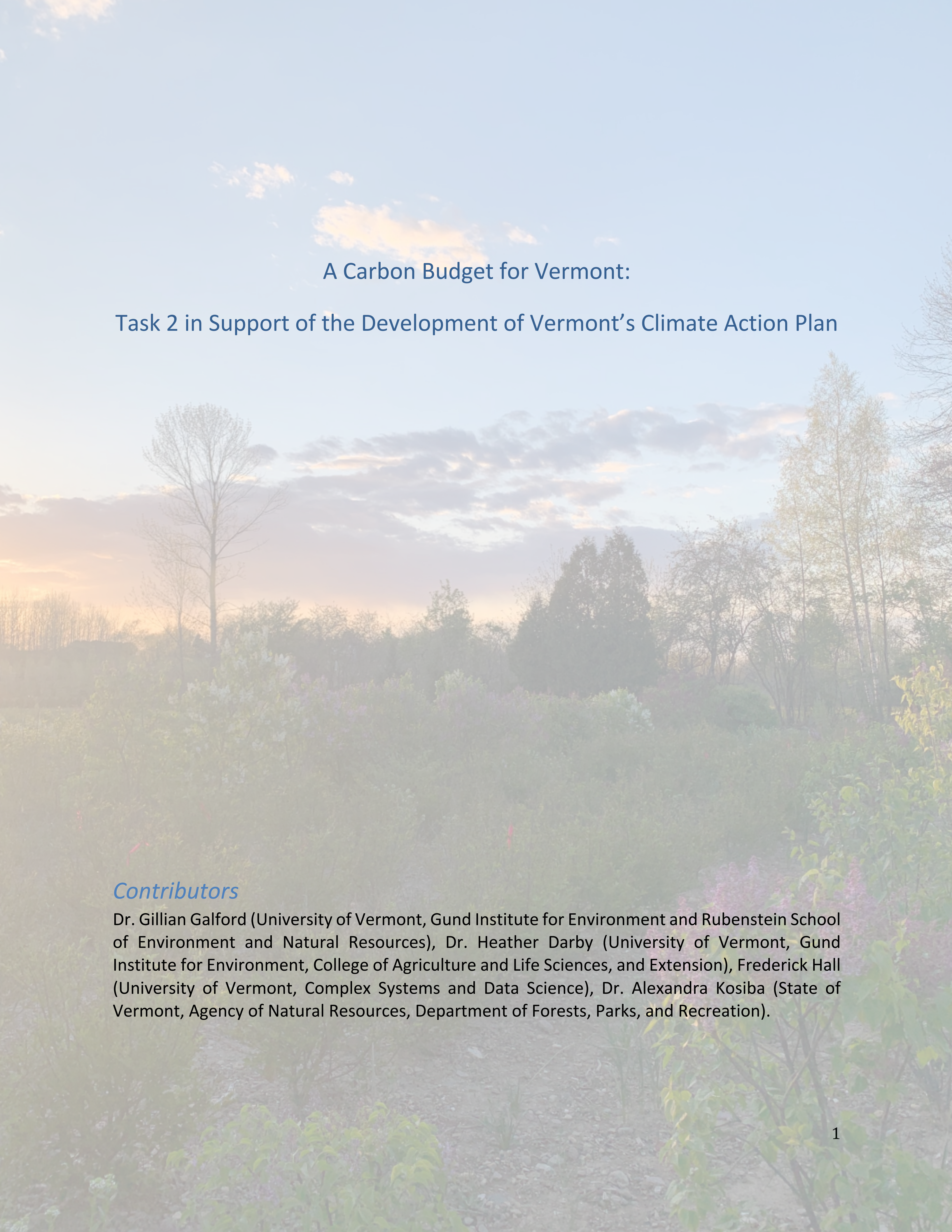

A Carbon Budget for Vermont:

Task 2 in Support of the Development of Vermont’s Climate Action Plan

Contributors

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Acronyms & Abbreviations

AFOLU	Agriculture, Forestry, and Other Land Use
ANR	Agency of Natural Resources (State of Vermont)
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
C	Carbon
CAP	Climate Action Plan
CH_4	Methane
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
DEC	Department of Environmental Conservation
EFG	Energy Futures Group
EPA	Environmental Protection Agency (United States)
EX-ACT	EX-Ante Carbon-balance Tool (developed by FAO)
FAO	Food and Agriculture Organization of the United Nations
FIA	Forest Inventory and Analysis (program of the United States Forest Service)
GHG	Greenhouse gas
GWP	Global warming potential
GPP	Gross primary productivity
GWSA	Global Warming Solutions Act (Vermont)
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
LULUCF	Land Use, Land Use Change, and Forestry
MT	Metric ton
MMT CO_2-e	Million metric tons of carbon dioxide equivalent
NLCD	National Land Cover Database (United States Department of Agriculture)
NWL	Natural and Working Lands
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
SIT	State Inventory & Projection Tool (developed by EPA)
USDA NASS	US Department of Agriculture National Agriculture Statistical Service
VAAFM	Vermont Agency of Agriculture, Food, and Markets
VCC	Vermont Climate Council
VFCI	Vermont Forest Carbon Inventory

Executive Summary

The Vermont Carbon Budget has been developed to inform the Vermont Climate Council, its subcommittees, and related task groups on the current balance of greenhouse gas (GHG) emissions and carbon stocks related to agriculture, forestry, and other land uses (AFOLU) in Vermont. This is a strong foundation for improved understanding of all carbon sources and sinks and for more accurate tracking and accounting going forward. Vermont's proactive science-based climate change mitigation efforts are evidenced by its investments in both a GHG Inventory and this Carbon Budget.

The Vermont Carbon Budget presents stocks and fluxes of carbon based on the best available data on land use and land use management in Vermont, data and analysis compiled and shared for the first time here. We consider the GHG emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from AFOLU sectors (forests and harvested wood products, wetlands and water bodies, agriculture, grasslands and shrublands, and urban and developed lands). The period of focus is 1990 to 2020 (or as close to 2020 as possible, based on available data), so it can inform the Vermont Global Warming Solutions Act (GWSA, 2020) targets to reduce greenhouse gas (GHG) emissions: 26% below 2005 by 2025, 40% below 1990 by 2030 and 80% below 1990 by 2050.

Emissions from fossil fuels (8.6 MMT CO_2-e in 2017) are documented in the Vermont GHG Inventory (VT Agency of Natural Resources, 2021) and used in this analysis for scale and reference. Currently, the annual net GHG balance for AFOLU is -2.95 MMT CO_2-e yr^{-1} in 2020. The largest AFOLU source of GHG emissions is agriculture (0.49 MMT CO_2-e yr^{-1} in 2020), followed by grasslands and shrublands (0.05 MMT CO_2-e yr^{-1} in 2020). Three AFOLU sectors account for net sequestration, or uptake from the atmosphere, as noted with a negative sign: forests (-3.2MMT CO_2-e yr^{-1} for net forest sector in 2018), urban and developed (-0.28 MMT CO_2-e yr^{-1} in 2020) and wetlands and water bodies (-0.01 MMT CO_2-e yr^{-1} in 2020) See Table ES in this section. While the AFOLU carbon balance shows carbon sequestration, it does not account for even half of fossil fuel emissions reported in the Vermont GHG Inventory.

This Carbon Budget utilizes the most reliable data available, but acknowledges that there are significant challenges in tracking AFOLU GHG emissions. Limited data, particularly in a few key areas, needs to be remedied to aid in future carbon budgets. Specifically, a database could be created from existing nutrient management plans required for farms; such a database would centralize information on fertilizer rates and types and provide precise information about manure management at different rates and could be regularly updated. Additionally, tracking changes in land use requires knowing both the prior and the current land use for the same location. Existing data sets are either for a single period, have uncertainty or errors too great for stakeholders to consider legitimate, or miss key features that are unique to the Vermont landscape (e.g., clearing for single family homes in forests, small wetlands). New satellite products at higher resolution (e.g., 10 meters) could aid in development of rapid, annual land cover change data for Vermont.

Table ES: Vermont Carbon Budget estimates for stocks and fluxes of carbon and emissions from agriculture, forestry, and other land uses in Vermont compared to fossil fuel emissions.

Source	Stock (MMT CO_2-e)	Flux (MMT CO_2-e yr^{-1}) *			Components	Data source
	2020	1990	2005	2020		
Forests (net)	1,859	-5.1	-3.2	-3.2 (year 2018)	Forests, conversion from forests, and harvested wood products	Kosiba, 2021
Agriculture	63	0.70	0.61	0.49	Crops (including hay), fertilizers, livestock, management	Vermont Carbon Budget
Wetlands and water bodies	57	-0.01	-0.01	-0.01	Wetlands and water bodies	Vermont Carbon Budget
Grasslands and shrublands	41	0.06	0.05	0.05	Unmanaged and managed (e.g., pasture)	Vermont Carbon Budget
Urban and developed	15	-0.26	-0.27	-0.28	Trees	Domke et al., 2020; EPA, 2021; Nowak et al., 2013; Zheng et al., 2013
Net (AFOLU)	1,978	-4.61	-2.82	-2.95		Vermont Carbon Budget
Fossil fuels**	N/A	8.64	9.97	8.6	Vermont GHG Inventory definition	VT ANR, 2021
Net (AFOLU and fossil fuels)		4.03	7.15	5.65		Vermont Carbon Budget

*Note: Stocks represent storage. Negative fluxes indicate net sequestration (additional carbon storage). Positive fluxes represent sources to the atmosphere.

In the AFOLU sector, policies and management decisions may increase carbon sequestration or reduce greenhouse gas emissions. Issues related additionality, permanence, and leakage will need to be defined and addressed collaboratively across sectors. The state of Vermont has committed to a carbon balance approach for tracking and accounting for stocks and fluxes that utilize the most reliable, long-term data available. With this information, the Vermont Climate Council will be able to better develop a strategy for meeting the state's climate goals.

1 Introduction

The Vermont legislature passed the Vermont Global Warming Solutions Act (GWSA) in 2020. The GWSA sets targets for Vermont to reduce greenhouse gas (GHG) emissions: 26% below 2005 by 2025, 40% below 1990 by 2030 and 80% below 1990 by 2050. To accomplish this goal, the GWSA mandated the Vermont Climate Council (VCC) to develop a state Climate Action Plan (CAP). The VCC then identified five main tasks needed to inform the CAP:

1. Review the current GHG Inventory
2. Develop a Carbon Budget
3. Analyze pathways to achieve the Vermont GWSA
4. Research and recommend pathways for achieving the 2025, 2030, and 2050 targets
5. Develop a GHG tracking and reporting framework

This report fulfills the second task: to develop Vermont's Carbon Budget.

Carbon budgets quantify the amount of carbon stocked and sequestered as compared to greenhouse gas emissions and can be used to develop practices and policies that can achieve climate-related emissions limits. The agriculture, forestry, and other land use (AFOLU) sector provides opportunities to reduce emissions and boost carbon sequestration, and so the VCC has instructed the Vermont Carbon Budget to focus on AFOLU emissions. Many other states have done the same.

Carbon budgets quantify the amount of carbon stocked and sequestered as compared to greenhouse gas emissions and can be used to develop practices and policies that can achieve climate-related emissions limits. The Vermont Carbon Budget focus This Carbon Budget utilizes Intergovernmental Panel on Climate Change (IPCC) emissions methodologies to estimate carbon stocks and fluxes, including greenhouse gas (GHG) emissions related to activities in the agriculture, forestry, and other land use (AFOLU) sector, from 1990 to 2020 (or as close to 2020 as possible, based on the most recent data available). Land use involves GHG exchange, whether net to atmosphere (emissions) or net to land (storage or sequestration), of the GHGs carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). In this analysis, methods and analysis have been designed to meet the overarching objective of this Carbon Budget (1990-2020): to provide retrospective estimates of carbon stocks and fluxes to support the VCC in the development of the CAP.

This analysis includes an historical perspective on Vermont's emissions and a number of land use sources not included in Vermont's GHG Inventory, which was calculated using the U.S. Environmental Protection Agency's (EPA's) State Inventory and Projection Tool (SIT). This Carbon Budget uses the Food and Agriculture Organization of the United Nation's (FAO's) Ex-Ante Carbon Balance Tool (EX-ACT) for some land uses in the budget because it better accounts for emissions related to land use practices common to Vermont, including cover cropping, reduced tillage, and no-tillage.

The following research and analysis were completed as part of this task:

- Reviewed how other states are approaching carbon budgets to identify best practices on methodology and data sets and potential opportunities for collaboration on strategies.

- Used FAO's EX-ACT Tool as the framework for the Vermont Carbon Budget and used IPCC emissions methodologies to account for GHG emissions from agriculture and related land uses in the AFOLU sector.
- Utilized or constructed data products detailing AFOLU trends by sector from 1990 to 2020 (or as close to 2020 as possible) and supplemented inputs from EX-ACT with literature reviews and expert knowledge to categorize the stocks and fluxes requested by the VCC.
- Provided all data sets, including input data and EX-ACT spreadsheets, for reference.
- Identified where future carbon budgets would benefit from additional data collection.

At the outset of this project, the authors met with state technical staff and co-chairs of the VCC Agriculture and Ecosystems Subcommittee to finalize the methodology for Task 2 and develop a process for crafting a product that stakeholders will find easy to interpret and use. This report results from a facilitated and iterative process that incorporated recommendations from staff and members.

2 Methods

The VCC mandated that this task include recommendations for a replicable methodology for stock and flux computations, raw and compiled datasets, data sources, and a description of assumptions, caveats, or uncertainty; a complete Carbon Budget; and a written report. This report describes the context for the recommendations and the methods, results, and potential future actions for the Vermont Carbon Budget.

The Vermont Carbon Budget analyzes carbon stocks and fluxes for Vermont's natural and working lands using existing data and reports. Since new data was not collected in this task, the analysis uses known stock and flux parameters from statistical databases, reports, published scientific literature, expert knowledge, and comparison studies in Vermont, New England, and temperate North America ecosystems. When statistical data is not available (e.g., about common agricultural management associated with a particular land use), expert knowledge is used. All data sources used in the Vermont Carbon Budget are publicly available in databases or reports. Data sources were vetted with the input of Vermont Agency of Natural Resources (ANR) technical staff and the VCC. In cases where multiple data sources are available (e.g., agricultural land uses), this Carbon Budget prioritizes sources focused on Vermont and with a long-term record (i.e., 1990 to present).

IPCC methodologies for stocks and fluxes of carbon and GHGs require knowledge about land area by uses and carbon storage or flux per unit area. The IPCC uses Tier 1 (more general) emissions estimates when regional and other specific parameters needed for Tier 2 (more precise) emissions estimates are not available. Likewise, the Vermont Carbon Budget relies primarily on Tier 1.

The forestry estimates were compiled using widely used sources that conform to IPCC guidelines. (Kosiba, 2021).

This analysis estimates some land use emissions using the Food and Agriculture Organization of the United Nations (FAO) Ex-Ante Carbon Balance Tool (EX-ACT) (Bernoux et al., 2010; Bockel et al., 2013; Grewer et al., 2018). EX-ACT is an appraisal system that estimates the impact of field-level activities in AFOLU on GHG emissions and carbon sequestration. The EX-ACT tool accounts for (i) changes in five carbon pools (aboveground biomass, belowground biomass, dead wood, litter, and soil organic carbon) and (ii) emissions of CH_4, N_2O, and selected further CO_2 emissions (Bernoux et al., 2010; Grewer et al., 2018). EX-ACT follows the IPCC methodologies (IPCC, 2019) for accounting and generating Tier 1 GHG emission coefficients and carbon stock change factors for agriculture, forestry, and other land uses. The IPCC (2019) methodology allows combined use of Tier 1 and Tier 2 data. This analysis used Tier 2 factors wherever available, otherwise relying on default Tier 1 factors.

EX-ACT is intended for use in data-scarce contexts, where detailed data on soils, crop physiology, weather, and field measurements of GHG emissions and carbon stock changes are not available. The tool indicates the magnitude of GHG impacts. The method used by the Vermont Carbon Budget does not provide plot (field) or season-specific estimates of GHG emissions, and the tool is not suited to ground-truth actual, realized GHG impacts.

Global Warming Potentials

Global warming potentials (GWPs) account for differences in the average atmospheric lifetime and heat-trapping potency over a 100-year time horizon of the most important GHGs (IPCC, 2013). A method developed by the IPCC, the use of GWPs permits an inventory to calculate and present results on emissions from multiple GHGs in a single equivalent unit, the carbon dioxide equivalent (CO_2-e). The term “GHG impact” refers to the net impact of all GHG emissions and carbon sequestration due to a production system or practice. Negative numbers indicate net carbon sequestration, whereas positive numbers indicate net GHG emissions.

Vermont’s inventory reports on seven GHGs using GWP values to calculate CO_2-e values. This is consistent with IPCC guidance from the Fourth Assessment Report (AR4) (Forster et al., 2007) and is the current standard in state inventories. The IPCC’s Fifth Assessment Report (AR5) contains updated GWPs. The IPCC has also indicated that shorter time horizons may be appropriate for estimation of some GWPs, including CH_4 (IPCC, 2013). See Table 1 for GWP values. To be consistent with Vermont’s GHG Inventory, the Vermont Carbon Budget uses AR4 GWP potentials with 100-year time horizon.

Table 1: IPCC AR4 and AR5 Global Warming Potentials and Atmospheric Lifetimes for the three most significant greenhouse gases in Vermont’s GHG Inventory

GHG	AR4 GWP Value (CO_2-e) *	AR4 Atmospheric Lifetime (years)*	AR5 GWP Value (CO_2-e)	AR5 Atmospheric Lifetime (years)
CO_2	1	Variable	1	Variable
CH_4	25	12	28	12.4
N_2O	298	114	265	121

*AR4 values are used in Vermont’s GHG Inventory

Data collection and processing

All data used for the Vermont Carbon Budget are available upon request with this report. Four steps to data collection were taken:

1. Review of quantitative data from statistical databases and reports. The team utilized the USDA resources, as the data has been collected in a consistent way over time and is likely to be available in perpetuity. Additional, more detailed, information was collected from State of Vermont reports when available.

2. Review of the literature and land use reports by extension representatives and state employees. EX-ACT requires some input information that is not available from statistical data bases or reports in Vermont, and some national data sources on land uses is available but requires review when used at a fine level (e.g., USDA, 2020; USDA NASS, 2021). In such cases, the Carbon Budget relies on peer-reviewed literature and expert review based on the knowledge and experience of extension agents or state employees. For example, the Vermont Agency of Agriculture, Food, and Markets (VAAFM) tracks farms that participate in water quality projects, such as the use of cover crops, so this Carbon Budget accessed this data initiative plus experts' knowledge of participation by additional farms to ensure the most accurate input information possible. Other common land use practices that are essential to calculating the Carbon Budget, such as the type of tillage (full, reduced or no) are not reported in existing data sets but are well-documented in other ways, such as a farm's nutrient management plan. Co-author Dr. Heather Darby reviewed over 80% of the nutrient management plans for farms in Vermont and calculated the rate of use for common practices for each agricultural land use class. In the case of vegetable crops, Dr. Vern Grubinger (University of Vermont Fruit and Berry Specialist) provided information on common management practices.

3. Live interviews. Semi-structured interviews with extension representatives and state employees (i.e., Agency of Natural Resources; Agency of Agriculture, Food, and Markets) about each management practice completed, confirmed, or refined data collected in steps one and two.

4. Interview follow-up. Experts addressed specific written follow-up questions to address information not available in previous steps, or where confirmation was needed. Interviews were conducted individually or in online groups.

The initial Vermont Carbon Budget was developed for 2017, the most recent GHG Inventory year available for Vermont at the time and a USDA National Agricultural and Statistics Service census year, which allowed a more complete data set compared to non-census years. Other census years were prioritized for data continuity, with data filling from surveys or interpolation. Many management practices were estimated based on historical knowledge, best practices, and regulatory changes.

Approaches

The approaches employed in the Vermont Carbon Budget are designed to meet the requirements mandated by the VCC for this task and are described at the beginning of this Methods section. This report includes AFOLU sectors that hold carbon (stocks) and sequester or emit carbon on an annual basis (fluxes) (Table 2).

Table 2: Overview of sectors considered in Vermont's Carbon Budget (1990-2020) from greatest to smallest contributor

Carbon Budget	Sector
Stocks	Forests
	Agriculture
	Wetlands and water bodies
	Grasslands and shrublands
	Urban and developed
Fluxes	Anthropogenic – fossil fuel emissions
	Anthropogenic – land change emissions
	Agriculture
	Grasslands and shrublands
	Wetlands and water bodies
	Urban and developed
	Forests

The VCC's CAP *Task 1: Greenhouse Gas Inventory Review* report summarizes both primary and supporting methods and data for each sector in the Vermont GHG Inventory. The EPA and IPCC guidance on inventory development recommend the use of key category analysis to identify the sectors and the categories within each sector in each jurisdiction (IPCC, 2019; US EPA, 2021). The Task 1 report recommends key category analyses be added to Vermont's Inventory and provides scale and trend key category examples (Hill et al., 2021). Vermont's inventory classifies emissions by seven sectors, and each sector has multiple categories based on IPCC guidelines. The sectors in Vermont's are: 1) Transportation mobile sources; 2) Residential, commercial, and industrial fuel use; 3) Agriculture; 4) Industrial processes; 5) Electricity consumption; 6) Waste; and 7) Fossil fuel industry. Vermont's GHG Inventory considered agricultural stocks and fluxes related to enteric fermentation, manure management, agricultural soils, liming, and urea fertilization and calculated emissions related to 1.372 MMT CO_2-e in 2017 using the EPA SIT tool. The methods for the current inventory generally follow guidelines for each sector from the EPA and IPCC and are mostly consistent within the preceding inventories.

2.1 Anthropogenic—fossil fuels

Vermont's most recent GHG Inventory was prepared by the Air Quality and Climate Division (AQCD) of the Department of Environmental Conservation (DEC) within the Agency of Natural Resources (ANR) (VT Agency of Natural Resources, 2021). The comprehensive GHG Inventory covers the years 1990–2017 and is the most recent estimate of GHG emissions related to the burning of fossil fuels in Vermont (Figure 1). The Inventory's reported GHG emissions levels from 1990 and 2005 serve as the basis for emissions reduction targets established by the 2020 GWSA, including associated targets for 2025 (26% below 2005), 2030 (40% below 1990), and 2050 (80% below 1990).

