	3.4%	0.6	3.7%
Atmosphere	***Net Storage***	**9.9**	**49.0%**	**3.5**	**19.6%**	**1.4**	**8.9%**
Net Storage	***TOTAL***	**-11.3**	**-55.9%**	**-15.2**	**-84.9%**	**-15.5**	**-96.4%**

The following description is intended to inform the reader about the approach or source of data for each component of the Maine Carbon Budget Version 2 (Figure 2). You might find the interpretation of the figure most logical starting from the left side and working to the right, following the order shown in the headings listed below.

Gross Emissions

The gross emissions of greenhouse gases (GHGs) from human activity, as reported by the Maine Department of Environmental Protection in the series of Biennial Greenhouse Gas Emissions Reports, are drawn from the U.S. EPA State Inventory Tool (SIT) improved with additional data for Maine. These are the GHGs of concern driving human-caused climate change and dominated by fossil fuel combustion in the energy sector. Estimates for gross GHG emissions at the state-level are known with a high level of certainty relative to the other budget components. The estimate for the source of Maine's gross GHG emissions over the 2017 to 2021 time period is the sum of sources from the Transportation, Residential, Industrial, Electric Power, Commercial, Agricultural N_2O and Waste categories, all expressed as $MMTCO_2e$/yr.

Combined with the emissions from industrial processes (primarily cement making) and waste, Maine's gross emissions are estimated to be +16.1 $MMTCO_2e$/yr added to the atmosphere on average over the 2017 to 2021 period. Gross GHG emissions have declined over the last three inventory periods, from an average of +20.2 $MMTCO_2e$/yr from 2007 to 2011 to +17.9 $MMTCO_2e$/yr from 2012 to 2016 (Table 2). The data show steady declines in the Commercial and Industrial sectors over these three inventory periods, but the other energy sectors have been variable. Among all sectors, transportation has been responsible for the majority of GHG emissions across all inventories, accounting for about 40% to 50% of the total gross emissions at each time period.

Carbon Storage in Natural & Working Lands & Waters

The net emissions reflecting the rate of additions and removals of carbon to the atmosphere by all of the NWLW sectors of Maine combined is shown to be relatively steady over the past two inventory periods, from –14.4 $MMTCO_2e$/yr to –14.7 $MMTCO_2e$/yr over the previous (2012–2016) and most recent (2017-2021) time periods, respectively. However, because gross emissions have been declining over the same time periods, the overall proportion of gross GHG emissions that are offset by the net uptake of carbon in NWLW has increased from -51.0% in the 2007 to 2011 time period to 80.4% in 2012–2016 and -91.3% in 2017–2021. Net uptake (i.e., negative CO_2 emissions) by the Forestland has been the largest contributor in taking up carbon from the atmosphere, accounting for -94.6%, -126.8%, and -137.9% of gross GHG emissions over the past three inventory periods, respectively. Not all of that carbon uptake remains in Forestland, though, with portions moved laterally to other "buckets" and ultimately returned to the atmosphere via wood products decay or emissions from carbon lost to the inland and coastal waters. As such, we evaluate the more true representation of the role that the forest and forestry sector play in contributing to GHG mitigation by calculating the actual storage of carbon in the Forestland and Wood Products pools during this time period, as described below. The other NWLW sectors, meanwhile, vary from small sinks (negative emissions) to small sources of GHG emissions.

Forestland

Start evaluating the carbon budget contribution of the forest sector in this box. These estimates of stock change in the major forest ecosystem pools come from the US Forest Service Forest Inventory and Analysis (FIA) program. The FIA data represent measured and modeled stock values for carbon at the first (2017) and last (2021) years in the inventory period, accessed online via the EVALIDator tool v2.1.1. The FIA recently revised its estimation procedures with updated National Scale Volume and Biomass equations for U.S. forests (Westfall et al. 2023). We used these new estimates to calculate carbon stock change in the Forestland sector for all three inventory periods covered in this report. While the Forestland carbon estimates remain consistent across time periods in this report, they differ from those reported for 2006 to 2016 in the State of Maine Carbon Budget Version 1 because of this change in US Forest Service methodology.