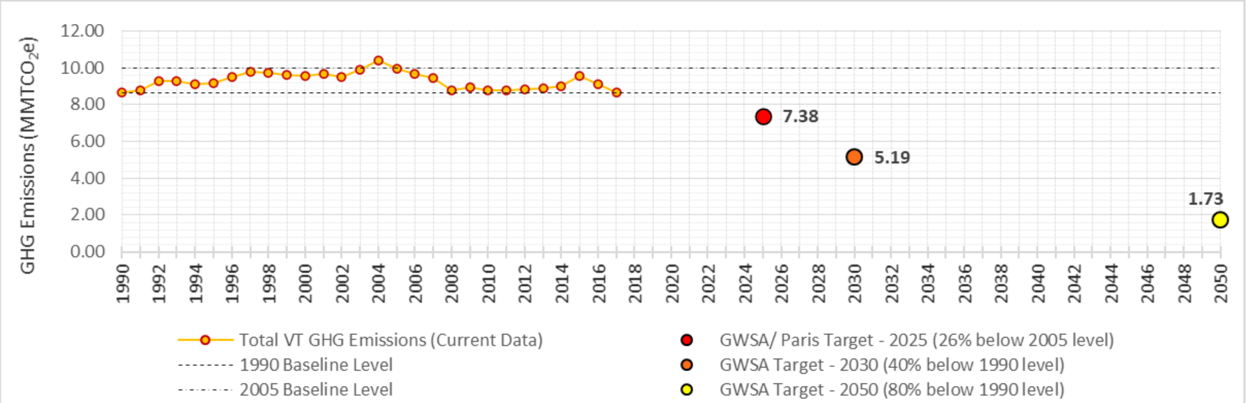


Figure 1: Vermont greenhouse gas emissions and mandated reduction targets as defined in the 2020 Global Warming Solutions Act 153 (GWSA) 10 V.S.A. § 578 (VT Agency of Natural Resources, 2021).

For AFOLU emissions, this Carbon Budget utilizes Vermont's fossil fuel emissions as reported in the 2017 inventory (VT Agency of Natural Resources, 2021). The table below shows a subset of Vermont's total emissions that account for GHG emissions solely from fossil fuels during the years 1990–2019 (Table 3). Note that the "Fossil Fuel Industry" sector in the GHG Inventory is only emissions of fugitive natural gas (CH_4) from transmission and distribution within Vermont. This sector is not related to the combustion of natural gas, which is capture in the Residential/ Commercial/ Industrial (RCI) Fuel Use sector.

Table 3: Categories representing greenhouse gas emissions from fossil fuel sectors in Vermont's GHG Inventory (VT Agency of Natural Resources, 2021).

Electricity Supply & Demand (Consumption-based)
Coal
Natural Gas
Oil
Residential/ Commercial/ Industrial (RCI) Fuel Use
Coal
Natural Gas
Oil, Propane, & Other Petroleum
Transportation/Mobile
Motor Gasoline (Onroad and Nonroad) (CO_2)
Diesel (Onroad and Nonroad) (CO_2)
Hydrocarbon Gas Liquids, Residual Fuel, Natural Gas (CO_2)
Jet Fuel & Aviation Gasoline (CO_2)

Fossil Fuel Industry
Natural Gas Distribution
Natural Gas Transmission

2.2 Anthropogenic—land use change

Land use change can cause loss of carbon from the landscape or enhance carbon sequestration. For example, land clearing may cause additional release of carbon to the atmosphere by decomposition (e.g., slash from forest clearing, soil disturbance) that is not quickly recovered in the new land use (e.g., impervious surfaces, residential areas). Alternatively, land use change involving planting riparian zones in agricultural landscapes will a) increase carbon storage in soils and aboveground biomass b) rapidly uptake carbon, as younger forests have faster growth rates compared to older forests.

Change in forest area (e.g., loss of forest) is a particularly good example of how a known land use change could have a large impact on GHG emissions, although the exact magnitude will depend both on the land use history of the forest and the future land use trajectory. The main challenge in tracking GHG emissions sources and sink in land use change and land cover change is that attribution requires knowledge of both the prior land use class and the new land use class. Further, tracking could require many years of data past detected land use change, as forest management can temporarily change the site to shrubland after large trees are cut. In a detailed analysis, e.g., using a long-term process-based model, it is ideal to account for the land use history over 100–250 years, as natural and working lands are impacted in multiple ways. In 250 years in Vermont, changes in land use might include one area transitioning from forest to pasture to secondary forest to residential use. Even in thirty years in Vermont, land use accounting may include multiple transitions, requiring detailed (e.g., annual), spatially explicit, and well-validated data. One potential data set is the USDA National Land Cover Database (Yang et al., 2018), though this data set is limited by its frequency (every five years), spatial resolution (30-meter pixels, which miss many small-scale features in Vermont), and accuracy (not highly trusted due to mapping errors within Vermont), including errors in classifying recent forest management.

The potential for double counting is another complication in computing attribution of GHG emission sources and sinks to specific land use changes. In the case of reforestation of riparian forests on agricultural land, there would be a net increase in carbon sequestration, but it is unclear how it would be counted. Cost metrics would consider this area to now be “forest” and counted as part of the forest stock and flux (see Forests section for methods); similarly, the area (and therefore carbon) reported in agriculture would decline even though the riparian forest is additional carbon on a farm. Much more data and analysis are needed to distinguish land use change trajectories (e.g., agriculture to forest) from net change in land uses (e.g., increase or decrease in a land use area). To date, no such data set identifies or tracks these land use changes (see Section 4 Discussion for further consideration of this topic).

An important, but perhaps overlooked, influence on carbon storage and management in Vermont is the landowner, who many manage multiple land uses at one time (e.g., crops, forest). The strategy to consider land use by sector (e.g., agriculture and forest separately) disconnects practices that sequester carbon (e.g., forest management) from those that might produce GHGs (e.g., agriculture via enteric fermentation). Likewise, landowners, who are the decision-makers on their land's use, are often considered by sector; a better, more holistic approach is to consider landowners' full portfolio of land use management. Although there is a challenge in terms of accounting for carbon emissions, net carbon sequestration by landowners is critical for Vermont to achieve its state-level climate change mitigation goals.

Within the data limitations described above, the actual GHG emissions and sequestration calculations are embedded in the land use categories in this report. Further, this report accounts for and addresses the ways in which land use change is particularly relevant to GHG emissions or potential carbon sequestration.

Forest cover to other land uses

When considering forests and land use in the context of the Vermont Carbon Budgets, it is useful to review the definition of forest from the US Forest Service Forest Inventory and Analysis (FIA) Program:

> ***Forest land****: Land that has at least 10 percent crown cover by live tally trees of any size or has had at least 10 percent canopy cover of live tally species in the past, based on the presence of stumps, snags, or other evidence. To qualify, the area must be at least 1.0 acre in size and 120.0 feet wide. Forest land includes transition zones, such as areas between forest and nonforest lands that meet the minimal tree stocking/cover and forest areas adjacent to urban and built—up lands. Roadside, streamside, and shelterbelt strips of trees must have a width of at least 120 feet and continuous length of at least 363 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet wide or less than an acre in size. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree—covered areas in urban settings, such as city parks, are not considered forest land.*

Within this definition, Vermont is the fourth most heavily forested state in the country—73% forest cover by Vermont's total area, 76% of Vermont's land area (MRLC 2016)—but the amount of forest has declined annually since the 1990s (Williams et al 2021, Kosiba 2021). While it is extremely hard to pinpoint the exact amount of forest loss, based on estimates of forest cover provided by the US Forest Service, approximately 4,500 acres of forest land are converted to non-forest land annually—which is less than 0.1% of Vermont's forest area (Kosiba, 2021). These estimates are approximate because some land use changes, particularly reversion of agriculture or development to forests under natural processes may take decades. Because land use change is dependent on economic and demographic decisions, there is some indication that forest loss es may have increased in recent years (USDA Forest Service, 2020). If these higher losses continue, we could see cumulative losses of over 300,000 acres of forest land may be converted to non-forest by 2050 after factoring in some non-forest land that may revert to forest land, the Forest Service estimates that a total (USDA Forest Service, 2020) or about 5% of all land in Vermont.

As development and urbanization compromise forests, the health, productivity, and carbon sequestration potential of forests decline. A recent forest carbon inventory confirmed that land use change has resulted in reduced carbon sequestration in Vermont. This is concerning because forest land that is converted both emits stored carbon and reduces future forest carbon sequestration (Kosiba, 2021). This concern is addressed throughout the Forest and Urban and Developed sections of this report.

Agriculture to other land uses or changes in management

Loss of agricultural lands is a concern in Vermont. Many groups aim to maintain working landscapes and open lands (e.g., Vermont Land Trust), but residential and commercial zones continue to develop on former agricultural lands, particularly in more populous regions. The nature of this development will affect carbon storage. Disturbance of soils caused by construction creates an immediate loss of carbon from soils to the atmosphere. Residential areas with trees and lawns may, over time, regain some or all the carbon stored in an agricultural area; however, the more impervious surface there is, the less carbon that will be regained (Pouyat et al., 2006) (see also Forests and Urban and Developed sections).

Changes in agricultural areas do not always result in lower carbon storage land uses. For example, many farms have expanded natural plantings in riparian zones or shifted cultivation practices to increase soil carbon storage. The shift from low biomass systems (e.g., pasture, hay, or annual crops) to forested or grassland ecosystems increases both aboveground (plant) and belowground (soil) carbon storage in the landscape. Shifting cultivation practices, for example changing to reduced tillage or changing manure management strategies within agricultural land uses, can change carbon storage and thus shift the carbon budget.

Changes to urban or developed

Conversion of forest or other natural land covers to urban or developed land use creates fluxes of carbon to the atmosphere due to increased decomposition of biomass. In the case of forests, some fraction of aboveground biomass might be harvested and/or stored in wood products. These changes also reduce the carbon stock stored on the landscape by reducing aboveground biomass because the replacement ecosystem (e.g., urban trees, turf, pavement) is likely to have a lower biomass than the previous land use. See Section 2.7 Urban and Developed.

2.3 Forests

Quantifying the amount of forestland in Vermont is critical in determining the Carbon Budget for Vermont forests. Based on data from multiple sources and as discussed above, Vermont has been losing forestland to other land uses since the early 1990s, but it is difficult to get precise and accurate estimates. Data from FIA estimate the loss to be an average of 4,191 acres per year (between the years 2005 and 2019), with some years seeing much larger forest losses (USFS 2020), and NOAA’s Coastal Change Analysis Program (C-CAP) estimates forest loss at an average of 2,051 acres per year (years 1996–2016). Both estimates have a high degree of uncertainty (see Figure 2 for uncertainty of FIA estimates). Despite uncertainty in the amount of forest being lost, statewide total carbon storage and sequestration decline with any loss of forestland.

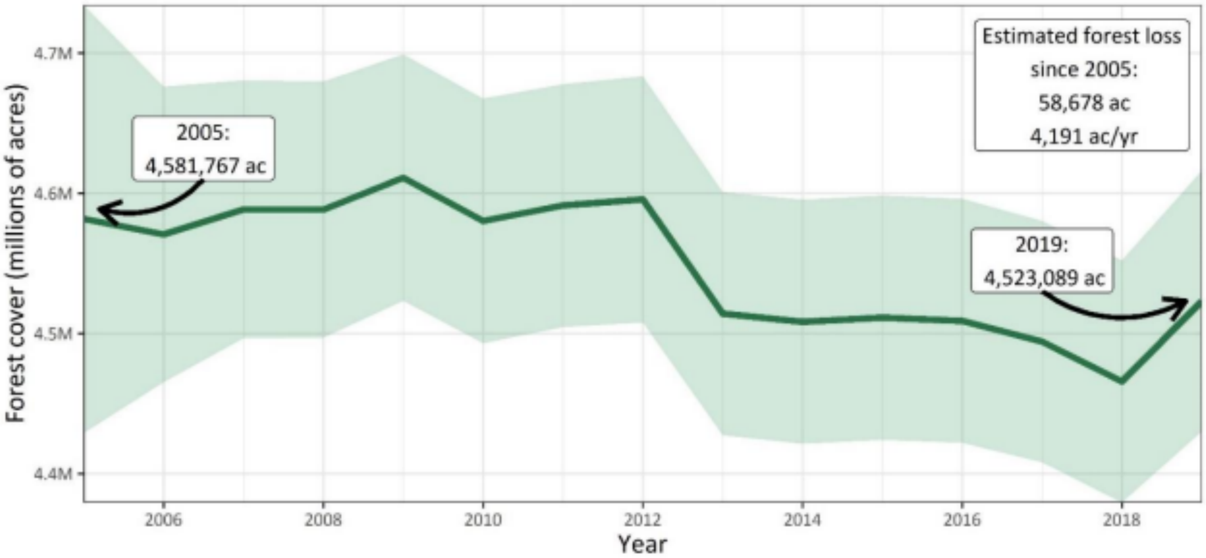


Figure 2: Estimated forest loss in Vermont 2005–2019 (Kosiba, 2021)

Note: The estimated forest cover (in millions of acres) declined between 2005 and 2019 according to the USDA Forest Inventory and Analysis program (solid green line). Data were derived from forest inventory plots sampled on a rotating basis and extrapolated to the entire state; a complete inventory of all plots occurs every five to seven years. There is 95% confidence range that the actual amount of forestland is within the shaded green area. (Kosiba, 2021)

Forests methods

A recent report by the State of Vermont ANR, the Vermont Forest Carbon Inventory (VFCI) examines current analyses and data sets on forest carbon storage and fluxes (Kosiba 2021). This report informs the Vermont carbon budget. In the United States, nearly all estimates of forest ecosystem carbon rely on data collected from the National Forest Inventory plot network and administered by the FIA program. Vermont has 1,124 permanent FIA plots measured on a rotating basis; a complete inventory of all plots occurs every 5–7 years (USFS, 2020).

VFCI used the state-level values for forest carbon stocks and fluxes computed from FIA data available from Domke et al. (2020). All forest carbon estimates were converted to metric tons of CO_2 equivalent (MT CO_2-e). Data for harvested wood product (HWP) were extracted from Dugan et al. (2021), who used the Carbon Budget Model for the Canadian Forest Sector (CBM-CFS3) to track carbon stocks and fluxes across Vermont's wood products sector. Specific information on Vermont timber harvest volumes were gathered by Dugan et al. (2021) from Vermont Forest Resource Harvest Reports, Vermont State Land Timber volume reports (Vermont Department of Forests, Parks and Recreation, 2019), and other sources. HWP data span the years 1995– 2016. For subsequent years, the average harvest between 2007 and 2016 was used. They assumed that all HWP carbon is emitted when a wood product is retired. Note that this analysis only considered HWP exports, not imports, and includes emissions from all GHGs, which were converted to CO_2-e. The forest stocks and fluxes included in the Vermont Carbon Budget are described in Table 4. Because fluxes are computed as the different in stock between two subsequent years, the most recent year of flux data is 2018. Note that trees in cities and towns are not included in the forest sector but are included under urban and developed.

Table 4: Forest carbon stocks and fluxes included in the Vermont Carbon Budget

Stocks	**Pools**	**Source**
Forests that have remained forests	Aboveground biomass—C stored in living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This pool includes live understory.	Domke et al. (2020)
	Belowground biomass—C stored in living biomass of coarse living roots with diameters greater than 2 millimeters.	
	Dead wood—C stored in nonliving woody biomass either standing, lying on the ground (but not including litter), or in the soil.	
	Litter—C stored in duff, humus, and fine woody debris above the mineral soil, including woody fragments with diameters of up to 7.5 centimeters.	
	Soil organic C (SOC)—C stored in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.	
Harvested wood products (HWP)	In use—C stored in durable wood products	Dugan et al. (2021)
	In landfill—C stored in solid waste disposal sites	
Fluxes	**Pools**	**Source**
Forestland remaining forestland	Aboveground biomass	Domke et al. (2020)
	Belowground biomass	
	Dead wood	
	Litter	
	Soil organic C (SOC)	
Land converted to forests (settlements, cropland)	Aboveground biomass	Domke et al. (2020)
	Belowground biomass	
	Dead wood	
	Litter	
	Soil organic C (SOC)	
Land converted from forests (settlements, cropland)	Aboveground biomass	Domke et al. (2020)
	Belowground biomass	
	Dead wood	
	Litter	
	Soil organic C (SOC)	
Harvested wood products (HWP)	Decay—C emissions from the decay of retired wood products	Dugan et al. (2021)
	Combustion—C emissions from bioenergy	
	Displaced emissions—C harvested and not emitted because stored in wood products or in landfills	

[a] 'Settlement trees' are trees in developed land, including transportation infrastructure and human settlements of any size (IPCC 2006).

2.4 Wetlands and water bodies

Wetlands and water bodies play an important role in the carbon cycle. Plants and organic matter bring carbon into these ecosystems through gross primary productivity (GPP). Some of this carbon from plants remains in the ecosystem (F_{cs}), whereas some of it is converted or lost as CH_4 (F_{me}) or CO_2 via plant respiration and soil respiration (R_P and R_S, respectively) (Bernal & Mitsch, 2012) (Figure 3). Carbon uptake and storage in wetlands and water bodies largely take in more carbon than is released as CH_4 (Bernal & Mitsch, 2012). Wetlands are the largest single natural source of CH_4 to the atmosphere (Walter & Heimann, 2000), though natural sources of CH_4 are considered separate from human-induced emissions, which have contributed the most to *increasing* global CH_4 emissions (Saunois et al., 2016). According to IPCC guidelines, GHG emissions from anthropogenic, or constructed, water bodies form part of the U.S. national emissions reporting system, whereas emissions from natural water bodies do not.

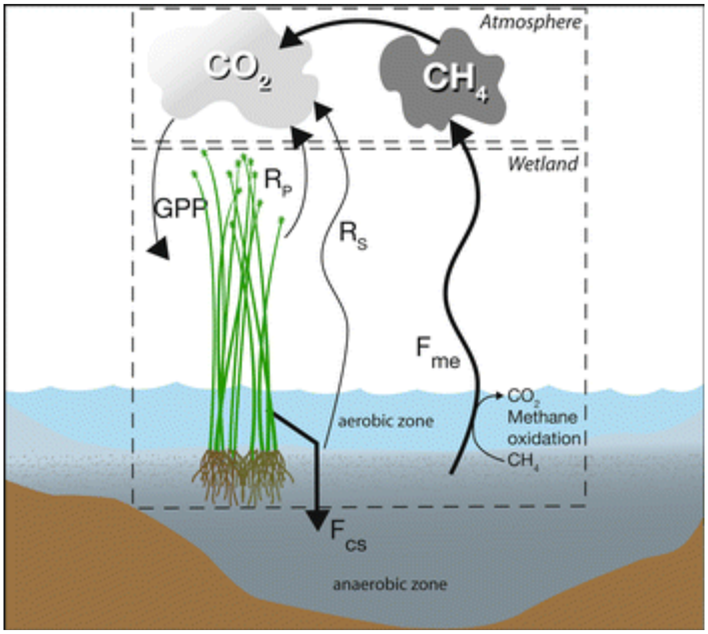


Figure 3: Overview of carbon cycle in wetlands and water bodies

Note: This is a conceptual representation of the carbon cycle in a wetland or water body, including Gross Primary Productivity (GPP), carbon flux into the ecosystem (Fcs), methane emissions (Fme) or carbon dioxide emissions via plant respiration and soil respiration (R_P and R_S, respectively) (Bernal & Mitsch, 2012).

In general, wetland emissions of CH_4 are poorly constrained or have high uncertainty due to high variability within and across sites, depending on conditions of temperature, water, and vegetation. Emissions estimates are further complicated by biology—the microbial production (methanogenesis) and microbial consumption (methanotrophy) of CH_4 (Knox et al., 2021; Turetsky et al., 2014). Variation in wetland and water body area over time (e.g., due to conversion to other land uses) is one of the largest factors affecting changes in carbon sequestration over time (Mitsch & Hernandez, 2013; Ringeval et al., 2010).

Recently, scientists have focused more on how historical human activities have increased methane emissions from wetlands and water bodies, for example through the release of gases from anoxic waters held at depths behind dams. This is particularly notable in tropical ecosystems where dams flooded large swaths of carbon-rich forests, which are now decomposing in deep, anoxic waters (Fearnside & Pueyo, 2012). Within temperate ecosystems, particularly in the northeast U.S., wetlands have primarily been lost over the last fifty to sixty years (Wilen & Bates, 1995). There is also some evidence that CH_4 production in wetlands increases with increasing land surface temperatures at latitudes above 45° north (Peltola et al., 2019). Related, global climate change seems to be increasing the flux of CH_4 from natural ecosystems, particularly from thawing of Arctic permafrost and increased tropical precipitation (Dlugokencky et al., 2009).

Methane emissions from wetlands and water bodies can be measured directly in the field, although this can be logistically and financially limiting (e.g., eddy covariance methods). Often, computer models are used to simulate the conditions creating CH_4 release, either through process ("bottom up") or inversion ("top down") models, although the two approaches often rely on the same data sets. Methane is often measured in isolation (Table 5); or in combination with CO_2 uptake—the net of CH_4 and CO_2 fluxes in temperate zones is largely net carbon sequestration (negative flux) (Table 6). Small, artificial water bodies such as ditches remain poorly quantified but may be important sources of emissions (Peacock et al., 2021), although it is difficult to know the full extent of these types of water bodies within Vermont.

In the most recent inventory, the Vermont Agency of Natural catalogued 300,000 acres of wetlands (VT Dept. Environmental Conservation 2021), while the NLCD dataset estimates 227,296 acres of wetlands and water bodies (Yang et al., 2018). The most relevant estimate of carbon storage in wetlands for the region is 153 MTC ha^{-1} between 0–30 cm depth (Nahlik & Fennessy, 2016). This depth was selected for consistency with estimates in other land uses; Nahlik & Fennessy (2016) include an estimate for this region from 0–120 cm depth (527 MT C ha^{-1}), which would increase the estimated carbon stock over three-fold. In this Carbon Budget, the net carbon flux for wetlands and water bodies was based on the geometric mean (-524 g CO_2-e m^{-2} yr^{-1}) of the carbon flux estimates (Table 6) applied to the total area in wetlands. This bookkeeping approach did not use EX-ACT.

Table 5: Estimates of methane from wetlands and water bodies in temperate latitudes

Source	CH_4 flux Estimate ($g\ CH_4\ m^{-2}\ yr^{-1}$)	Notes
Zhu et al., 2015	30-47	
Peltola et al., 2019	1-10	Sites and data used all >45°N
Chu et al., 2014	49.7	Freshwater marsh
Peacock et al., 2021	0.1–44.3	Artificial ponds and ditches

Table 6: Estimates of net carbon flux (CO_2 plus CH_4) from wetlands and water bodies in temperate

latitudes

Source	Carbon flux estimate (g CO_2-e m^{-2} yr^{-1}) *	Notes
Knox et al., 2015	-965	Drained agricultural peatland
	-381	Restored wetlands from agricultural use; flooding inhibited respiration so they were net carbon sink
Gorham, 1991	-106	Net rate with CO_2 and CH_4 in North American peatlands
Mitra et al., 2005	-587	General range for wetlands
Bernal & Mitsch, 2013	-524	Temperate flow-through wetlands, Ohio
	-686	Created temperate marshes (10-years), Ohio
	-887	Created temperate marshes (15-years), Ohio
Peacock et al., 2021	-359	Artificial ponds and ditches
Bernal & Mitsch, 2012	-1162	Wetland communities
	-513	Riverine communities

*Note: includes CO_2 and CH_4 fluxes. Negative fluxes indicate net sequestration.

2.5 Agriculture

Carbon stocks in Vermont agriculture are estimated based on crop type. A recent research project, State of Soil Health in Vermont, led by co-author and University of Vermont Extension Professor H. Darby, has improved data and understanding of agricultural carbon storage (White et al., 2021). Here, carbon stocks are estimated by area in each crop type and typical stock per unit area. The State of Soil Health in Vermont provides carbon stock estimates for corn, hay, pasture, and vegetable crop types. The State of Soil Health in Vermont used many sites across Vermont: at the time of this report (September 2021), measurements were completed at 18 vegetable, 24 hay, and 96 corn fields. For estimates presented here, all corn areas (silage, grain, sweet) in our data set (USDA NASS, 2021) (see Sections 2.5.1 and 3.5.1) were assigned the carbon stock for corn from the State of Soil Health in Vermont (White et al., 2021) (Table 7). Likewise, all areas reported in hay or haylage were assigned a value for hay; minor grains and soybean were assumed most like corn carbon stocks, so that value was used. Vegetable crops corresponded to the carbon stock for vegetables. Carbon stocks for pasture are discussed in Section 2.6 Grasslands and shrublands.

Table 7: Carbon stock estimates to a depth of 30 cm, values used by crop types (White et al., 2021)

Crop	MT CO_2-e ha^{-1}	MT C ha^{-1}
Hay (hay, haylage, including alfalfa)	365	99.7
Corn (silage, grain, sweet, grains and soybean)	314	85.5
Vegetables	254	69.3

The EX-ACT Tool was used to account for GHG emissions in management of agricultural lands and livestock. EX-ACT follows IPCC methodologies for stocks and fluxes of carbon, which require knowledge about (i) magnitude of a particular agricultural practice (e.g., acres in corn, head of dairy cattle) and (ii) carbon storage or flux per unit area related to the management techniques associated with that practice. The methods used for cropland management, fertilizer use, and livestock management are described below.

EX-ACT can account for upstream energy emissions for fertilizer and pesticides, including the production, transport, storage, and application. This accounting is distinct from the conversion of fertilizers directly into GHGs. Based on the input of the VCC and reviewers from the Carbon Budget task group, upstream energy emissions were not included in this analysis. This is consistent with the methods used in the Vermont GHG Inventory. As such, fertilizers that directly create GHG emissions are considered, but other fertilizers and pesticides and upstream emissions are not considered in this Carbon Budget.

2.5.1 Cropland management

The rates at which croplands can sequester carbon and/or emit CO_2, CH_4, and N_2O depend on activities and management practices. See section 3.5.1. for details regarding croplands in Vermont. Following is a description of EX-ACT processes and data used by Vermont for cropland management stocks and fluxes.

1. Carbon stocks from aboveground and belowground biomass. The default values for aboveground and belowground biomass stocks, growth rates, and carbon content for each land use are based on Tier 1 estimates (IPCC 2019).
2. Carbon stocks from litter and dead wood. The Vermont Carbon Budget assumes no litter and dead wood pools in all non-forest categories. For land use change between forest and non-forest categories, default carbon stock values from IPCC (2006) are used.
3. Changes in soil carbon stocks. This analysis estimates soil organic carbon stocks for mineral soils to a depth of 30 cm using default values from IPCC (2006). When soil organic carbon changes occurred over time (due to land use change or management change), a default period of twenty years to reach a new equilibrium soil carbon stock is assumed. Improved management practices on cultivated cropland were analyzed using carbon change rates (Smith et al. 2007) instead of a carbon stock difference approach.
4. Emissions of CH_4, N_2O, and other GHG sources. This analysis estimates direct N_2O emissions from field application of nitrogen using the IPCC's default GHG emission factors (IPCC 2006). We calculated nitrogen application rates based on state-level reports of synthetic and organic fertilizer use. This analysis estimates CH_4 emissions from enteric fermentation using a Tier 1 approach (IPCC 2006). For N_2O and CH_4 emissions from manure management, the Tier 2 method from IPCC (2006) is used. This analysis does not include CH_4 emissions from flooded rice, as is an option in EX-ACT, because the area in rice is negligible in Vermont. Likewise, biomass burning of crop residues with fire is not a management practice used in Vermont and so was not considered.

Table 8 describes cropland management factors accounted for in EX-ACT: types of tillage, carbon and manure inputs, and crop residue management. See Section 3 Results for practices by crop types.

Table 8: Description of cropland management factors that impact flux and are utilized in EX-ACT

Description of types of tillage	
Full tillage	Characterized by substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g., <30%) of the surface is covered by residues.
Reduced tillage	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion). Normally leaves surface with >30% coverage by residues at planting.
No-till	Direct seeding without primary tillage and minimal soil disturbance in the seeding zone. Also includes no soil disturbance, such as perennial crops with no seeding. Herbicides are typically used for weed control.
Description of carbon input levels	
Medium carbon (C) input	Defined by one of the following conditions for annual crops: 1. all crop residues are returned to the field; or 2. all crop residues are removed or burnt BUT organic amendments (e.g., manure) are applied; or 3. low residue crops are cultivated (e.g., cotton, green maize, vegetables, tobacco) or frequent rotation with bare fallow BUT using practices that increase C input above low residue varieties (e.g., organic amendments, cover crops/green manures, and mixed crop/grass systems); or 4. no mineral fertilization or N-fixing crops BUT using practices that increase C input by enhancing residue production (e.g., irrigation, cover crops/green manures, vegetated fallows, high residue yielding).
High C input without organic amendments	Crop residues are neither removed nor burnt. Significantly greater crop residue inputs over medium C input cropping systems due to additional practices (e.g., production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations), but without manure applied.
High C input with organic amendments	Represents significantly higher C input over medium C input in cropping systems due to an additional practice of regular addition of animal manure.
Description of management of crop residues	
Retained	Crop residues are neither removed nor burnt but are left in the field during harvest (e.g., stover, husks).
Exported	Crop residues are removed from the field (e.g., straw, compost).

2.5.2 Fertilizer use

Fertilizers affect emissions in several ways, including the energy used in production, transport, storage, and application and the conversion from N-synthetic fertilizers to N_2O. Based on consultation with VCC subcommittee members and State of Vermont staff, emissions from energy related to fertilizer production, transport, etc. were not included in this Carbon Budget. Instead, this report focuses on land-based emissions to parallel the current VT GHG Inventory.

EX-ACT accounts for nutrient inputs from organic and inorganic fertilizers, which are not counted in the manure management section for livestock. In Vermont, fertilizers are largely constrained to the use of lime and the use of synthetic fertilizers, primarily nitrogen (N), phosphorous (P), and potassium (K) fertilizers or a combination. Fertilizer usage is self-reported by farmers in broad categories (multi-nutrient, nitrogen, phosphate, potassium, sec/micro, or miscellaneous—lime, calcite, compost) and by form (bagged, bulk, or liquid) (L. Boccuzzo, personal communication, July 29, 2021). Publicly available reports on fertilizer use include self-reported data in 2018-2019 and 2019-2020 (VT Agency of Agriculture, Food and Markets, 2020; VT Agency of Agriculture, Food and Markets, 2021).

EX-ACT requires fertilizers to be input as lime and as N-fertilizers (synthetic and organic) by nutrient composition (e.g., N-P-K composition), data that is not recorded in the Vermont's Annual Report, Fertilizer (VT Agency of Agriculture, Food and Markets, 2020; VT Agency of Agriculture, Food and Markets, 2021). All values were converted to metric units for use in EX-ACT. The following assumptions and data were used for 2020:

1. Multi-nutrient fertilizers are assumed to be N-P-K 19-19-19 for agricultural uses in bulk and bag form and 9-18-9 in liquid form, based on farming and extension knowledge (H. Darby).
2. The amounts of N, P, and K were input to EX-ACT directly as reported.
3. The sec/micro & miscellaneous fertilizer categories were broken into several types of fertilizer based on its form. Lime is a large component of the miscellaneous category. Calculated with the assumption that roughly 96 acres per farm receive 1.5 tons of lime/acre across 125 registrants (farms), a total of 18,000 tons of lime or roughly 8,000 acres receiving 2 tons/acre, was calculated as the most reasonable estimate. Lime was assumed to be in the "bulk" subcategory. After accounting for lime, the remaining sec/micro & miscellaneous categories, bulk inputs were assumed to be NPK 5-4-0 to represent compost, corn starter, or blended fertilizers. The non-agricultural fertilizer uses were subtracted from the total bagged fertilizer use, and the remaining bagged nutrients were assumed to be organic mixed nutrients with a typical NPK of 5-4-3. The liquid nutrients were assumed to be a multi-nutrient like fish emulsion with an NPK of 4-1-1.

Reconstruction of historical uses is limited by available data sets. Cao et al. (2018) estimates the distribution and use of N-synthetic fertilizers in the U.S. from 1850-2015 based on geospatial analysis of land cover data harmonized with annual national commercial nitrogen consumption data from USDA for 1952–present. Comparison of this data subset for Vermont lines up well with the Vermont 2018–2019 and 2019–2020 fertilizer reports (Cao et al., 2018; VT Agency of Agriculture, Food and Markets, 2020; VT Agency of Agriculture, Food and Markets, 2021) for synthetic N fertilizer and thus was used as an input to EX-ACT for this report. For VAAFM reports

(2020, 2021), it was assumed that 90% of N fertilizer was ammoniacal and that the remaining 10% was in the form of nitrate (C. Giguere, personal communication, September 13, 2021).

One issue in the fertilizer data was noticed. In data from 1990–2009, there was a sudden decline in estimated N-synthetic fertilizer use in the period 2010–2020, but no apparent change in agricultural practices or legislation could explain this drop. Through consultation with Cary Giguere (Director, Public Health, Agricultural Resource Management for Vermont Agency of Agriculture, Food, & Markets), it was learned that the Burlington International Airport historically purchased about 3,000 English tons of urea per year from an agrochemical dealer based in Vermont to use as a deicer. This is 1,251 metric tons of N, or 25% of the total N-synthetic fertilizer estimated for 1990 agricultural uses. and would have been reported as an agricultural sale. At some point during this period, the airport shifted its purchase to a non-agricultural source, and so the fertilizer purchased by the airport stopped being erroneously counted in agricultural sales of N fertilizer (C. Giguere, personal communication, September 13, 2021). In this Carbon Budget, the 1990-2009 N-synthetic fertilizer estimates input into EX-ACT account for (subtract) this non-agricultural use. Further investigation may be able to identify exact timing for this shift.

Less data was available for other fertilizer categories. The United States Department of Agriculture National Agriculture Statistical Service census (USDA NASS, 2021) provides data on acreage treated with fertilizers, pesticides, and soil conditioners. This acreage was used to create a ratio relative to the 2019-2020 reported uses of P, K, and limestone (USDA NASS, 2021; VT Agency of Agriculture, Food and Markets, 2021). This ratio was then used to hindcast consumption of P, K, and limestone.

2.5.3 Livestock management

In estimating livestock GHG emissions, EX-ACT considers livestock category, number of head, quality of feed/forage, and complementary manure management. The livestock categories found in Vermont are cattle, chickens, goats, hogs, sheep, rabbits, turkeys, llamas, alpacas, bison, chukars, ducks, geese, and guineas. To estimate the number of head in each category, a historical estimate of livestock numbers was developed by the report team by fusing USDA census data (gathered every five years) and survey estimates (annual) (USDA NASS, 2021). The number of head in years without records were inferred through linear interpolation from the prior and following records. If there were no data available at the start of the record, the livestock count was assumed constant until the second year with recorded data. In the scale used by EX-ACT, North American livestock are highly productive, commercialized, and fed with high-quality feed and forage. Complementary manure management systems in Vermont were categorized as primarily solid storage, with some use of liquid/slurry, deep bedding, and digesters (Table 9).

The Carbon Budget divided manure management practices for cattle into the three subgroups of beef, dairy, and heifer/calves, since each of these livestock subgroups spend different percentages of time on pasture and in deep bedding. Daily spreading of manure was the common practice in 1990 and has been slowly replaced by liquid/slurry. Currently, the manure management practice of using liquid/slurry storage makes up approximately a third of the total head of cattle. In the past five years, composting and digester practices have become more prevalent, and those practices are now used with 5% of the total head across these three groups. The allocation to pasture, range, and paddock have remained stable over the years, except for with dairy cattle. Pasture, range, and paddock management has increased as the percentage of organic dairy cows have grown over the last three decades. Organic diary accounted for 29.4% of total dairy head in 2020 and has impacted the allotment to pasture, range, and paddock from 20% in 1990 to 28% in 2020 (State of Vermont, 2020).

See Results in section 3 for emissions related to manure management by livestock over time.

Table 9: Manure management systems for livestock used in Vermont and defined by EX-ACT

Manure management system	Description
Pasture/Range/Paddock	The manure from pasture and range-grazing animals is allowed to lie as deposited and is not managed.
Daily spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.
Solid storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure can be stacked because of the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Liquid/Slurry	Manure is stored as excreted, or with some minimal addition of water or bedding material, in tanks or ponds outside the animal housing. Manure is removed and spread on fields once or more in a calendar year. Manure is agitated before removal from the tank/ponds to ensure that most of the volatile solids are removed from the tank.
Anaerobic digester	Anaerobic fermentation of slurry and/or solid. Biogas is captured and flared or used as a fuel.
Compost	Biological oxidation of a solid waste including manure, usually with bedding or another organic carbon source, typically at thermophilic temperatures produced by microbial heat production.

2.6 Grasslands and shrublands

Grasslands and shrublands are considered areas dominated by graminoid (grass-like) or herbaceous vegetation. The grassland module in EX-ACT considers grasslands and shrublands as well as related uses such as rangelands. This land use category accounts for carbon storage in pasture soils due to management, including in the case of degradation (e.g., erosion). In its estimate of GHG emissions or storage, EX-ACT considers area in grassland to have a modest carbon uptake rate. Total storage is less than forested ecosystems (Janowiak et al., 2017). The biomass of grasslands is also less than in forests, but grassland soils store much of the carbon in the ecosystem through extensive belowground biomass and soil organic carbon.

Grasslands and shrublands are a complicated land use and thus complicated for calculating the carbon budget. For example, grasslands can be used as pastures for grazing, but not all grasslands are pastures. In some grassland data sets (e.g., the USDA National Land Cover Database (NLCD) dataset) (Yang et al., 2018), it is difficult to discern if crops like hay are included or excluded from grassland estimates. Generally, greater than 80% of total vegetation are not subject to intensive management, such as tilling, but the vegetation can be utilized for grazing or pasture (Yang et al., 2018). Grasslands used for hay and haylage are accounted for in Section 2.5.1 Cropland, and these crops include more management details in EX-ACT.

Total area in grassland management is reported by the USDA every five years in the National Resources Inventory (NRI) (USDA, 2020). The NRI is considered a more consistent data source than some other data sets, such as the USDA National Land Cover Database (NLCD) dataset (Yang et al., 2018). Grasslands and shrublands that are not accounted for in other types of land use management (e.g., hay, pasture) are relatively rare in Vermont. In fact, the NLCD and the USDA Cropland Data Layer report no grassland classes in Vermont except pasture and hay (Yang et al. 2018, Han et al. 2012). The NRI data sets includes estimates of acres experiencing erosion (from water or wind) or overgrazing. Expert knowledge from H. Darby, A. Corse, and R. Patch indicates that the Cropland Data Layer overestimates water-related degradation. Based on experience and study by VAAFM staff, the generally accepted fraction of severely degraded grasslands in Vermont is 25%. The NRI report on “prime grasslands,” considered “improved grasslands” in this EX-ACT analysis as grasslands that benefit from continual improvements to maintain this status (Table 10). The remaining grasslands were considered non-degraded. Between census years, area grassland was estimated through interpolation for the purpose of this budget.

Table 10: Grassland degradation levels and definitions used in EX-ACT

Grassland degradation level	Description
Severely degraded	Implies major long-term loss of productivity and vegetation cover due to severe mechanical damage to the vegetation and/or severe soil erosion.
Non-degraded	Represents low or medium intensity grazing regimes, in addition to periodic cutting and removal of above-ground vegetation, without significant management improvements.
Improved grassland	Represents grassland which is sustainably managed with light to moderate grazing pressure (or cutting and removal of vegetation) and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).

Recent measurements of soil carbon storage by State of the Soil Health in Vermont include pastures (grazed, non-harvested grasses). Across sixteen sites in Vermont measured at the time of this report, pasture grasslands stored 290 MT CO_2 ha^{-1} (79 MT C ha^{-1}) (White et al., 2021). This is the best estimate of carbon storage for Vermont grasslands.

2.7 Urban and developed

Urban and developed landscapes may have different carbon dynamics than the agricultural or natural lands found in the same region, but just as in agricultural and natural lands, the primary pools of carbon storage and sources of carbon fluxes in urban and developed areas are vegetation (including trees) and soils.

Trees growing along roads and in yards, parks, and open spaces provide important climate mitigation effects by sequestering and storing atmospheric CO_2 in wood and soils. However, estimates of carbon storage and sequestration rates for trees within urban and developed land uses are challenging because there is no standard definition of what constitutes an urban forest, which makes it difficult to compare data from various sources. Additionally, estimating tree carbon, especially annual sequestration, is challenging and imprecise. It requires modeling a tree's biomass based on the carbon in a reference set of sample trees. These models can be especially inaccurate for street and yard trees because the growing conditions are highly variable compared to forest-grown reference trees (McHale et al., 2009; McPherson et al., 2016). Finally, to compute the actual climate mitigation effect of a tree, the maintenance inputs should be included (Nowak et al., 2013), and this is most often either unknown or highly variable.

Vermont's urban and developed areas make up less than 2% of the state's land area (9,623 $miles^2$ or 24,923 km^2) (Nowak and Greenfield, 2008). Despite challenges to estimating carbon stocks and fluxes in urban and developed environments, several forestry and climate scientists have estimated the total carbon storage and annual carbon sequestration of Vermont's urban trees. According to these estimates, trees in urbanized areas store about 15 MMT CO_2-e and sequester 157,000–500,000 MT CO_2-e yr^{-1} (Domke et al., 2020; EPA, 2021; Nowak et al., 2013; Zheng et al., 2013). On a per area basis, some estimates suggest that Vermont's street trees sequester CO_2 at a higher annual rate compared to forest trees (Nowak et al., 2013), as urban trees tend to have wider tree crowns, experience less competition from other trees, and have a greater leaf area compared to forest-grown trees. However, urban trees have significantly shorter lifespans and greater maintenance demands, which affect their lifetime carbon storage potentials (Nowak et al., 2013). The estimates in this report consider the unique life span and dynamics of urban trees. Given that urban and developed areas have increased 3% in the last twenty years (Yang et al. 2018), this report assumed the same rate of change in carbon fluxes to estimate 1990 and 2005 levels.

Research in soil carbon storage in Boston and Syracuse, which have climates like Vermont, found that urban soils contained 1.6 times less soil organic carbon storage than pre-urban development (Pouyat et al., 2006). Residential soils in the northeastern United States are estimated to hold a mean of 14.4 g m^{-2} soil organic carbon (Pouyat et al., 2006). Within urban and developed soils in the northeastern United States, soil organic carbon storage ranges from 3.3 kg m^{-2} (impervious surfaces, rock/gravel/quarries, commercial-industrial-transportation) to 14.4 kg m^{-2} in residential land uses.

3 Results

The Vermont Carbon Budget indicates net sequestration, or carbon storage, at a current rate of -2.91 MMT CO_2-e yr^{-1} for land uses (Table 11); this is 34% of the annual fossil fuel emissions in Vermont, using the definition of fossil fuels from the Vermont GHG Inventory. Forests, open space in urban and developed areas, wetlands and water bodies, and wetlands and water bodies and are the main sources of sequestration. Agricultural management practices for crop types, carbon inputs, tillage, and residues account for 0.53 MMT CO_2-e yr^{-1} and are declining. Grassland and shrublands account for 0.05 MMT CO_2-e yr^{-1} currently. These emissions are discussed in the following sections.

Table 11: Vermont Carbon Budget estimates for stocks and fluxes of carbon and GHGs land uses based on recent trends and data

Source	Stock (MMT CO_2-e)	Estimated flux (MMT CO_2-e yr^{-1}) *			Components	Data source
	2020	1990	2005	2020		
Forests	1,859	-5.1	-3.2	-3.2 (year 2018)	Forests, conversion from forests, and harvested wood products (HWP)	Kosiba, 2021
Wetlands and water bodies	57	-0.01	-0.01	-0.01	Wetlands and water bodies	Vermont Carbon Budget
Grasslands and shrublands	41	0.06	0.05	0.05	Unmanaged and managed (e.g., pasture)	Vermont Carbon Budget
Agriculture	63	0.74	0.64	0.53	Crops (including hay), fertilizers, livestock, management	Vermont Carbon Budget
Urban and developed	15	-0.26	-0.27	-0.28	Trees	Domke et al., 2020; EPA, 2021; Nowak et al., 2013; Zheng et al., 2013
NET (AFOLU)	1,978	-4.57	-2.79	-2.91		Vermont Carbon Budget
Fossil fuels**	N/A	8.64	9.97	8.60	From VT GHG Inventory, see Section 2.1	VT ANR, 2021
Net (AFOLU and fossil fuels)		**4.07**	**7.18**	**5.69**		**Vermont Carbon Budget**

*Note: Stocks represent storage. Negative fluxes indicate net sequestration (additional carbon storage). Positive fluxes represent sources to the atmosphere.