The estimated average annual stock change in each pool is calculated as the difference in quantity (carbon mass) from the first to last date, divided by the number of years in the inventory and converted to units of CO_2 equivalent. The estimates for each component pool as defined by FIA are organized here as Live Biomass (including above- and below- ground), Dead Organic Matter (including coarse woody debris and fine litter), and Soils (including organic soils). According to the FIA data (**Table 3**), the Live Biomass pool gained approximately -10.9 $MMTCO_2e$ on average each year between 2017 and 2021 while -5.6 $MMTCO_2e$/yr was added to the Dead Organic Matter pool. These gains in forest ecosystem carbon stock were counteracted in part by an estimated +1.7 $MMTCO_2e$/yr loss of carbon in the Soils pool over this inventory period. The estimated net storage of -14.8 $MMTCO_2e$/yr in Maine's Forestland pools represents a -91.9% offset of the state's +16.1 $MMTCO_2e$/yr gross emissions over the 2017 to 2021 period.

Table 3. ***FIA estimates of forest carbon emissions / removals by pool* (MMTCO$_2$e/yr) *on Forestland in Maine for each 5-year inventory period.***

(MMT CO$_2$e / year)	2007-2011	2012-2016	2017-2021
Forest Carbon Pools	**-10.4**	**-14.9**	**-14.8**
Live Aboveground	-8.7	-14.2	-9.3
Live Belowground	-1.5	-2.6	-1.6
Dead Wood	-1.0	-1.4	-5.6
Litter	-0.1	0.2	0.0
Soil Organic	0.8	3.1	1.7
Wood Products	**-1.5**	**-1.2**	**-1.6**
In Use	-1.2	-0.8	-0.9
SWDS	-0.4	-0.4	-0.7
TOTAL	**-11.9**	**-16.0**	**-16.4**

Carbon input to the Forestland component happens through the fixation of CO_2 from the atmosphere into live biomass through the process of photosynthesis. Carbon is returned from the forest ecosystem to the atmosphere as CO_2 or CH_4 through plant maintenance respiration, organic matter decomposition (soil respiration), methane production (methanogenesis), and biomass burning. The balance between uptake and release (i.e., net "vertical" carbon exchange between Forestland and the Atmosphere, shown here as *Net Uptake* to Forestland in Figure 2) is not measured directly but inferred here to be -22.2 MMTCO$_2$e/yr meaning that more C is being removed from the atmosphere than is being released by the Forestland pools. This estimated rate of net annual atmospheric CO_2 uptake for the 2017–2021 measurement period is calculated as the sum of the stock change in the forest ecosystem pools (-14.8 MMTCO$_2$e/yr) plus the carbon removed "laterally" through wood harvest (-6.0 MMTCO$_2$e/yr) plus the carbon leaving through the aquatic system (-1.4 MMTCO$_2$e/yr), as explained below.

Wood Products

The inputs to this box represent the carbon removed in forest harvesting that is used in wood products, as reported annually in the Maine Forest Service's Wood Processor Report (2020). The fate of the estimated -6.0 MMTCO$_2$e/yr in harvested wood is tracked through a product life cycle model (Wei et al. 2023). The model estimates how long different types of wood products will store carbon based on their durability while "in use" (e.g., paper lasts less than a decade while wood in furniture and buildings can last over a century) or as solid waste disposal in the "landfill" pool. The model estimates that -0.9 and -0.7 MMTCO_2e were added annually from 2017 to 2021 to the In Use and Landfill pools, respectively. Subtracting these stock changes from the harvest inputs, the remaining +4.4 MMTCO_2e is released back to the atmosphere on an annual basis, represented here as *Decay* from the Wood Products box.