** For AFOLU emissions, this Carbon Budget utilizes Vermont's fossil fuel emissions as reported in the 2017 Inventory (VT Agency of Natural Resources, 2021). Note that the "Fossil Fuel Industry" sector in the GHG Inventory is only emissions of fugitive natural gas (CH_4) from transmission and distribution within Vermont.

3.1 Anthropogenic—fossil fuels

Total annual GHG emissions range from a peak of 10.39 MMT CO_2-e in 2004 to a low of 8.59 MMT CO_2-e estimated for 2019 (Figure 4, VT Agency of Natural Resources, 2021). Transportation and mobile uses of fossil fuels have been the largest contributor to this category of GHG emissions, primarily due to motor gasoline (75% of transportation and mobile emissions). Residential/commercial/industrial fuel is dominated by oil, propane, and other petroleum products (roughly 70% of emissions in this category). Fugitive natural gas emissions from the Fossil fuel industry sector are 0.2–0.3% of total fossil fuel emissions reported (VT Agency of Natural Resources, 2021).

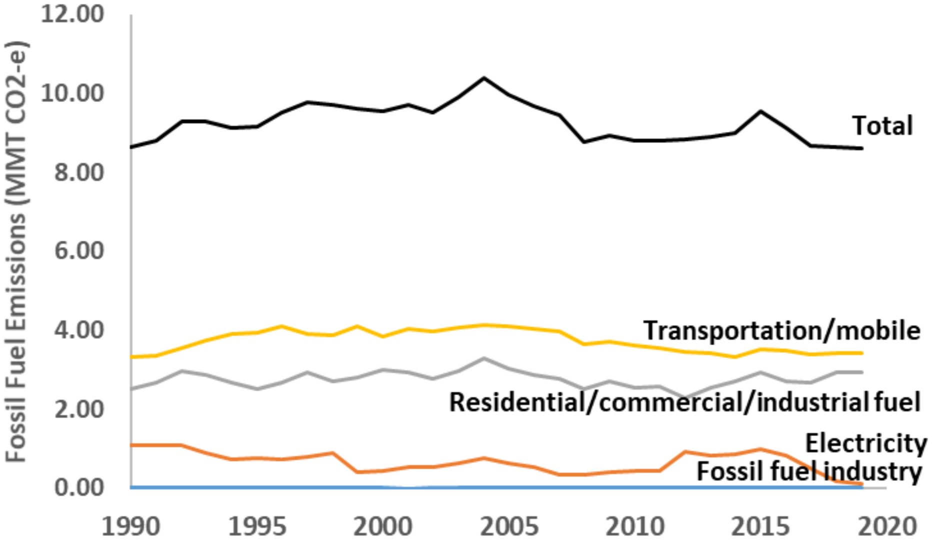


Figure 4: Total annual GHG emissions in Vermont (VT Agency of Natural Resources, 2021)

3.2 Anthropogenic—land use change

Vermont's landscape remains dominated by forest land cover and land uses, although forested land cover has decreased over time (see 3.3. Forests). According to the NLCD (Yang et al., 2018), Vermont is largely forested (76%) and used for pasture/hay crops (13%) (Figure 5).

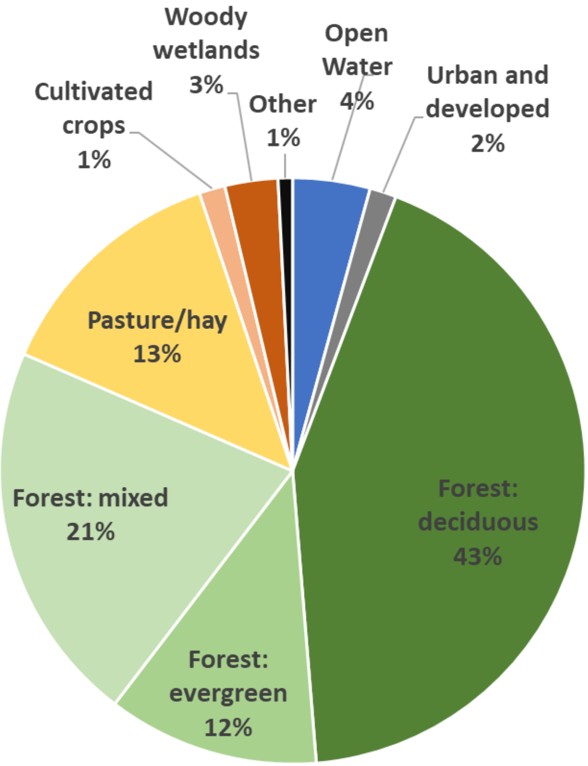
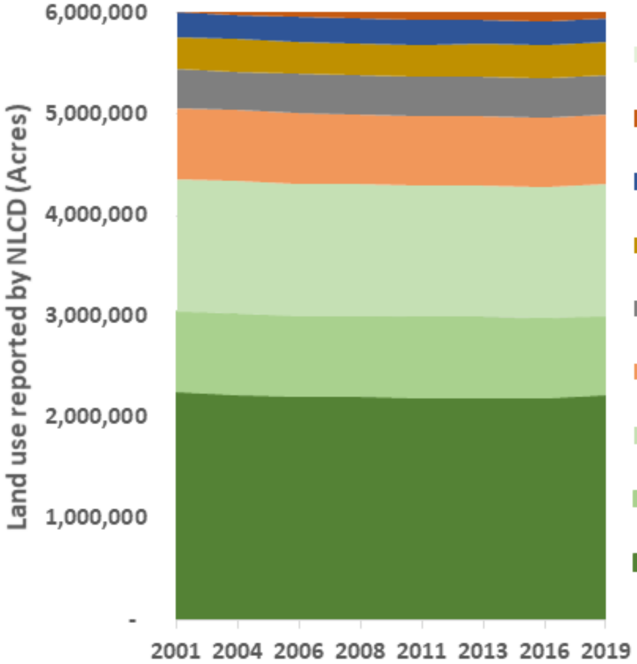


Figure 5: Approximate distribution of land uses in Vermont circa 2017 (Yang et al., 2018)

The NLCD data is the most consistent, long-term record of land use change available for Vermont, but it has serious flaws. NLCD data is spatially explicit with 30-meter pixels and could allow for calculation of land use change trajectories (i.e., area transitioning from one use to another use), and an updated NLCD map is released every 2–3 years (2001-2019). However, conversations with VCC subcommittee members, State of Vermont staff, and authors’ experiences with this data set suggest it is often inaccurate within Vermont. For example, forest fragmentation is a large concern in Vermont and is not captured by the methods used in the NLCD. For reference, Figure 6 shows changes in land use over time according to the NLCD (Yang et al. 2018).



	2001	2019
Grasslands and shrublands	48,629	90,162
Cultivated Crops	82,273	99,671
Open Water	243,165	238,085
Wetlands	319,148	323,563
Urban and developed	382,750	396,006
Hay/Pasture	703,724	677,392
Mixed Forest	1,310,406	1,314,342
Evergreen Forest	801,438	783,672
Deciduous Forest	2,251,869	2,220,335

Figure 6: Land use area (acres) reported in the USDA National Land Cover Database (NLCD) for Vermont 2001–2019 (Yang et al., 2018)

3.3 Forests

Vermont's forests store over 1,730 MMT CO_2-e (data for 2018; Figure 7), which is equivalent to over 200 years of state annual CO_2 emissions (Vermont Agency of Natural Resources, 2020). Harvested wood products (HWP), both in use and in landfill, contribute an additional 1.2 MMT CO_2-e in C storage (Figure 7). When timber is harvested from the forest in the form of sawlogs, pulpwood, chips, and roundwood, the stored C is not immediately released into the atmosphere. About a third of wood harvested in Vermont is for durable products, like floors and furniture, which store C for the life of the product. When HWP reach the end of their life, they continue to store carbon as they slowly decay in landfills. The amount of carbon stored in HWP both in use and in landfill has been accumulating over time, acting as a net sink of atmospheric CO_2 (Table 12).

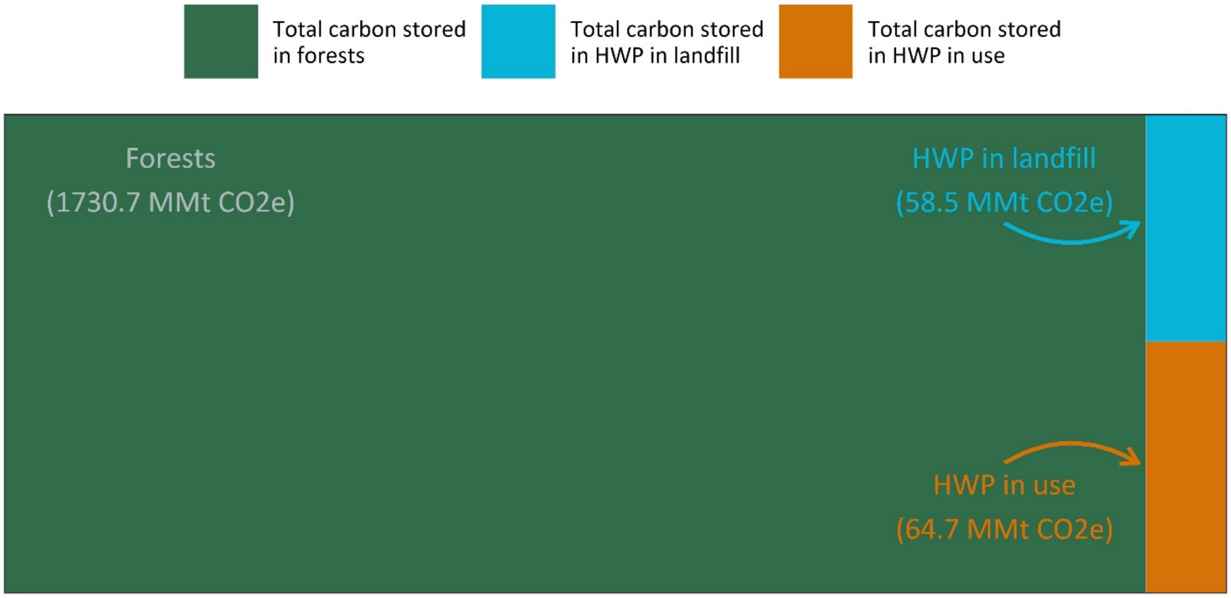


Figure 7: Estimated total carbon storage in Vermont's forests and carbon stored in harvested wood products (HWP) both in use and in landfill

Notes: All data are for 2018. Carbon is expressed as million metric tons of carbon dioxide equivalent (MMT CO_2-e). Forests is the sum of all five carbon pools and green categories. Harvest data only capture aboveground carbon removed and not fluxes between carbon pools that may accompany management. Forest carbon storage was extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis program, and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). HWP estimates were extracted from Dugan et al. (2021), who modeled HWP emissions based on harvest reports provided by the Vermont Department of Forests, Parks, and Recreation using the Carbon Budget Model.

Table 12: Vermont forest carbon stocks 1990–2019 in MMT CO_2-e

Stocks	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Forests	1566	1573	1580	1584	1591	1599	1602	1610	1613	1621	1628	1632	1639	1646	1650
HWP in use	49	50	52	53	54	55	57	57	58	58	59	59	59	59	60
HWP landfill	34	35	36	37	39	40	41	42	44	45	46	47	48	49	50
Total	**1648**	**1658**	**1668**	**1674**	**1684**	**1693**	**1700**	**1709**	**1715**	**1724**	**1733**	**1738**	**1746**	**1755**	**1760**
Stocks	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Forests	1657	1661	1668	1676	1679	1687	1690	1698	1701	1709	1716	1720	1723	1731	1734
HWP in use	60	60	60	61	61	61	62	62	62	63	63	64	64	65	65
HWP landfill	51	51	52	53	53	54	55	55	56	56	57	57	58	58	59
Total	**1768**	**1772**	**1781**	**1789**	**1794**	**1802**	**1807**	**1815**	**1819**	**1828**	**1836**	**1841**	**1845**	**1854**	**1859**

Notes: Forest C stocks include the forests and harvested wood products (HWP) in use and in landfill. The total is provided in the bottom rows. Estimates of stocks from forests were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas *inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 2006). Harvested wood product estimates were extracted from Dugan et al. 2020 who used Vermont timber harvest data to model stocks of harvested wood products since 1940.*

For forests that have remained forests, carbon storage has increased over time. In 2019, Vermont's forests stored an estimated 1,734 MMT CO_2-e (Figure 8). Between 1990 and 2019, total C storage increased by 168.7 MMT CO_2-e**.** Across all five C pools, C increased or remained stable (Figure 9). Soils store more than half of the C in the forest: 946 MMT CO_2-e compared to 796 MMT CO_2-e for the four other pools combined. The live biomass C pool is the most dynamic of the C pools and has increased at the fastest rate.

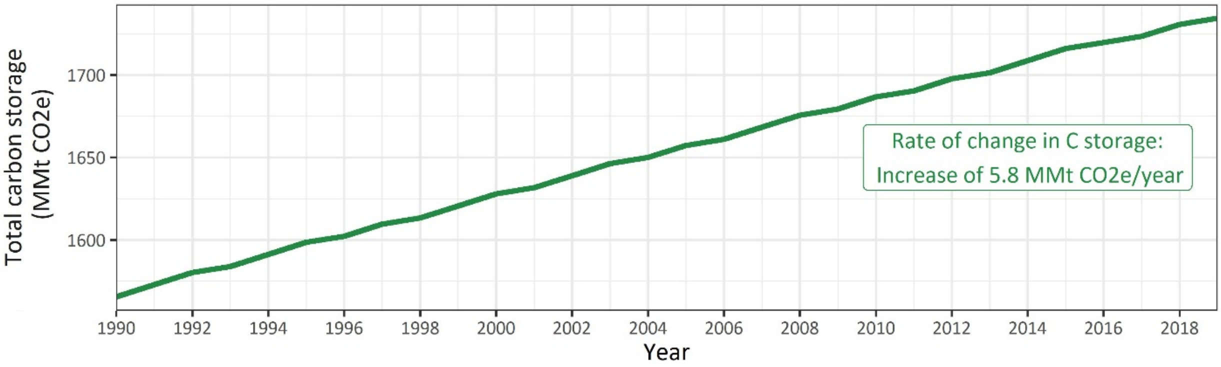


Figure 8: Estimated total carbon storage for forests that have remained forests in Vermont 1990–2019

Notes: Carbon is expressed as a million metric tons of carbon dioxide equivalent (MMT CO_2-e). Estimates were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006).

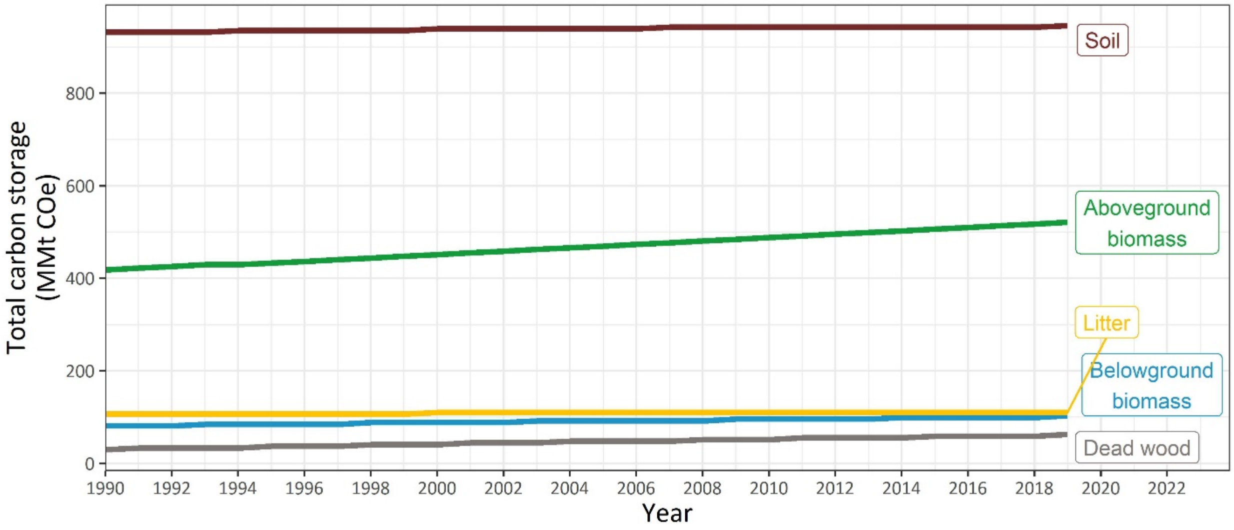


Figure 9: Estimated total carbon storage for forests that have remained forests 1990–2018 in Vermont, shown by carbon pool

Notes: Carbon is expressed in million metric tons of carbon dioxide equivalent (MMT CO_2-e). The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs, and branches). Estimates were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis (FIA) program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006).

On average, Vermont's forests store 389 MT CO_2-e per acre, but the relative contribution to total storage varies by carbon pool (Figure 10). Soils store more than half of the total carbon. The live biomass pool (a combination of the aboveground and belowground live biomass pools) makes up about 36% of the total carbon storage. Note that these values are the estimated average carbon per acre in Vermont; an actual acre of forest may store less or more carbon and the ratios among the pools may differ.

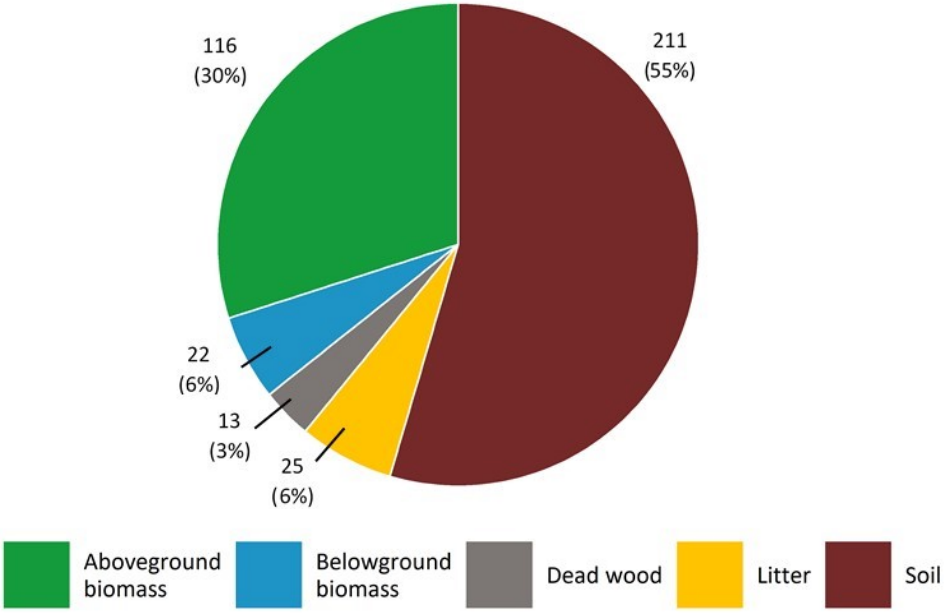


Figure 10: Estimated average forest carbon storage per acre by carbon pool (relative contribution)

Notes: Carbon data are for 2018 and expressed as metric tons of carbon dioxide equivalent (MT CO_2-e). The relative contribution to the total storage shown in parenthesis as a percent. The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs, and branches). Estimates of carbon sequestration by forests were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis (FIA) program.

Fluxes

Loss of Vermont's forestland has resulted in carbon emissions to the atmosphere, though forests remain a carbon sink for the state (Figure 11). However, the annual rate of carbon sequestration has decreased over time. In the early 1990s, forests sequestered -6.0 MMT CO_2-e per year, but in 2019, the rate declined to -5.2 MMT CO_2-e, meaning that Vermont's forests are storing carbon at a slower rate than they did two decades ago. Multiple factors likely contribute to this decline. First, Vermont's forests are similarly aged following reforestation after state-wide land use clearing in the 1800s and early 1900s. While older forests store much more carbon than younger trees, they sequester carbon at a slower rate. A second factor is land use change. As forests are converted to other land types, not only is the C stored in trees and other biomass emitted, but there is also lost future C sequestration. A third factor may be climate change: higher air temperatures can speed up the rate of nutrient cycling in a forest.

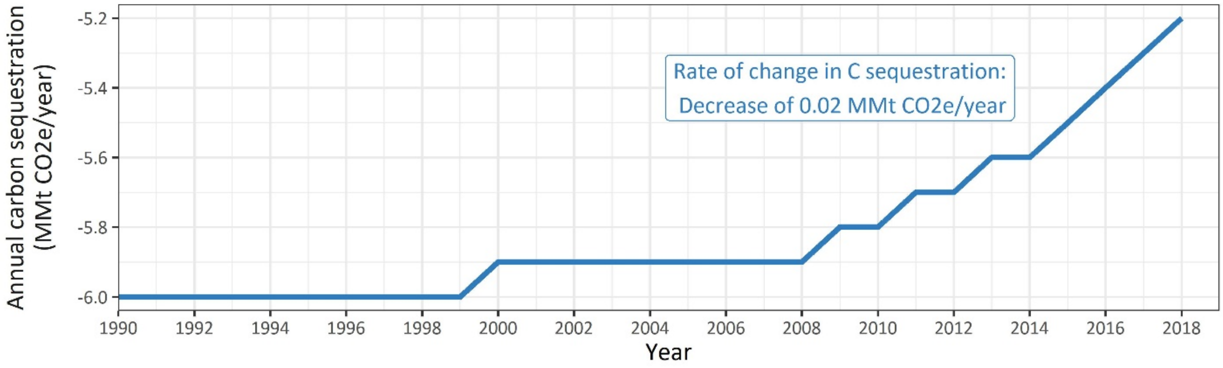


Figure 11: Estimated total carbon storage and net annual carbon sequestration for forests that have remained forests in Vermont 1990–2019

Notes: Carbon is expressed as million metric tons of carbon dioxide equivalent (MMT CO_2-e). For sequestration, negative values indicate negative emissions (net carbon uptake). Estimates were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis (FIA) program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). These data suggest that while the total carbon storage of Vermont's forests has increased, the amount of carbon sequestered each year has decreased.

All five of the forest C pools have remained a carbon sink (Figure 12), meaning that they sequester more C than they emit through respiration, decomposition, and disturbance. The live aboveground biomass pool sequestered twice the amount of C as the other four pools combined (-3.50 MMT CO_2-e compared to -1.75 MMT CO_2-e). However, the dead wood, litter, and soil C pools show a reduced rate of C uptake over time. These changes may be due to warmer air temperatures related to climate change. Warmer air temperatures can increase the rate of decomposition in a forest. This decline in the uptake of soils, litter, and dead wood pools also suggests that increased storage in live biomass is not being transferred into the dead wood, litter, and soil pools.

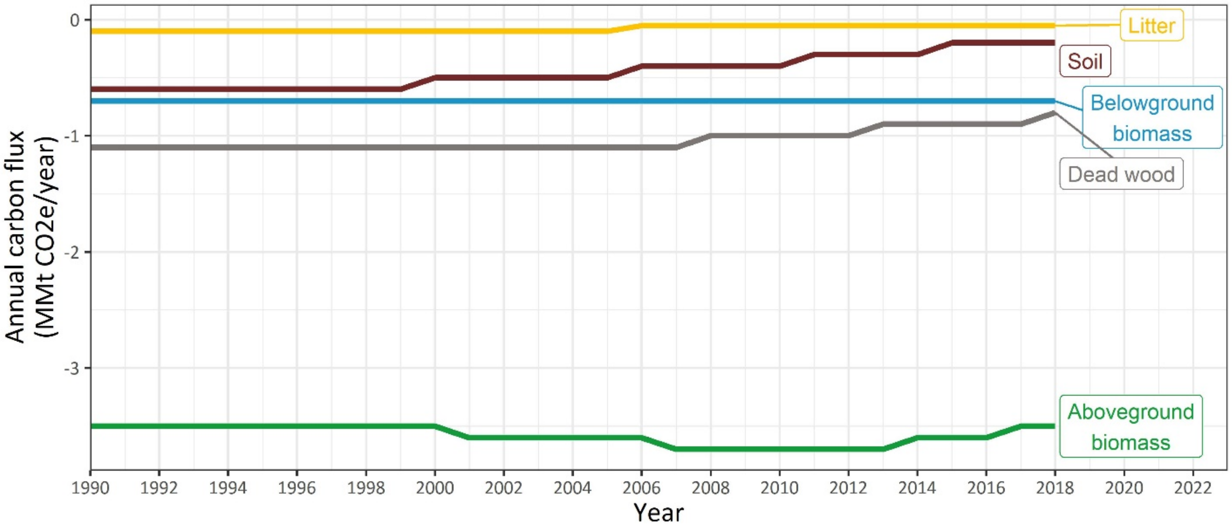


Figure 12: Estimated annual carbon sequestration (flux) for forests that have remained forests in

Vermont 1990–2018, shown by carbon pool

Notes: Carbon is expressed as a million metric tons of carbon dioxide equivalent per year (MMT CO_2-e yr^{-1}). Negative values indicate negative emissions (net carbon uptake), and positive values indicate positive emissions (net carbon release). The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs. and branches). Estimates were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis (FIA) program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006).

Per acre, Vermont's forests sequestered an average of -1.2 MT CO_2-e per acre (Figure 13), but the relative contribution to total sequestration varies by carbon pool, with the live biomass pool contributing 80% to the annual carbon sequestration. Carbon sequestered by live plants is transferred to the other pools over time as trees shed parts or die. While soils are the largest pool of stored carbon in a forest (Figure 10), they accrue carbon much more slowly than other pools, meaning that a loss of soil carbon can take a long time to recuperate. Note that these values are the estimated average carbon per acre in Vermont; an actual acre of forest may store and sequester less or more carbon and the ratios among the pools may differ.

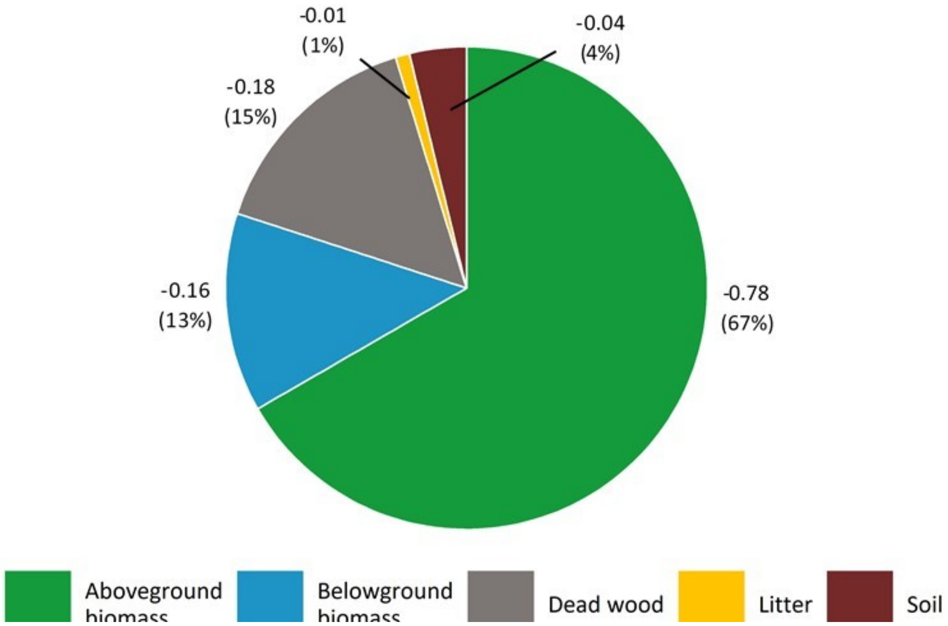


Figure 13: Estimated average annual rate of carbon sequestration per acre by carbon pool (relative contribution)

Notes: Carbon data are for 2018 and expressed as metric tons of carbon dioxide equivalent (MT CO_2-e; negative values indicate net uptake). The relative contribution to the total sequestration is shown in parenthesis as a percent. The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 *mm diameter), and (5) dead wood (standing dead trees, downed logs, and branches). Estimates of carbon sequestration by forests were extracted from Domke et al. (2020), who used data collected by the USDA Forest Inventory and Analysis (FIA) program.*

Taken together, Vermont's forest sector has both C sinks and sources (Tables 12, 13). In 2018 for example, forests sequestered -5.2 MMt CO_2-e. There were both lands converted to forests (net sinks; -0.2 MMt CO_2-e) and land converted from forests (net sources; +1.2 MMt CO_2-e). Combined land-use changes resulted in net emissions of +1.0 MMt CO_2-e. Importantly, land converted from forest not only emits stored carbon, but it also reduces the strength of Vermont's future forest carbon sequestration. Harvested wood products emitted +2.0 MMt CO_2-e from the burning of bioenergy and decay of retired products but added -1.0 MMt CO_2-e in sequestered C.

Table 13: Estimated forest sector carbon flux from 1990–2018

Year	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Forests	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5.9	-5.9	-5.9	-5.9	-5.9
Cropland converted to forest	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1
Developed land converted to forest	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1
Forest converted to cropland	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Forest converted to development	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
HWP emissions (combustion and decay)	3.0	3.1	3.1	3.2	3.2	3.2	3.4	3.3	3.2	3.1	3.1	3.0	2.9	2.9	2.8
HWP sequestration in durable wood products	-2.7	-2.6	-2.5	-2.3	-2.2	-2.2	-3.2	-2.1	-1.8	-1.5	-1.7	-1.3	-1.1	-1.2	-1.4
Total	**-5.1**	**-4.9**	**-4.7**	**-4.6**	**-4.3**	**-4.2**	**-5.1**	**-4.1**	**-3.9**	**-3.6**	**-3.7**	**-3.4**	**-3.2**	**-3.3**	**-3.5**
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	
Forests	-5.4	-5.3	-5.2	-5.9	-5.8	-5.8	-5.7	-5.7	-5.6	-5.6	-5.5	-5.4	-5.3	-5.2	
Cropland converted to forest	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	
Developed land converted to forest	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	
Forest converted to cropland	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	

Forest converted to development	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
HWP emissions (combustion and decay)	2.1	2.0	2.0	2.7	2.7	2.7	2.6	2.6	2.4	2.1	2.1	2.1	2.0	2.0	
HWP sequestration in durable wood products	-1.1	-1.0	-1.0	-0.9	-1.1	-1.0	-0.9	-0.8	-0.8	-1.1	-1.1	-1.1	-1.0	-1.0	
Total	**-3.4**	**-3.3**	**-3.2**	**-3.2**	**-3.2**	**-3.2**	**-3.1**	**-3.1**	**-3.1**	**-3.5**	**-3.5**	**-3.4**	**-3.3**	**-3.2**	

Notes: Figures expressed as a million metric tons of carbon dioxide equivalent (MMt CO_2e): negative values indicate negative emissions (net carbon uptake or sequestration) and positive values indicate positive emissions (net carbon release or emissions). Harvested wood product (HWP) emissions include bioenergy combustion and decay in landfills. Estimates of fluxes from forests, settlement trees, and land-use conversion were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 2006). Harvested wood product estimates were extracted from Dugan et al. 2020 who used Vermont timber harvest data to model emissions from harvested wood products.

3.4 Wetlands and water bodies

Wetlands and water bodies have changed over time, however, reliable sources of data that can catalog these changes are lacking. Even current data is insufficiently granular. The National Wetlands Inventory (US Fish & Wildlife, 2020; Wilen & Bates, 1995) will release new data in 2022, and this new data may help track more recent trends (losses or gains) in wetlands. However, a major limitation to the National Wetlands Inventory is that it can miss smaller water bodies and wetlands, both common to Vermont. The state has other data resources available, such as critical habitat maps and <1 m land use maps; however, these are limited in the scope of time that they cover. Still, change in wetland and water body areas are very small as a percentage of wetlands and water bodies (Figure 15, Yang et al., 2018). From 2001 to 2019, the NLCD reports a 1.4% increase in wetlands and a 2.1% decrease in water bodies, which may be within the margin of error of the dataset or could be influenced by a particular year (e.g., low water levels in 2019).

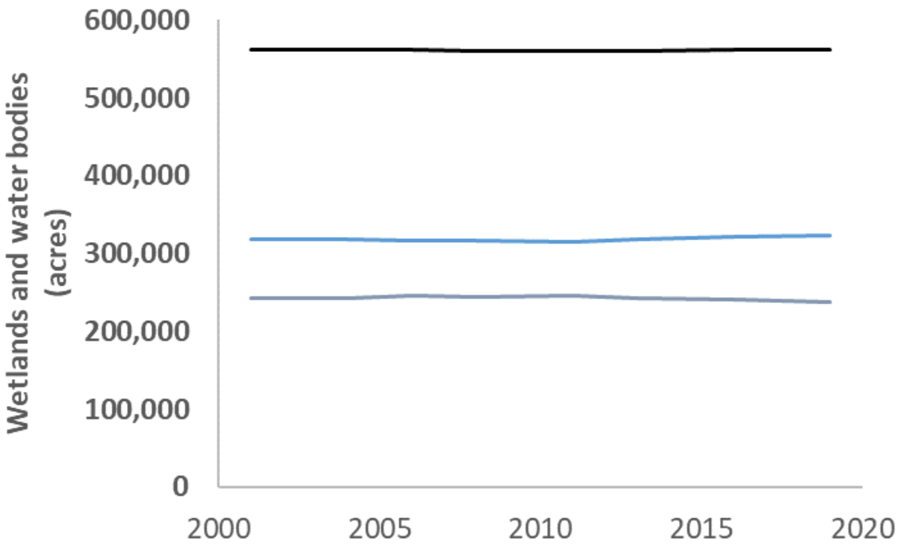


Figure 14: Area in wetlands and water bodies reported by NLCD (Yang et al., 2018)

Estimated carbon stocks in wetlands and water bodies (0–30 cm depth) are 57 MT CO_2 using NLCD estimates of area (as used in the flux estimates) (Yang et al. 2018); this increases to 68 MT CO_2 with ANR estimates of area (VT Dept. Environmental Conservation 2021). If considering carbon from depths of 0–120 cm, these estimates are multiplied by a factor of 3.4 (see Section 2.4 Wetlands and water bodies) (Nahlik and Fennessy 2016).

Today, carbon fluxes from wetlands and water bodies are estimated to sequester an additional (-)0.012 MMT CO_2-e yr^{-1}. As there has been little change in area over time, this flux rate is the same for 1990 and 2005 (Figure 16).

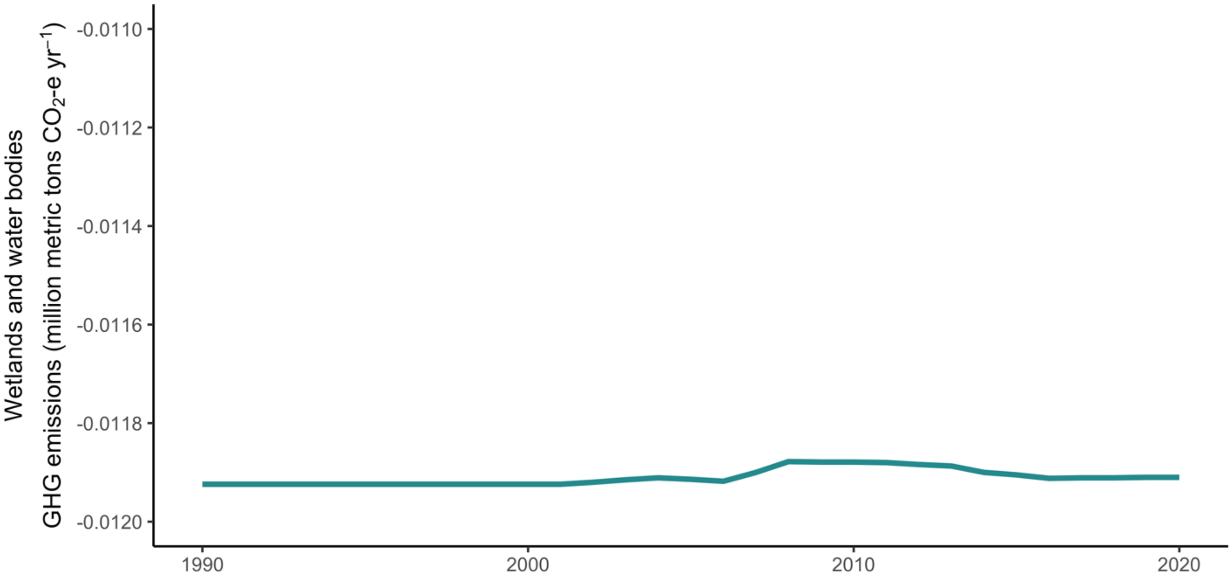


Figure 15: Net annual flux from wetlands and water bodies 1990–2020 (negative means sequestration)

3.5 Agriculture

Soil carbon stocks in cropped areas have declined over time, as the area of cropland has declined. Stocks of 86 MMT CO_2-e (23.5 MMT C) in 1990 have declined to 63 MMT CO_2-e (17.2 MMT C) in 2020 (Figure 17; Section 3.5.1). Hay and haylage crop areas store 80% of the soil carbon stock in croplands (50.6 MMT CO_2-e or 13.8 MMT C in 2020). Areas cultivated in corn account for 18% of the soil carbon stock (11.4 MMT CO_2-e or 3.1 MMT C in 2020). Minor grains (winter wheat, barley, oats, etc.) and soy account for roughly 1% of carbon storage, as do vegetable crop types.

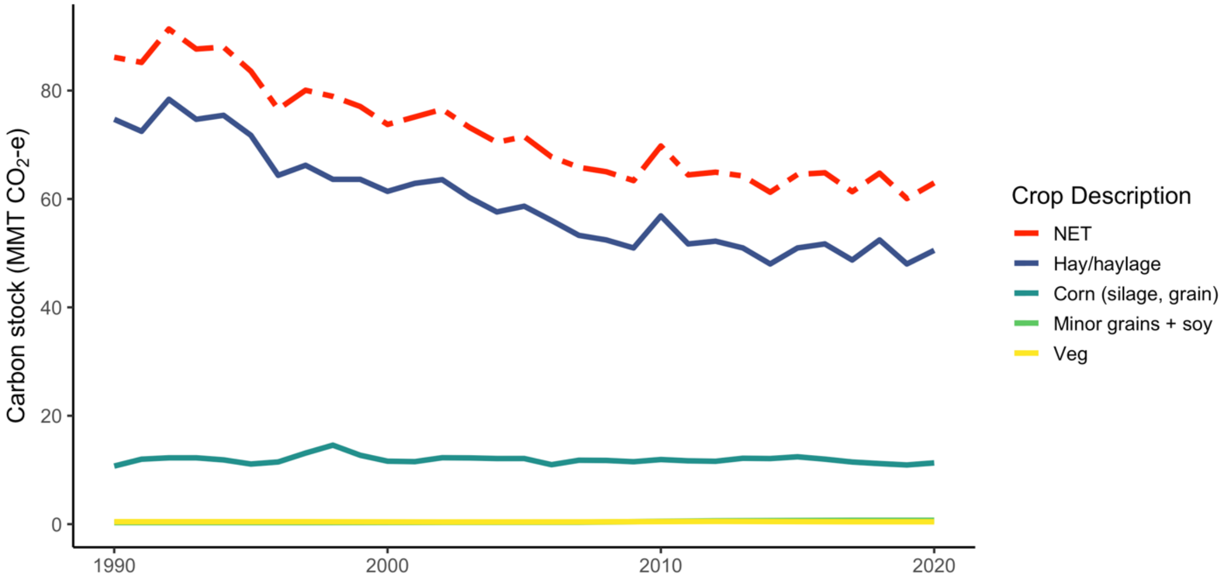


Figure 16: Soil carbon stocks by crop type 1990–2020 estimated through bookkeeping approach

Net GHG emissions from agriculture have decreased from 0.70 MMT CO_2-e (704,318 metric tons CO_2-e yr^{-1}) in 1990 to 0.50 MMT CO_2-e (497,036 metric tons CO_2-e yr^{-1}) in 2020 (Figure 18). These emissions reductions are largely due to reductions in livestock and cropland area, rather than to major changes in agricultural practices.

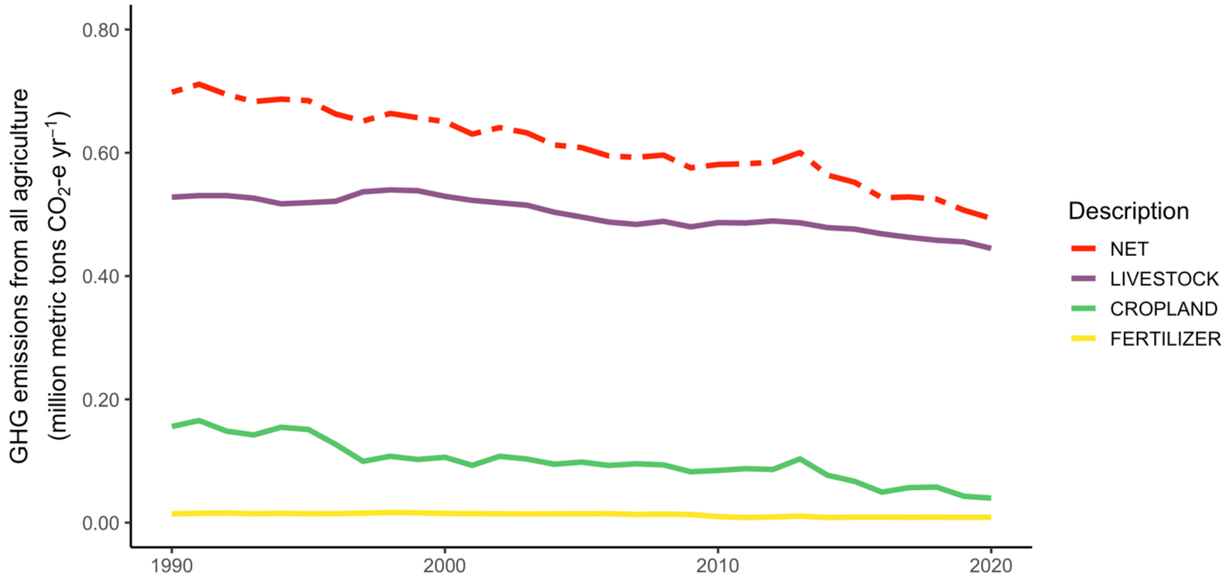


Figure 17: Net GHG emissions from agriculture in Vermont 1990–2020 based analysis in EX-ACT

3.5.1 Cropland management

The crop types considered in this Carbon Budget include hay, haylage, corn, small grains, vegetables, and soybeans (Figure 19) (USDA NASS, 2021). Note that the total area managed as croplands may be greater than the sum of all cropped area due to some uncropped areas such as buffer strips or drainage areas being counted. Total area in annual crops in Vermont has declined 26% since 1990, from 596,749 acres (annual crops) to 441,206 acres 2020 (USDA NASS, 2021). Perennial crops (berries, orchards, cut Christmas trees) reduced area over the same period by 43% from 22,726 acres (9,197 ha) to 12,909 acres (5,224 ha).