The Forest Sector (Forestland + Wood Products)

The forest sector's total contribution to the state's net emission calculation over the 2017 to 2021 period is considered the sum of the CO_2e added to the forest ecosystem (-14.8 MMTCO_2e/yr) plus the wood products (-1.6 MMTCO_2e/yr) pools, as shown in **Table 3**. This estimated -16.4 MMTCO_2e/yr total added to carbon storage in the forest ecosystem and wood products pools offsets approximately 101.9% of Maine's reported +16.1 MMTCO_2e/yr in gross GHG emissions for this time interval.

Agriculture, Urban, & Interior Wetlands

The calculations for the Agriculture, Urban, and Interior Wetlands sectors primarily relied on data from the US Environmental Protection Agency (EPA) National Inventory of U.S. Greenhouse Gas Emissions and Sinks report (2023). EPA data for these sectors are reported annually as emissions / removals, which we used here as the estimates for direct flux to the atmosphere (averaged for each of the three five-year time periods) from each "bucket". For these estimates, the EPA applies generalized flux factors for various carbon processes to the aerial extent of that land use type. We can then infer the stock change estimates within the boxes in our diagram using these flux data and other information, including land use change and aquatic transport. The emissions from Agriculture include both CO_2 and CH_4 emissions sources from soil management and fertilization, enteric fermentation from livestock, field burning, and manure management. The Urban sector accounts for carbon uptake in urban trees, but overall it represents a source of carbon in EPA data by accounting for the loss of carbon stocks due to the process of conversion from other land uses (e.g., Forestland-to-Settlements). The Interior Wetlands sector also represents a source, primarily due to CH_4 emissions from flooded lands. The Agriculture and Interior Wetlands sectors are two instances where the carbon "mass balance" is not represented by this diagram because the CH_4 form of carbon emissions has been converted to CO_2 equivalent to facilitate offset calculations.

Inland Waters

This represents the dissolved organic carbon (DOC) and particulate organic carbon (POC) that is suspended in freshwater and transported from the landscape to the coast via the major river systems of Maine. The US Geological Survey measures carbon concentrations and hydrologic flux (i.e., the amount of water leaving the landscape) at the mouth of streams and rivers. Based on these measurements, we used an empirical model (Wei et al. 2021) to estimate the total flux of DOC and POC in Maine as the lateral transfer from land to the inland water system. Some portion of this aquatic carbon is buried in the sediments of water bodies, some is released back to the atmosphere as CO_2 outgassing from the water column, and the remainder is exported from rivers to coastal estuary waters and the open ocean.

Based on the estimated export rate (*Riverine Export*, -0.7 $MMTCO_2e$/yr), the model apportions the estimates of Inland Waters total organic carbon as DOC and POC flux into (1) the quantity stored in the sediments of ponds, lakes, and reservoirs (storage in *Sediments*, -0.3 $MMTCO_2e$/yr), and (2) that released from the water column to the atmosphere (*CO_2 Emissions*, +0.8 $MMTCO_2e$/yr). That means that the fate of the total carbon mass delivered to the right side of the figure from *Aquatic Transport* would equal the absolute value (meaning ignore the + and -) of the sum of (1) carbon lost to the atmosphere (*Net Emissions*) plus (2) the carbon stored in Sediments plus (3) the carbon remaining in transport to the oceans as *Riverine Export* or a total of -1.8 $MMTCO_2e$/yr (= 0.8 + 0.3 + 0.7 $MMTCO_2e$/yr). Of this total carbon flux to Inland Waters, the amount that comes from each of the land uses (e.g., Agriculture, Urban) is calculated proportionally by the areal extent of that land use type in Maine (i.e., -1.4, -0.1, -0.3, and -0.03 $MMTCO_2e$/yr from Forestland, Agriculture, Urban, and Interior Wetlands, respectively) based on the 2021 Land Cover map for the state (**Table 1**).

Coastal Wetlands

Carbon burial in coastal wetlands soils was calculated based on the area of each habitat and measured or estimated carbon burial rates in the soils of these habitats. Carbon stocks were determined as a function of ecosystem area, and carbon density in the soils, to a depth of 1 m for salt marsh soils, 30 cm for eelgrass soils, and 25 cm for farmed seaweed soils. The total area of coastal wetlands used for the estimate was 161.3 km^2 (39,853 acres, Table 1), and a total burial rate in coastal wetlands soils of -0.07 MMTCO2e/yr.

Blue carbon stock and burial rate estimates for salt marsh soils are based on a total statewide marsh area of 73 km^2 of tidal and brackish salt marshes (18,095 acres; Maine

Natural Areas Program, 2019), an average carbon density over the upper 1 m of 0.041 gC per cm^3 of soil (Johnson et al., 2023 DOI:10.25573/serc.17018816), and an average burial rate of 74 gC per m^2 per year (Maine data published in Drake et al., 2015). The estimated burial rate for salt marsh soils is -0.0199 MMTCO2e/yr. A reduction in burial rate for saltmarsh soils compared to the 2012-2016 estimate is based on refined estimates of burial rates for this habitat in regional studies (Drake et al. 2015). Blue carbon stock and burial rate estimates for eelgrass meadow soils is based on a statewide mapped area of 87.7 km^2 (21,671 acres; Maine DEP 2018; Maine DMR 2010), an average carbon density over the upper 30 cm of 0.012 gC per cm^3 (Colarusso et al. 2023), and an average burial rate of 138 gC per m^2 per year (summarized in McLeod et al., 2011). The estimated burial rate for eelgrass meadow soils is -0.04 MMTCO2e/yr. A reduction in the burial rate for eelgrass habitat from the 2012-2016 estimate is based on recent mapping showing a reduction in eelgrass habitat areal coverage. For farmed seaweed soils, rates of carbon deposition per unit area and time were developed through an effort led by Duarte et al. 2024 and Gasser et al. 2024. The area of harvested seaweed is estimated to be 0.35 km^2 (86.4 acres; Brayden and Coleman 2023), and an average burial rate of 0.007gC m^2 per year (Duarte et al. 2024 and Gasser et al. 2024). The estimated burial rate for farmed macroalgae soils is -0.002 MMTCO2e/yr.

Blue carbon stocks and burial rates for wild macroalgae were not able to be estimated. Intertidal and subtidal seaweed estimates could be not determined as there is not currently sufficient information about the extent and area of these macroalgae beds for the entire state. There are several large, funded projects underway in the Gulf of Maine to continue development of remote sensing tools for intertidal seaweed species that could be paired with existing state-wide efforts to monitor saltmarshes and eelgrasses. There are no concerted state-wide efforts planned to monitor subtidal species of seaweed. Further, cost-effective monitoring, reporting, and verification tools for carbon deposition and storage rates for seaweeds are in development. We are hopeful that by the next Maine carbon budget effort (2026), all the necessary tools and data will be in place.

Coastal Waters

Finally, we complete the budget diagram by calculating the inferred CO_2 *Net Emissions* from Coastal Waters (+0.6 $MMTCO_2e$/yr) as coming from the *Riverine Export* flux (-0.7 $MMTCO_2e$/yr) from Inland Waters as apportioned by the model (Wei et al. 2021) minus the proportion of that flux that the model stores in Coastal Waters Sediments (-0.06 $MMTCO_2e$/yr).

Offset Calculations

Atmosphere – Add up all the top row net emissions in the ovals (starting with +16.1 MMTCO_2e). Net emissions are positive and net uptake is negative, so it is important to include the sign of the flux in the calculation. This gives you the net addition of greenhouse gas to the atmosphere, in this case +1.4 MMTCO_2e for the Atmosphere as shown in the figure.

Airborne Fraction - Gross emissions are fossil fuel, agricultural, and waste emissions (+16.1 MMTCO_2e) but only +1.4 MMTCO_2e remains as the Airborne Fraction. Therefore, the Airborne Fraction is [1.4/16.1 * 100] or approximately +8.7%.

Total Net Sink - The total GHG sink for all compartments included in this analysis is -14.7 MMTCO_2e representing an approximately -91.3% offset of Maine's +16.1 MMTCO_2e total gross GHG emissions for the 2017 to 2021 time period.

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