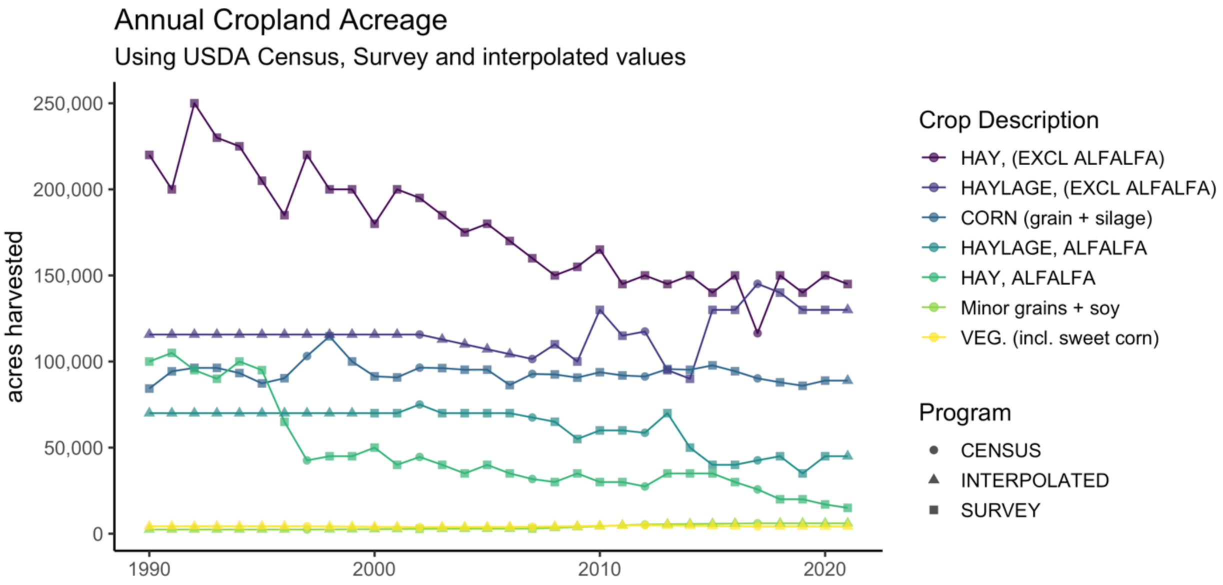


Figure 18: Crop types in Vermont by annual cropland acreage estimated from USDA NASS (census and survey information) and interpolation (USDA NASS, 2021)

Cropland management by crop type is illustrated in Figures 20–22). Beginning around the year 2000, most cropland systems in Vermont began using reduced tillage or no-tillage practices. Today, “no-tillage” (including no-till seeding and not tilling soils at all) is used in 79% of Vermont’s cropland acres (339,657 acres) and reduced tillage in 11% (48,032 acres). Full tillage account for the remaining 10% (42,232 acres) (USDA NASS, 2021), primarily with corn (40% of the crop, including both grain and silage), vegetable crops (100%), sweet corn (40%), and soybean (40%). Vermont croplands are considered medium or high carbon input systems, either with manure or no manure. Crop residues are either exported through harvest (e.g., straw) or remain in place (e.g., corn stover).

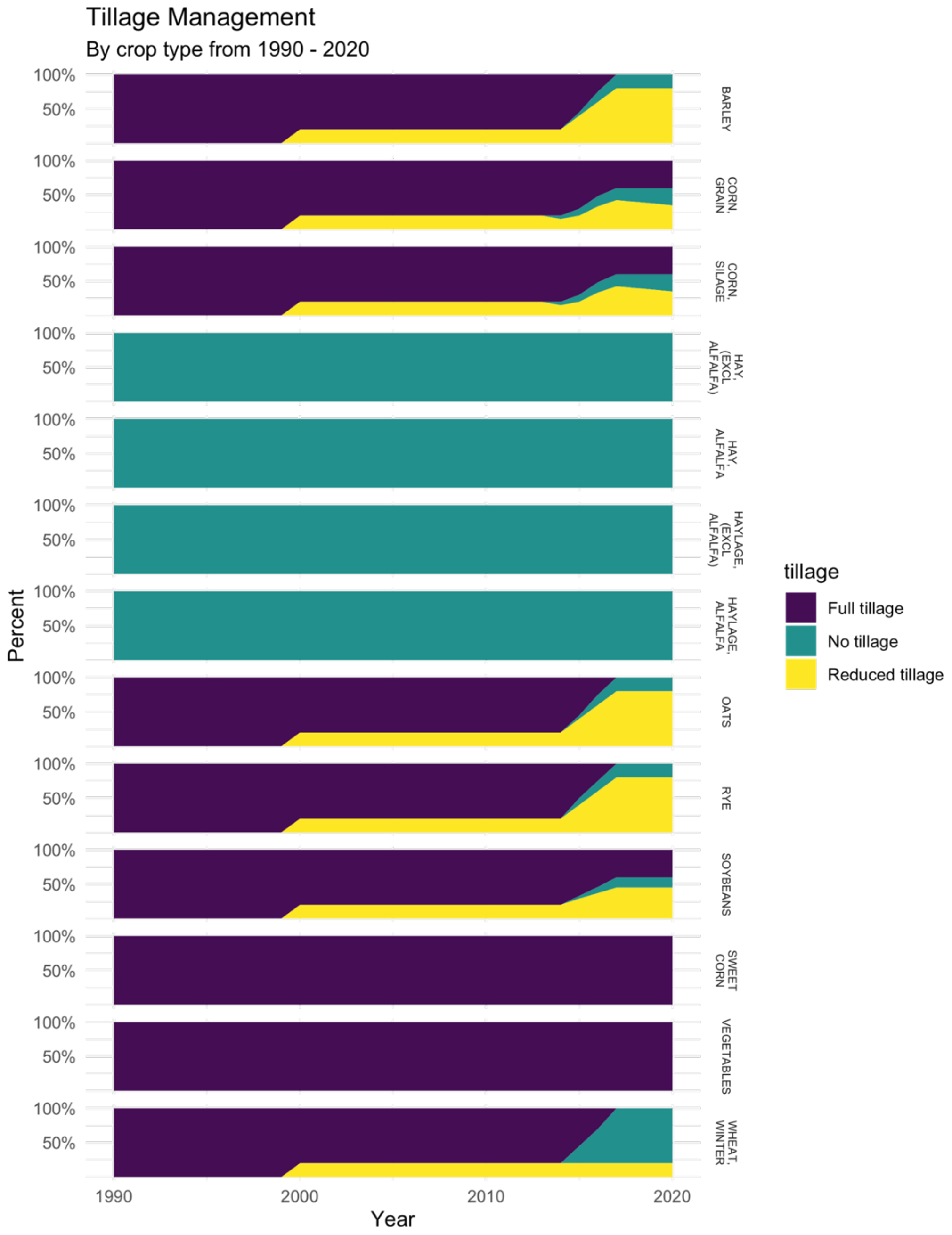


Figure 19: Tillage management by crop type 1990–2020

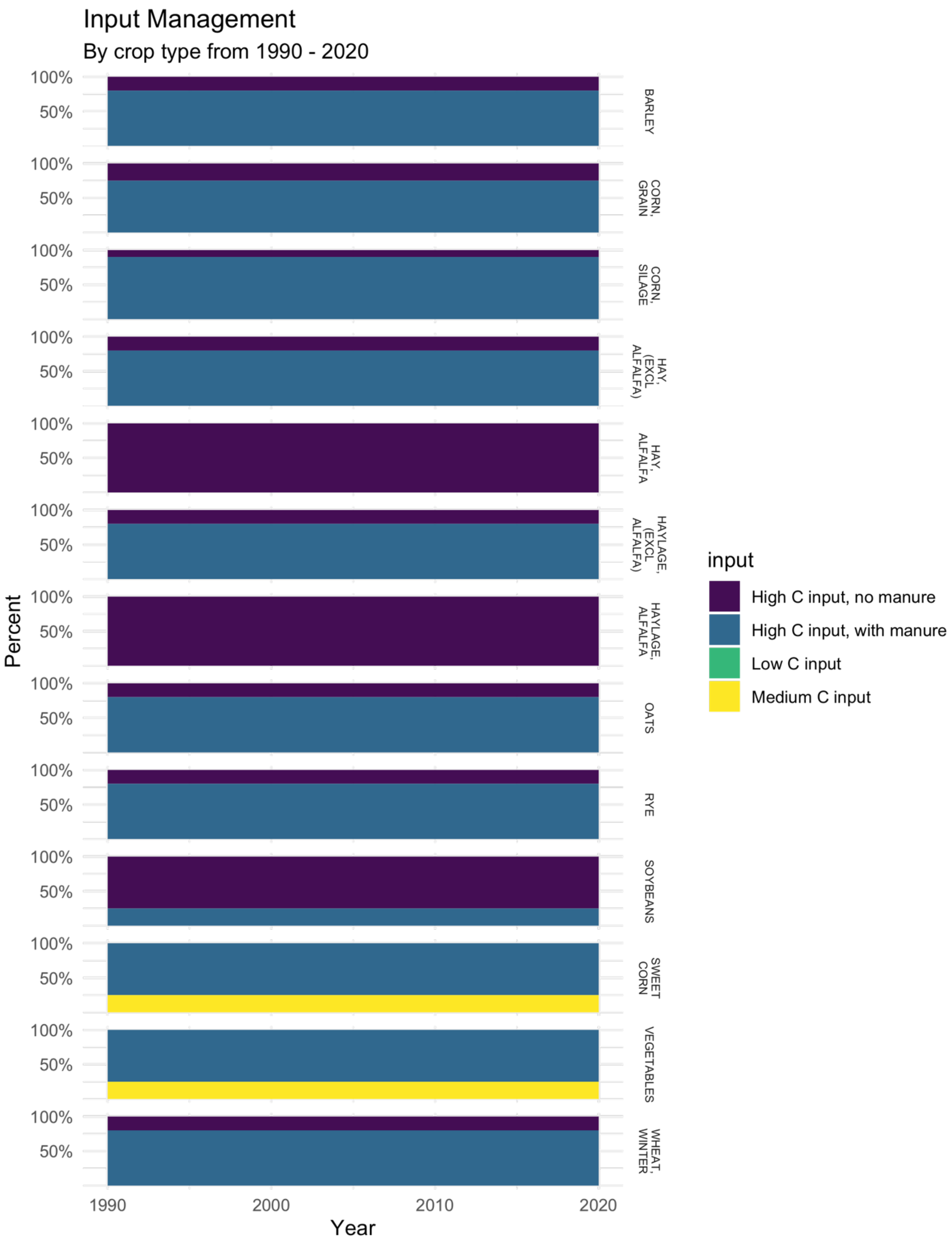


Figure 20: Carbon input categorization by crop type 1990–2020

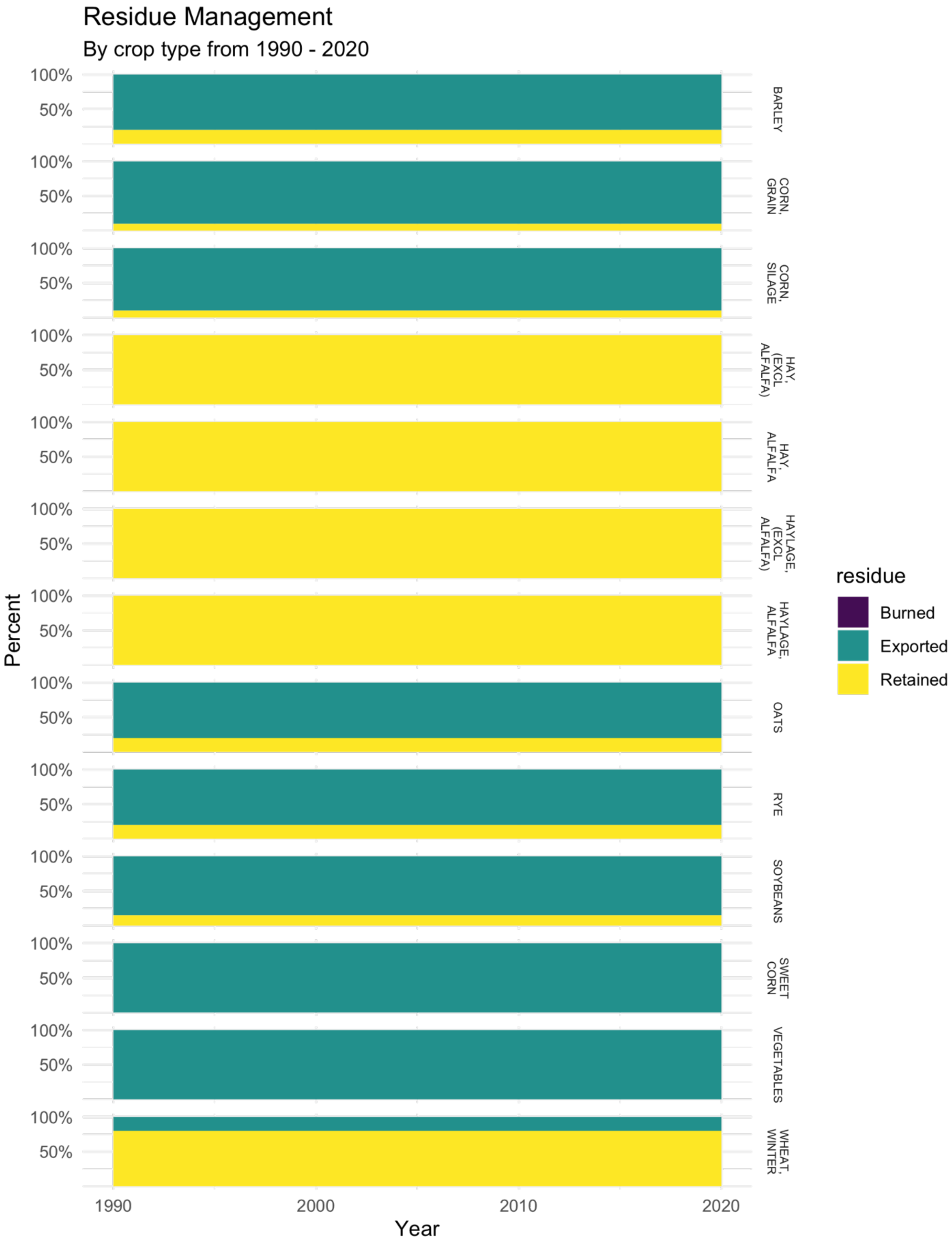


Figure 21: Residue management by crop type 1990–2020

Other Perennial Crops

EX-ACT has different parameters for perennial crops. As mentioned above, perennial crops (berries, orchards, cut Christmas trees) reduced area by 43%, from 22,726 acres (9,197 ha) in 1990 to 12,909 acres (5,224 ha) in 2020 (Figure 23). Management practices for the three perennial crops were: no-tillage, high carbon input, and no manure input or burning.

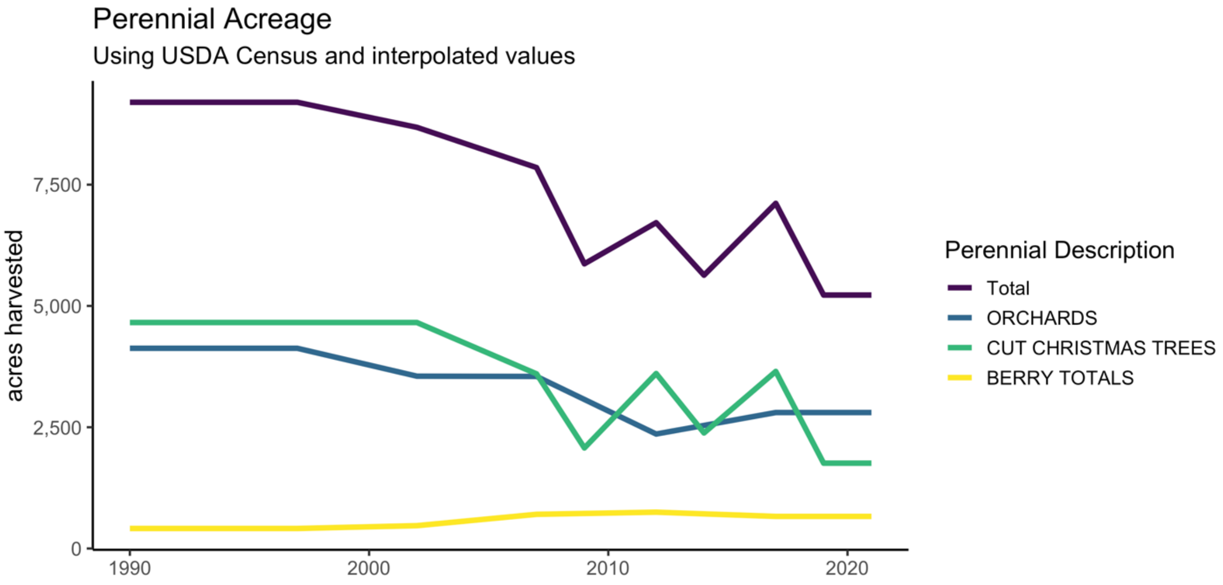


Figure 22: Area in specialty perennial crops (USDA NASS, 2021)

Cropland emissions

In Vermont, emissions related to cropland management have declined from 0.15 MMT CO_2-e in 1990 to 0.04 MMT CO_2-e in 2020, a substantial decrease due mostly to a decrease in cropland area over the same period (Figures 24, 25). As discussed in previous sections, emissions are the net balance of emissions that vary according to crop type, carbon inputs, tillage practices, and residue management. However, the greatest factor in emissions by crop type is area, and so emissions have declined as cropland area has decreased over time. Crop types of hay, haylage, and corn account for the greatest area and therefore the greatest emissions. Carbon input management affects if a crop type will be a source (positive emissions) or a sink (negative emissions or sequestration). Hay (excluding alfalfa) sequesters carbon because of the inputs of carbon through manure in the EX-ACT model. Conversely, alfalfa hay and alfalfa haylage do not include manure application to the fields and thus result in net emissions to the atmosphere.

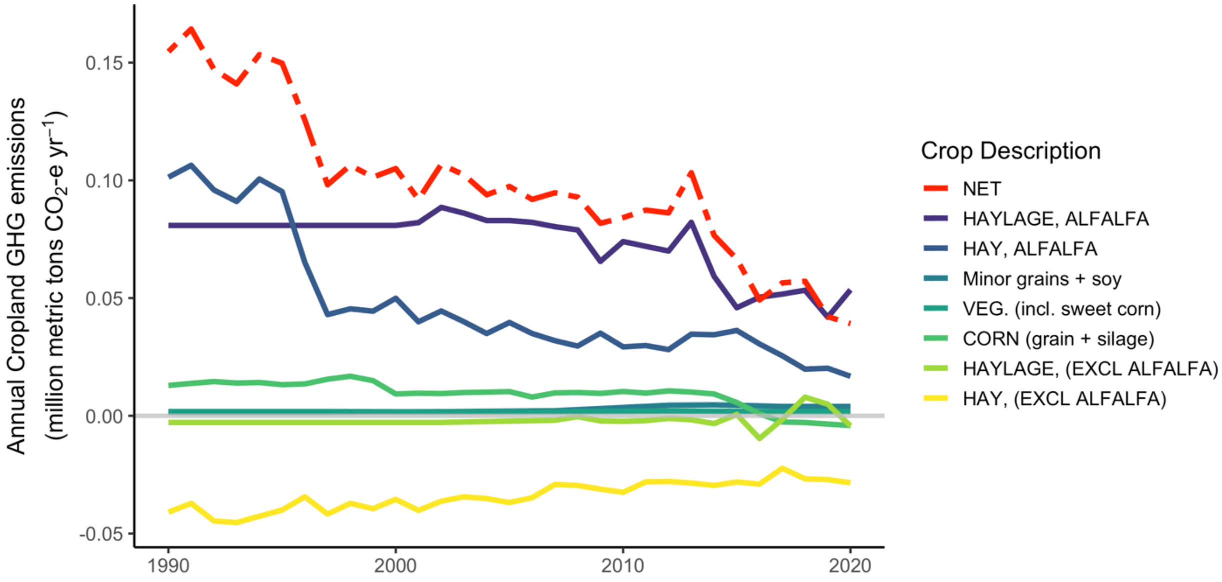


Figure 23: GHG emissions by crop type in Vermont 1990–2020 estimated with EX-ACT

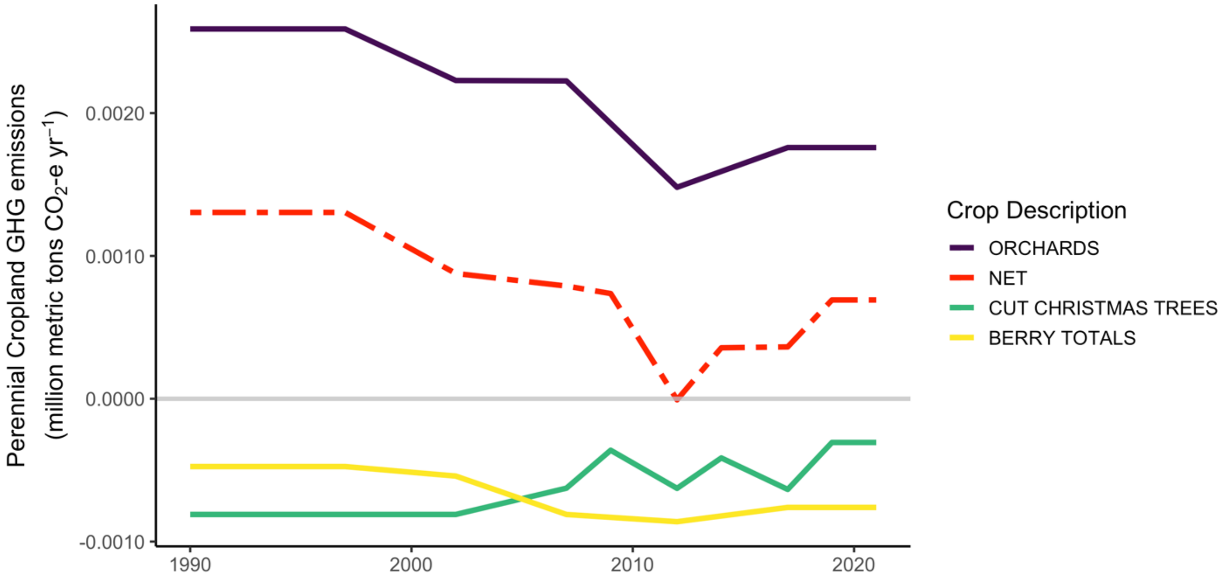


Figure 24: GHG emissions by perennial crop type in Vermont 1990–2020 estimated with EX-ACT

3.5.2 Fertilizer use

Following the methods described earlier in this report, fertilizers used in agriculture were calculated and then categorized in EX-ACT by lime and three types of synthetic fertilizers (Table 14).

Table 14: Estimated fertilizer application for 2019-2020 (VT Agency of Agriculture, Food and Markets, 2021)

Fertilizers	**Amount applied (metric tonnes)**	**Amount applied (tons)**
Lime application		
Limestone (tonnes per year)	16,329	18,000
Synthetic fertilizers		
Synthetic N-fertilizers other than Urea (N per year)	10,947	12,067
Phosphorus (P2O5 per year)	1,993	2,197
Potassium (K2O per year)	4,137	4,560

Since 1990, use of N-synthetic fertilizer has declined by roughly 58% (Cao et al., 2018; VT Agency of Agriculture, Food and Markets; 2020; VT Agency of Agriculture, Food and Markets, 2021), even when using the updated Cao et al. 2018 data for 1990-2009 to account for the urea used in deicer through agricultural purchase (Figure 26).

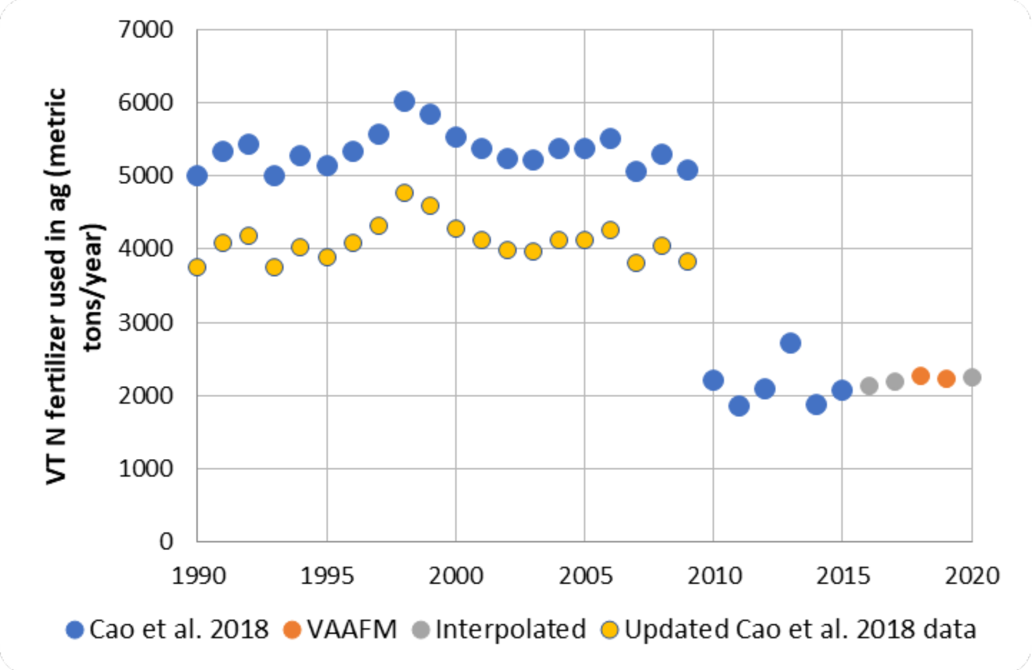


Figure 25: N-synthetic fertilizers used in Vermont agriculture 1990–2020, after Cao et al. 2018 and derived from VAAFM 2020, 2021

Fertilizer emissions

Fertilizer-related GHG emissions decreased over 60% from 1990 to 2020, to 0.04 MMT CO_2-e in 2019-2020. Fertilizer emissions are dominated by N_2O emissions from synthetic N-fertilizers

(Figure 27), which accounted for a total of 0.03 MMT CO_2-e in 2019-2020. Emissions are modeled with a linear trajectory that corresponds with N-fertilizer application rates (Huddell et al., 2020) in EX-ACT, so the declining trend over time is directly related to the decrease in fertilizer use over time. This declining trend for fertilizer use and emissions also corresponds to declining land in crop production.

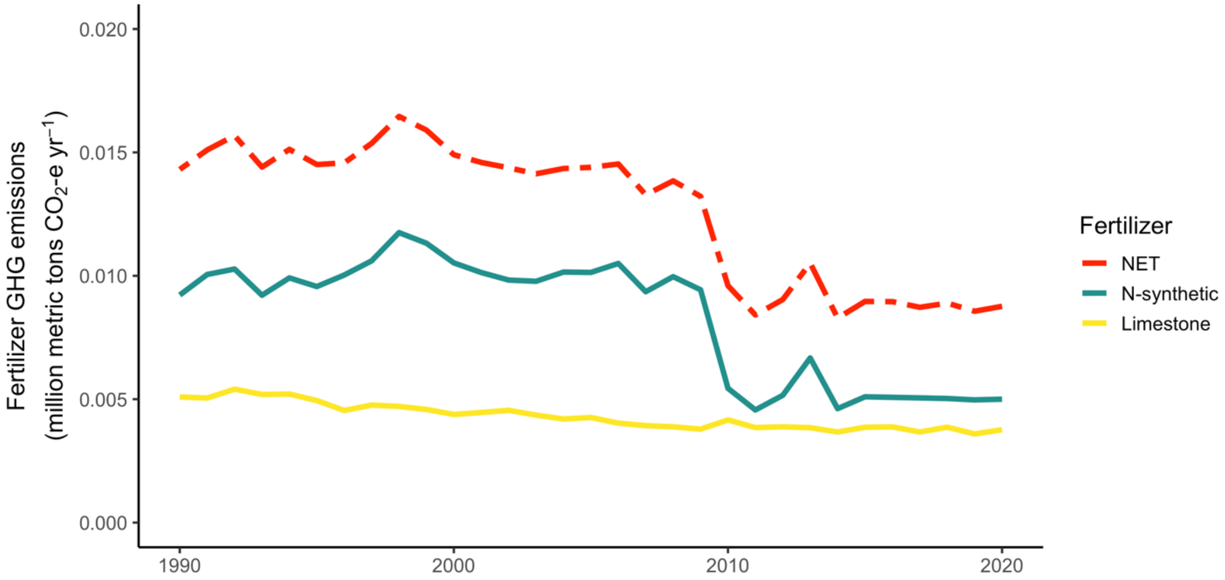


Figure 26: Emissions from N- fertilizers and limestone 1990–2020 estimated with EX-ACT

3.5.3 Livestock management

Vermont's major livestock categories include chickens (layers), dairy cows and calves, and beef cattle (Figure 28) (USDA NASS, 2021). All categories of major livestock have shown declines over the last thirty years. Additional livestock in minor categories include chickens (boilers), rabbits, goats, horses & ponies, hogs, alpacas, llamas, and bison (Figure 29). Due to the small numbers of minor livestock, there is more variability in this time series due to single producers coming on and offline. The steady increase in chickens (boilers) is notable (Figure 29).

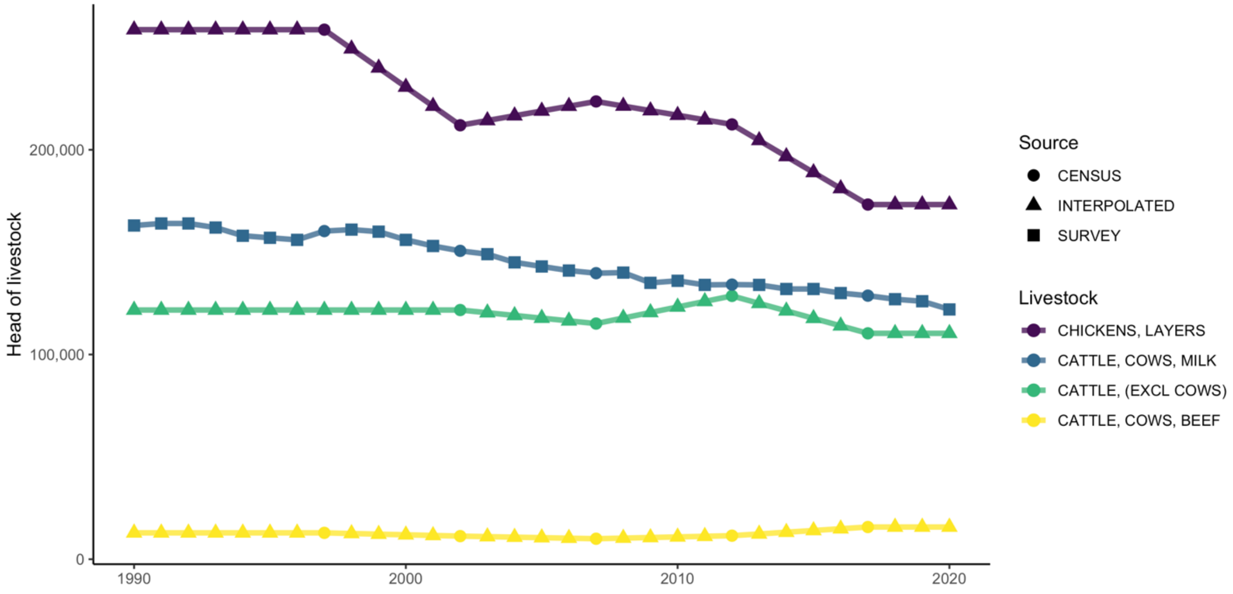


Figure 27: Number of the most common categories of livestock 1990–2020 estimated from census data, survey information, and interpolation (USDA NASS, 2021)

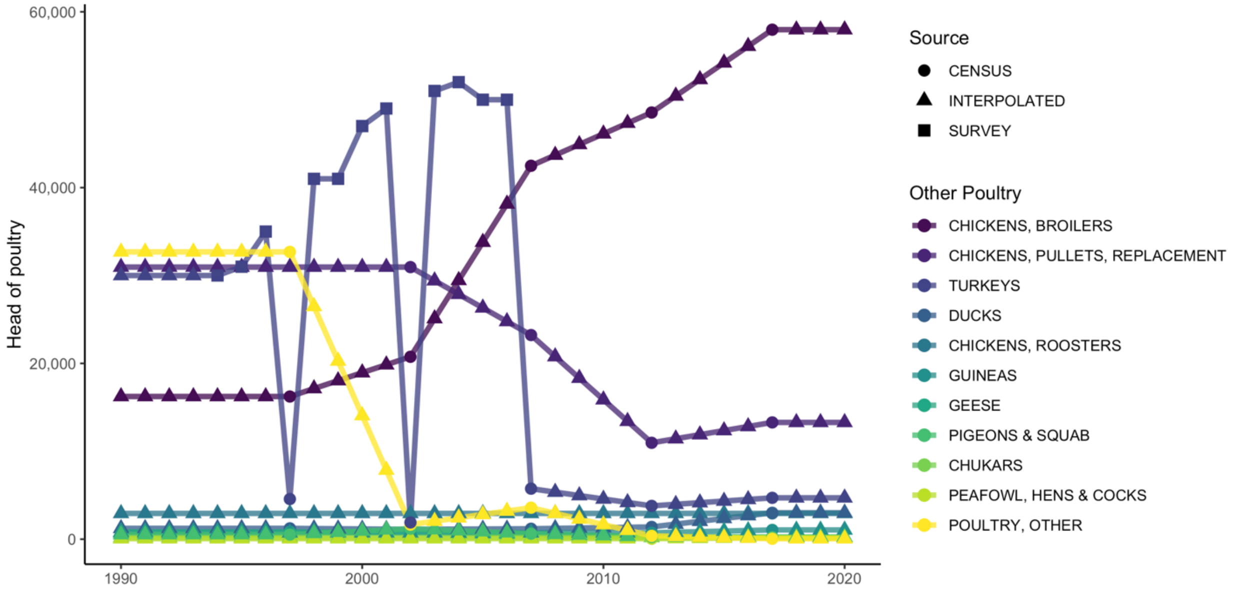


Figure 28: Number of less common categories of poultry livestock 1990–2020 estimated from census data, survey information, and interpolation (USDA NASS, 2021)

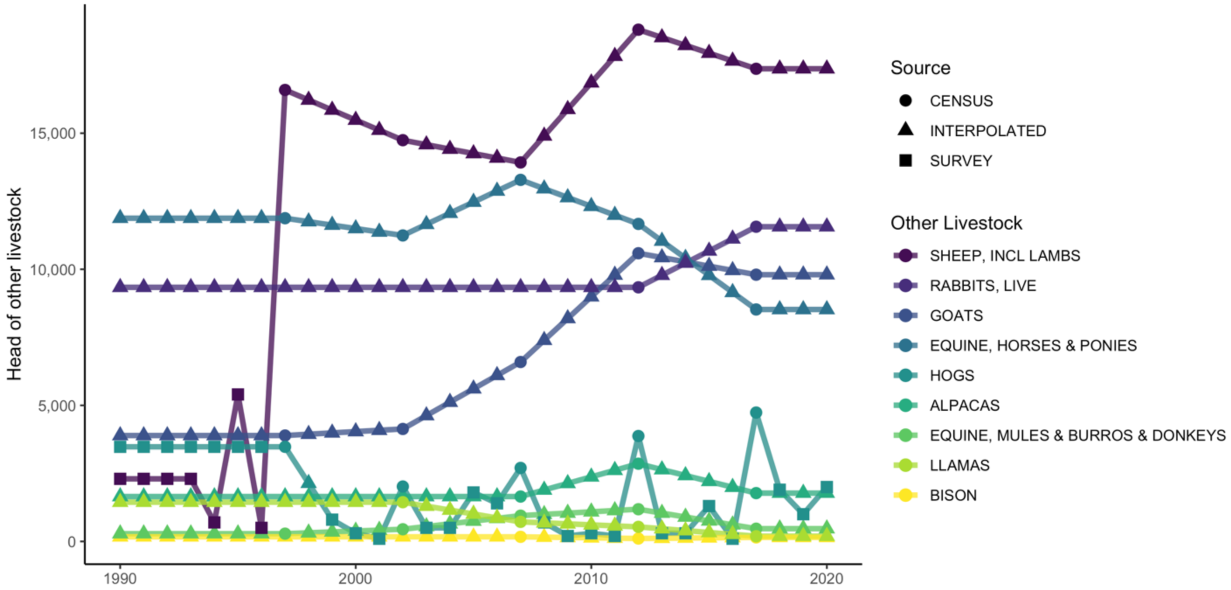


Figure 29: Number of less common categories of non-poultry livestock 1990–2020 estimated from census data, survey information, and interpolation (USDA NASS, 2021)

Manure management for cattle (dairy, calves/heifers, and beef) has evolved over time (Figure 30), according to experts with knowledge of Vermont's cattle and nutrient management plans. Farmers rapidly shifted from daily spread to liquid/slurry in the 1990s and increases in organic or pastured cattle over recent decades resulted in more manure in pasture. Solid storage is still used in some cases or seasons, and there have been minor increases in new techniques like anerobic digesters.

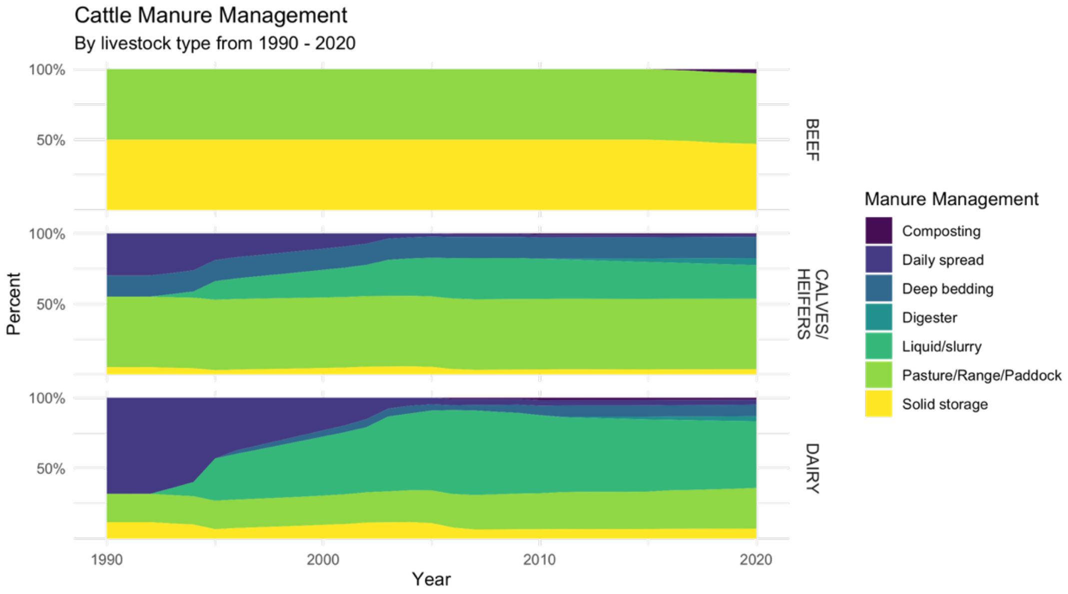


Figure 30: Changes in manure management by percent of total manure from cattle 1990–2020 based on expert knowledge

Livestock emissions

Emissions from livestock are primarily driven by enteric fermentation in dairy cows (0.3 MMT CO_2-e in 2020) and cattle (non-milking) (0.1 MMT CO_2-e in 2020). Large animals and herd sizes drive the emissions from livestock due to high rates of enteric fermentation (Figure 31).

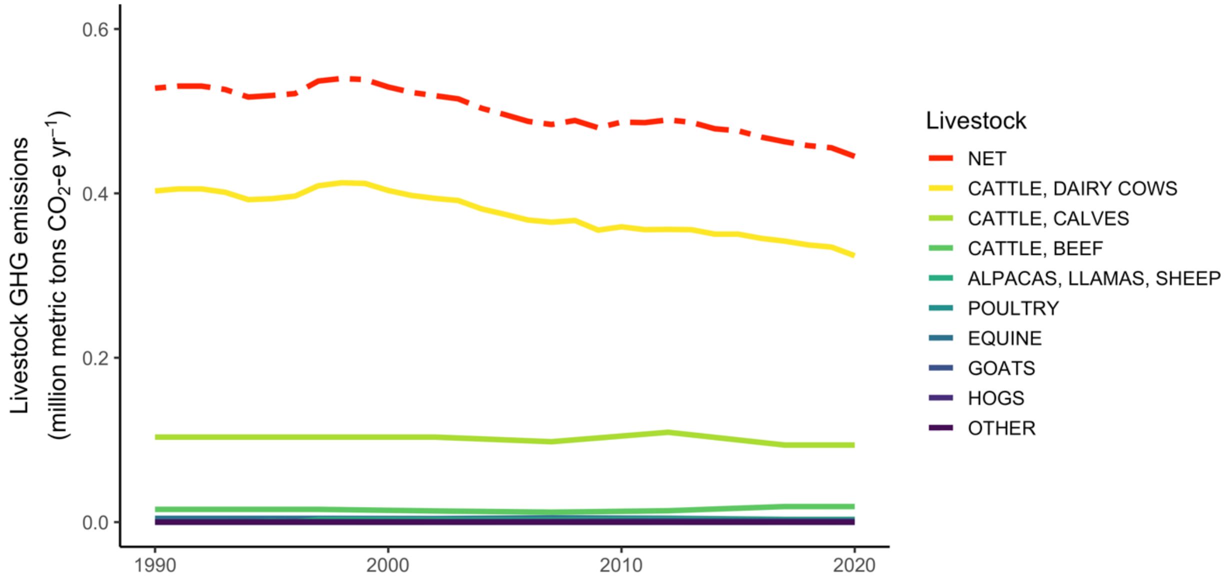


Figure 31: Greenhouse gas emissions by livestock type 1990–2020 based on analysis conducted in EX-ACT

3.6 Grasslands and shrublands

There are roughly 350,000 acres of grasslands and shrublands in Vermont (USDA, 2020). Total area in grasslands and shrublands decreased through the 1990s to the mid-2000s and have increased since (Figure 32). EX-ACT defines degraded grasslands and shrublands as having major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe erosion. Based on data from the USDA and input from experts (see section 2.6 Grasslands and Shrublands), an estimated 25% of grasslands and shrublands are degraded, largely from sheet or gully erosion (caused by water) or management such as overgrazing (USDA, 2020). Degraded grasslands and shrublands have a diminished capacity to retain carbon, either in biomass or soils.

Prime and improved grasslands and shrublands have increased from 11% to 15% of grasslands in Vermont between 1990 and 2020 (USDA, 2020). Improved grassland management may include activities that either intentionally build carbon stocks or do so as a by-product of other goals. For example, rotational grazing—the alternating of grazing and resting of grasslands—increases grassland productivity, thereby increasing carbon. Farmers in Vermont have also begun to reduce grazing access in riparian zones to promote water quality. This can reduce soil erosion as well as increase shrubland development, increasing biomass compared to degraded riparian zones used by cattle.

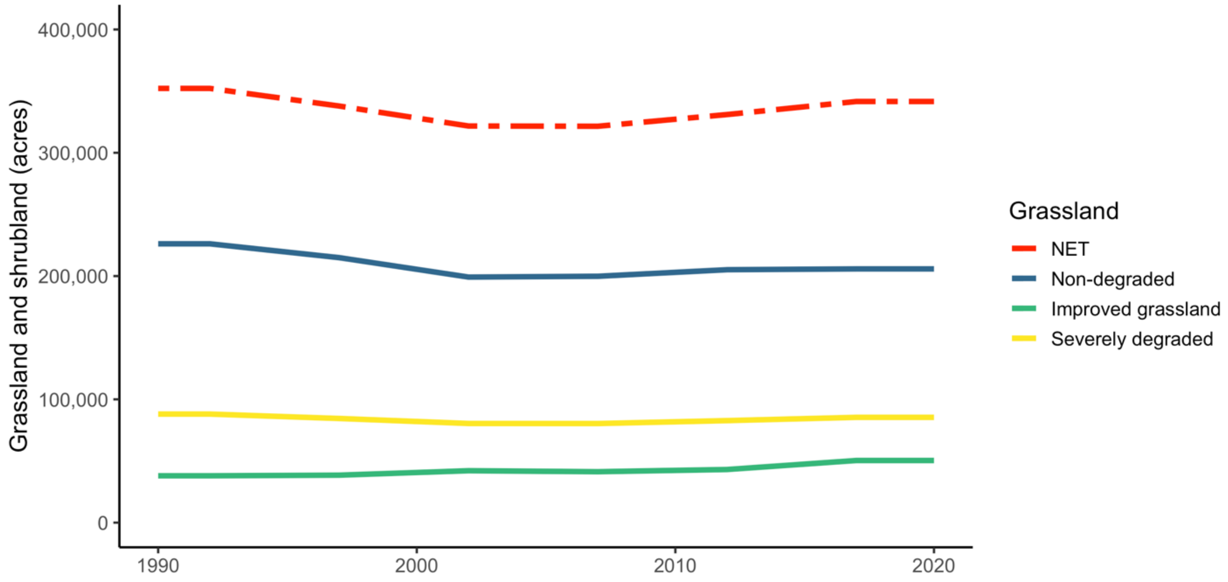


Figure 32: Estimated area of grasslands by condition 1990–2020

Carbon stocks in grasslands and shrublands were estimated with the carbon stock values reported in section 2.6 (White et al., 2021). Variation in carbon stock over time is primarily driven by total grassland area, with some additional carbon sequestration in recent years due to an increase in improved pasture. For example, total grassland area in 1990 is slightly greater than in 2020 (352,194 acres compared to 341,591 acres) but the contribution of improved grasslands increased from 11% in 1990 to 15% in 2020, contributing to enhanced carbon storage. Thus, carbon stocks were lowest in the early 2000s (37.7 MMT CO_2 in 2003 and 2004), down from the 1990s (40 MMT CO_2 in 1990), and they rebounded, even increasing by 2020 (41.4 MMT CO_2 in 2020).

Grasslands and shrublands in Vermont may sequester carbon if activities are undertaken to increase soil carbon, biomass, or protect certain zones from grazing (e.g., over -18,893 MT CO_2-e in 2020). Currently, many organizations in Vermont support farmers in plans for rotational grazing, which may improve grassland productivity and contribute to enhanced carbon storage. Grasslands experiencing degradation, such as water-driven erosion of soils, are a source of carbon (72,231 MT CO_2-e in 2020) that outweighs sequestration from well-managed grasslands (Figure 33). The balance of carbon could tend more towards sequestration if more acres used improved management practices (e.g., rotation grazing).

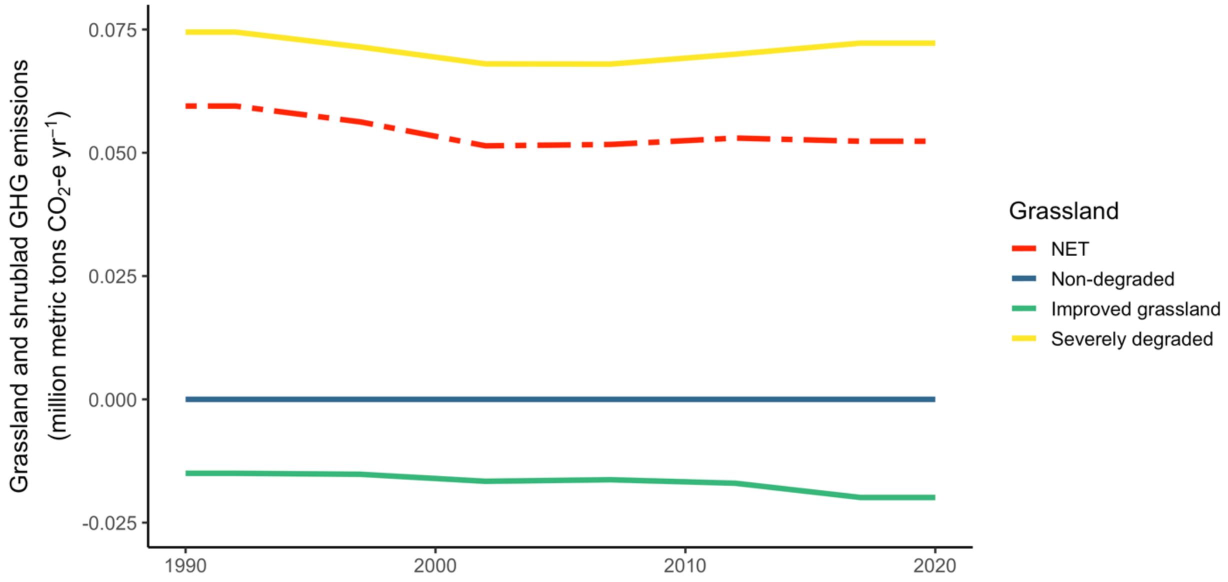


Figure 33: Estimated emissions for grassland areas by condition 1990–2020, where non-degraded grasslands are considered net neutral in EX-ACT estimates

3.7 Urban and developed

Urban and developed areas experienced growth in some parts of Vermont between 1990 and 2020. According to the NLCD, there has been a 3% increase in urban and developed areas, which can be categorized as open space (50% of area) or low intensity development (29%), medium intensity development (17%), and high intensity development (only 4%) (Figure 34; Yang et al., 2018). Transition to urban and developed appears as an increase in carbon storage. However, while locally very important, the storage amounts are small compared to loss of forest cover (some of which may result in urban and developed areas, but the carbon loss would be tracked in forest cover change).

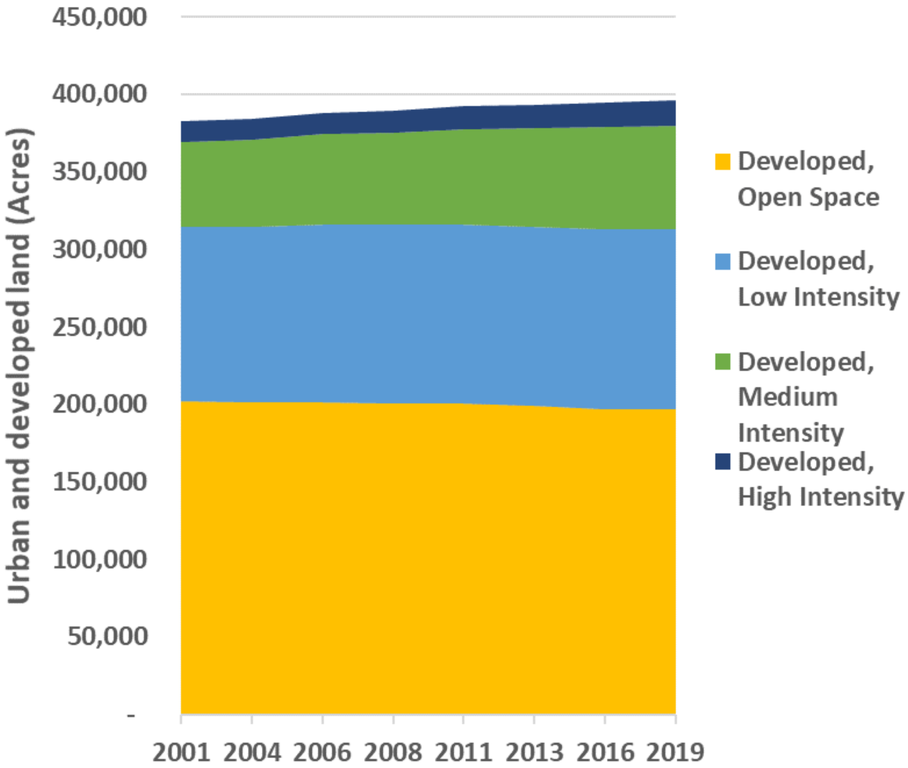


Figure 34: Urban and developed land area 2001–2019 with data from NLCD (Yang et al., 2018)

Vermont's trees in urbanized areas are estimated to store about 15 MMT CO_2-e and sequester (-) 0.28 MMT CO_2-e yr^{-1} (in the range 157,000–500,000 MT CO_2-e yr^{-1}) as of 2020 (Domke et al., 2020; EPA, 2021; Nowak et al., 2013; Zheng et al., 2013). Given modest changes in urban and developed areas, fluxes have not changed much over time (-0.26 MMT CO_2-e yr^{-1} in 1990 and -0.27 MMT CO_2-e yr^{-1} in 2005. There is a relatively small pool of carbon in urban and developed soils (<<<.0001 MT CO_2-e km^{-2} or 0.00001 MT CO_2-e) that does not significantly change carbon storage or fluxes for the state.

4 Discussion and Future Work

This carbon budget provides a strong foundation for more accurate tracking and accounting of carbon and GHG fluxes in Vermont. GWSA legislation set Vermont ahead of many states in the U.S. and VCC's leadership in commissioning a CAP and series of tasks—including this carbon budget—will help Vermont to reach its climate mitigation goals. Indeed, Vermont is unique among states in leading this type of work. There will be opportunities in the future for Vermont to help other states think through and benefit from Vermont's experience developing a carbon budget related to AFOLU.

Moving forward, it is recommended that Vermont incorporate some of the approaches used in the Vermont Carbon Budget to augment existing methods and datasets in its GHG Inventory. For example, the EX-ACT model may provide more accurate flux estimates for many land-based sectors than the current GHG Inventory methods because EX-ACT accounts for additional impacts of management actions. Likewise, a particular advantage of EX-ACT is its accounting for carbon sequestration in agriculture. Also, the Vermont Forest Carbon Inventory used in this carbon budget (Kosiba, 2021) could improve the estimates of carbon fluxes related to forests in the GHG Inventory. This would require adequate staffing to run the models, update input data sets, and interpret data. If an EX-ACT approach is adopted for use in a future Carbon Budget or to supplement the GHG Inventory, the quality and quantity of data inputs will be important. In fact, any model that considers management and sequestration will require input data on crop management, particularly residues, tillage, cover crops, and nutrient additions (fertilizer application rates, manure management). Vermont has much of this information in farms' nutrient management plans; the challenge is extracting that information into a centralized database.

The VCC and its subcommittees will also need to consider how to account for land use change. What is the appropriate mechanism for tracking land use change? How should accounting for land use change be carried out to avoid double-counting within land uses? Does a new data set need to be developed to track land use trajectories specific to the sectors within the Carbon Budget or GHG Inventory? Can existing data sets be modified for use? Currently, NLCD data has the longest time record, but it is not credible for accuracy in Vermont. New data products, like the Vermont High Resolution Land Cover available through the Vermont Center for Geographic Information, are coming online (2018 and soon 2021) with 0.5-meter resolution. This data set contains eight land cover classes: tree canopy, grass/shrubs, bare soil, water, building, roads, other paved and railroads. A more rapid land use change analysis might include high resolution (10 m) annual information, but it would need to be created and supported.

Accounting for C Sequestration to Meet State-level Goals

How do we best account for the uptake and storage of atmospheric C into plants and soil for Vermont's state-level GHG reduction goals? When we talk about a Net Zero goal for Vermont by 2050, that considers both the positive emissions, from burning fossil fuels and biomass, and the negative emissions, such as the sequestration of C by plants and soils. A comprehensive C budget should reflect what the atmosphere sees—in other words, it should quantify the actual change in atmospheric CO2 concentrations caused by the day-to-day activities of people, industries, and natural systems in Vermont. To establish this goal, the VCC will need to evaluate if there are other fluxes that should be included in the Vermont Carbon Budget and how to accurately measure stocks and fluxes across these sectors, considering the many data limitations. As is shown in this first Vermont Carbon Budget, it is difficult to quantify all these sources and sinks of CO2 accurately and precisely.

Management decisions to increase C sequestration or reduce C emissions will require clear definitions of *additionality*, *permanence*, and *leakage*, along with a method for tracking and accounting. Additionality is additional carbon sequestered or emissions reduced that would not have occurred under *business-as-usual*. First the 'business-as-usual' level must be defined as a benchmark for tracking changes in C sequestration and storage. 'Avoided emissions' constitute C that was not emitted to the atmosphere because of a change in land use or management, like conserving a parcel of forest slated for development. 'Avoided emissions' are not included in the Vermont Carbon Budget because they are hypothetical. Only real (measured or estimated) fluxes are considered. Yet, reducing sources of emissions is critically important for stabilizing atmospheric CO_2 concentrations. Also critically important is permanence, the need for additional C sequestered to be stored for a long period of time or it risks being emitted back to the atmosphere. Lastly, changes to land use and forestry for increased C storage in forests can result in market leakage, which occurs when reductions in timber harvests in one location are counteracted by harvesting higher amounts elsewhere to meet wood market demands, thus negating the intended C benefit. If there is a resultant increase in timber harvesting that occurs outside of Vermont, additional fossil fuel emissions may result from importing HWP.

Below are specific recommendations for components of this Carbon Budget.

4.1 Anthropogenic—fossil fuels

Updates to fossil fuel estimates should come from the State of Vermont's GHG Inventory.

4.2 Anthropogenic—land use change

Tracking shifts from one land use type to another is challenging because it requires spatially explicit information over time. For example, changes in forest cover could be enhanced with information on the next land cover type, as an impervious surface versus residential property could have large differences for carbon loss and future sequestration. Further, many areas that have been reforested, such as riparian zones, are "counted" as forest cover, although they were formerly agricultural lands. Does the resulting carbon sequestration get credited to the agriculture sector or the forest sector? Without traceability in land use change, the accounting becomes flawed.

All estimates of AFOLU GHG emissions could benefit from improved availability of annual land cover and land use change data, including through remote sensing. Many new data products manage high frequency of observations at high spatial resolution (10 m). The frequency and resolution would increase accuracy in assessing land based GHG emissions. For example, improved data may capture small-scale forest clearings for single-family home development that would not be caught in more moderate resolution data sets (e.g., Landsat sensors with 30 m resolution).

4.3 Forests

Vermont's forest stores and sequesters an immense about of C (Tables 12, 13) and provides numerous other benefits like clean water and air, wood products, biodiversity, and beauty. However, the rate of C sequestration in the forest sector is declining. Continuing to sequester C at similar levels as the recent past will require planning across multiple areas.

Within the sector, forests that have remained forests are sequestering C at a slower rate than they did in the past (Table 13). At the same time, there has been both an increase in emissions from the conversion of forests to other uses and a decrease in additional sequestration from land in other uses being converted back to forest (Table 13). These trends cause a net increase in land use emissions over time. Emissions from HWP have declined over this period primarily because harvest volumes have reduced (see Dugan et al. 2021). However, declines in harvest volumes have also resulted in declines in the amount of C sequestered in durable wood products because wood used for durable wood products comprise about 30% of typical harvest volumes (Dugan et al. 2021). If land use decisions on forest conversion and management continue their current trajectory, Vermont's forests will continue to grow and sequester C in the coming decades with or without human management. If the net sequestration of Vermont's forest sector continues to decline, Vermont's forests could become a C source after 2050 (Dugan et al. 2021, Figure 34).

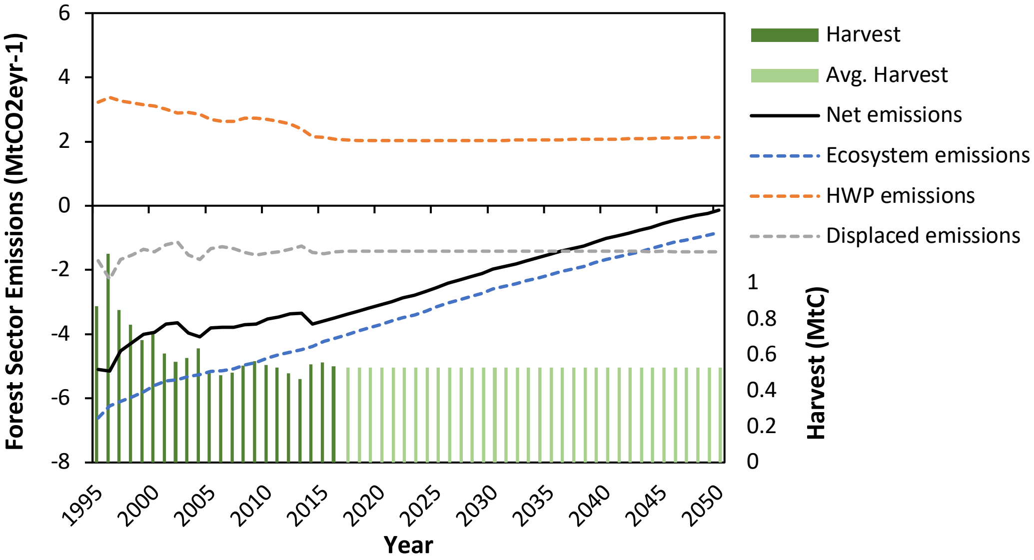


Figure 35: Modeled annual CO_2-e balance for the Vermont forest sector, from Dugan et al. 2021

Note: Net emissions (black) is the sum of sequestration from the forest ecosystem, emissions from HWP sector, and displaced emissions from substituting wood products for other emission intensive materials and fossil fuels (left axis). The historical harvest removals, Tg C/yr, are shown by the dark green bars and the 10-yr average (2007–2016) harvest is shown by the light green bars (right axis). To avoid double counting harvesting emissions, all emissions from harvesting from the ecosystem are tracked in the harvested wood products (HWP) sector, rather than as removals from the ecosystem.

Data limitations

As for all sectors included in the Vermont Carbon Budget, data on C storage and flux in Vermont's forest sector needs improvements to increase both accuracy and precision. Aside from HWP, stocks and fluxes for Vermont's forests are derived from 1124 FIA plots that are measured on a rolling basis. While the FIA data is an incredibly valuable resource, Vermont's varied topography, soils, and forest conditions may require a higher plot-sampling density or additional data sources, like remote sensing imagery. With high variability across Vermont's forests, these estimates have a large amount of uncertainty, for instance see (Figure 6). Under a changing climate, forest conditions and dynamics may change, requiring the ability to precisely and accurately detect and quantify changes in forest carbon over time. There are developing analytical products that combine FIA ground-based measurements and remotely sensed data (LiDAR, satellite imagery) to provide spatial carbon estimates. These products may also help improve C flux estimates due to land use conversion, timber harvests, and natural disturbance events.

Data on HWP also have limitations. Timber harvest data come from voluntary reporting by wood processing mills, and do not capture (1) imported wood, (2) small timber mills and firewood operations, (3) spatial patterns in forest harvesting by product type. Further, modeling of carbon storage based on timber harvest product is not Vermont-specific but taken from regional estimates (see Dugan et al. 2021). The Governor's Forest Carbon Task Force in Maine is examining these same data limitations for forest sector C tracking and accounting; the results there may help to improve subsequent versions of the Vermont Carbon Budget.

Correct carbon accounting

There may be both double counting and missed accounting in the forest sector C estimates. For example, double counting of C may occur by including emissions from land use conversion and HWP. When a parcel of forestland is cleared for development or agriculture, the aboveground C is considered an immediate source of emissions to the atmosphere, but it is much more likely that some of the wood was used for fuel, pulp, lumber, or other products that stores the carbon for a longer period, which would be reflected in the HWP estimates. On the other hand, the C estimates for HWP may also underestimate C removed in harvests because these values are derived from wood volumes received by mills. Some harvested wood never reaches mills, but is used by woodworkers, homesteaders, firewood purveyors, or other small operations.

4.4 Wetlands and water bodies

Research shows that different wetland types (e.g., fens) and statuses (e.g., pristine, drained, and flooded) have different impacts on methane emissions (Turetsky et al., 2014). Further, research through field-based measurements in California suggests that converting drained agricultural peat soils to flooded wetlands can help reduce GHG emissions, particularly through mitigation with carbon sequestration rather than reduced emissions of CH_4 (Knox et al., 2015). In fact, Mitsch et al. (Mitsch et al., 2013) emphasize that wetlands will be more important for carbon sequestration than methane production in 300 years. A comparison of two created riverine wetlands in Ohio showed that GPP was an important determinate in CH_4 emissions under identical soil and water conditions and could increase net carbon sequestration (Nahlik & Mitsch, 2010). Differences in vegetation have been found to alter carbon sequestration rates nearly three-fold (Bernal & Mitsch, 2012).

The amount of area in wetland or water body land uses is a large determinant for net carbon sequestration (Ringeval et al., 2010). If Vermont plans to utilize restoration or construction of wetlands and water bodies, the total area in this land use will play a large role in its contribution to future carbon budgets. If Vermont wishes to account for differences in water body types, further research may be needed, or use of a process-based model could be explored, to understand nuances in site conditions, particularly in the case of wetland creation or restoration (e.g., Treat et al., 2018). Further sources of raw data, such as observation networks like AmeriFlux and Fluxnet, could be considered for characterizing fluxes in similar ecosystems.

Vermont's seasonal cycles may also play a role in net carbon sequestration and methane fluxes. A study in Ohio, in a location with a notably shorter winter than Vermont, found 40% of annual methane emissions were produced in winter for the studied water body (Morin et al., 2014).

Conversely, in a study of northern latitude wetlands. Treat et al. (2018) note that there are too few measurements outside the growing season to characterize non-growing season CH_4 emissions from wetlands.

4.5 Agriculture

EX-ACT is a useful tool for considering the impact of agricultural management on carbon sequestration and GHG emissions. Results from EX-ACT could augment the existing Vermont GHG Inventory, which uses less data and does not integrate management considerations. Future-looking scenarios that aim to understand the direction and magnitude of change in agriculture emissions could be coarsely informed through modeling with EX-ACT. More detailed policy analysis, such as estimated emissions reductions and/or soil carbon in agriculture, would benefit from process-based modeling, such as with the DeNitrification Decomposition (DNDC) model. The DNDC model is well parameterized and validated for this region and is used in California's emissions scenarios work.

New databases could greatly improve the tracking of emissions from agriculture. For example, a centralized database on fertilizer use and manure management would improve estimates of fertilizer related GHG emissions, as current reports are based on self-reported fertilizer use. Since mid-sized and large farm operations in Vermont file nutrient management plans that contain information on fertilizer types, rates, and application and manure management, extraction of this data to anonymized, pooled data set would facilitate more precise estimates.

Activities that may increase soil carbon storage (e.g., manure application, reduced tillage, or no tillage) should be accounted for in the agricultural sector. EX-ACT can estimate the impact of these management options, but the use of these best management practices, often for water quality, is not well-known. Existing data tracks participation by farms supported by state-funded programs (e.g., cover crops), but this data represents only a fraction of the total uptake of carbon storage practices. The estimates used in the Vermont Carbon Budget for these practices are the consensus of a group of experts; better census or survey data could enhance our understanding of practice adoption if it is to be promoted under the Vermont CAP.

4.6 Grasslands and shrublands

Activities in grassland and shrublands—such as those that promote productivity, reduce erosion, and foster biodiversity—may also increase carbon storage. These types of "win-win" activities may have a small impact on Vermont's total GHG budget; however, synergies between economic activities and best management practices for water quality could make them quite viable considering the potential area of grasslands and shrublands area.

4.7 Urban and developed

If further quantification and tracking of carbon in urban and developed landscapes is desired and deemed necessary in support of Vermont's CAP, some refinements could be made to these estimates. For example, annual remote sensing of land cover and carbon densities could be used (e.g., Raciti et al., 2014), although they should be evaluated for cost-effectiveness relative to the need and impact on policy implementation as compared to current estimates.

Acknowledgements

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