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# A Land-Use-Based County-Level Carbon Budget for Chittenden County, Vermont

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# A LAND-USE-BASED COUNTY-LEVEL CARBON BUDGET FOR CHITTENDEN COUNTY, VERMONT

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## ABSTRACT

As interest grows in mitigating atmospheric carbon dioxide ($CO_2$) concentrations, there is an increasing need to understand the factors that determine fluxes of carbon (C) to and from the atmosphere. This project quantifies the natural and anthropogenic sources and sinks of atmospheric $CO_2$ on a county scale. In collaboration with the Hubbard Brook Research Foundation's (HBRF's) Sciencelinks Carbon Group, a net C budget for Chittenden County, Vermont has been created, with key C sources and sinks categorized in terms of land use.

The primary goal of the budget is to provide up-to-date and accurate decision-making information to planners and policy-makers in the county, allowing the most tangible benefits to be gained from mitigation efforts. This project creates and tests a methodology that is easily replicable in any county in the United States. This methodology will facilitate the process of developing county-level C balance data beyond Vermont and the Northeast.

This study suggests that Chittenden County is a net sink for C; 1.12 Tg C accumulate per year in the county's biomass and soils while 0.418 Tg C are emitted each year through anthropogenic activity within the county. C emitted in the manufacture of imported products is not considered.

This work contributes to a larger ongoing study by the HBRF which compares C emissions and sequestration among seven counties representing different patterns of land use.

## ACKNOWLEDGEMENTS

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# TABLE OF CONTENTS

Page

## LIST OF TABLES

## LIST OF FIGURES

Figure | Page

# COMPREHENSIVE LITERATURE REVIEW

## 1. The Global Carbon Cycle

The global carbon (C) cycle is just one of many nutrient cycles occurring on, above, and below the Earth's surface. Carbon, oxygen (O), nitrogen (N), phosphorus (P), sulfur (S), and many other nutrients in varying concentrations are constantly moving among water, soil, atmosphere and living things, interacting in a variety of ways. Any discussion of the C cycle intrinsically deals with many other nutrients as well, especially those that bond with C in chemical compounds (such as oxygen in $CO_2$ and CO) or are required by living things in concert with C (such as N and P). For the purposes of this brief background, however, only C will be considered.

Currently, Earth contains about $10^{23}$ g of C, mostly buried in sedimentary rocks [A]. The largest near-surface, and thus active, C pools are the ocean, soils and the atmosphere. C is also an important component of all the living biomass on Earth (Table A).

**Table A: Earth's largest active C pools [A].**

| Pool | C ($10^{15}$ g) |
|---|---|
| Ocean | 38,000 |
| Soils | 1,500 |
| Atmosphere | 750 |
| Land Vegetation | 560 |

C contained in biomass fluctuates constantly into and out of soils and the atmosphere, changing in magnitude on a seasonal basis. Other, larger sources of C are much less variable – for instance, C in oceans has a mean residence time of 11 years and C in the atmosphere has a mean residence time of 5 years. Despite the differences in variability between the biomass, ocean and atmospheric pools, annual fluxes between the three are among the largest on Earth [A].

## 2. Carbon Cycling at Smaller Scales

C fluxes can be measured on a global scale as described above, or on smaller scales such as the region, country, ecosystem, state or watershed. Depending on the scale of the measurements, net fluxes for different parts of the cycle will vary according to the characteristics of pools in those areas. A simple example: In a temperate forest ecosystem, C can be sequestered in plants and in the soil. Plants absorb C from the atmosphere and use it to create biomass, while also releasing some C back into the atmosphere through respiration. Eventually, the plants die and begin to decompose. Microbes drive decomposition, and their respiration releases C back to the atmosphere as well. Some C may also be moved by soil organisms or become dissolved in groundwater, moving deeper into the soil. Soil C may remain stable for a long period of time, or it may be released when the soil is disturbed. This cycle was observed in detail in the forested watersheds of the Hubbard Brook Experimental Forest in New Hampshire [15].

The processes described in the example above occur in concert with, but without any obvious connection to, the large C pools in the ocean, or the C far below the soil. The region in which the analysis is taking place determines which pools are important. Figure A below, from the First State of the Carbon Cycle Report by the US Climate

Change Science Program [20], outlines all the currently understood sources and fluxes of the C cycle.

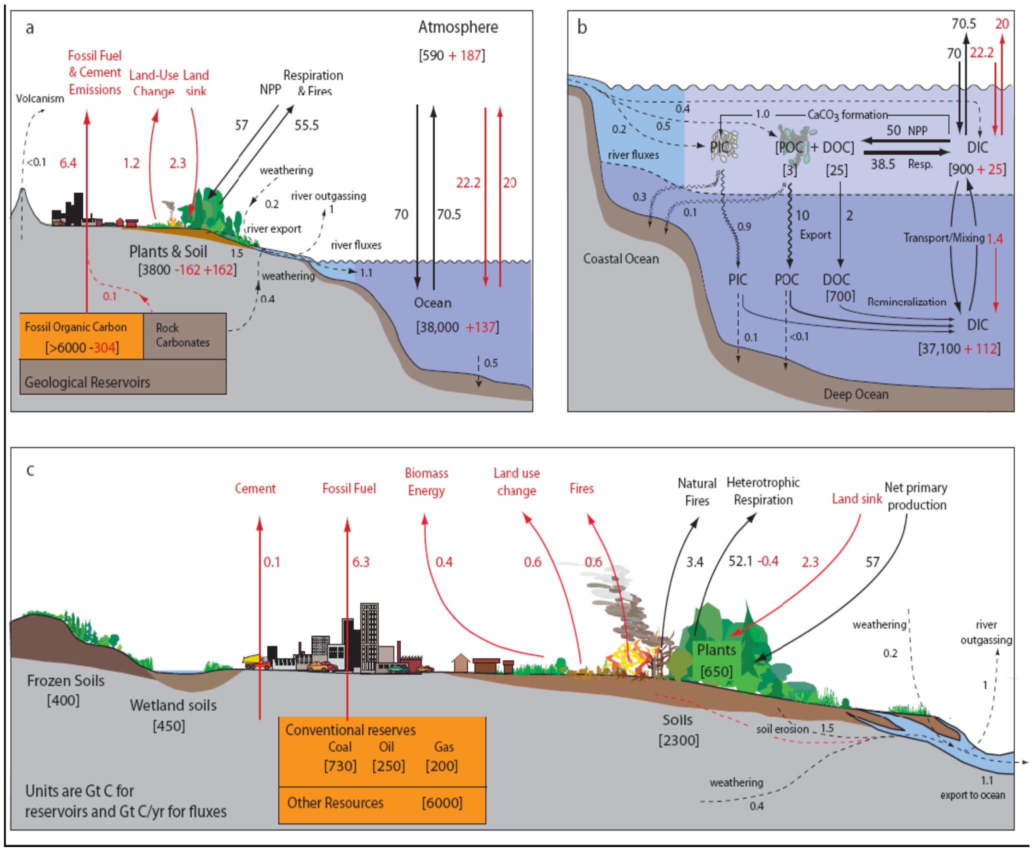


**Figure A: "Schematic representation of the components of the global carbon cycle. The three panels show (A) the overall cycle, (B) the details of the ocean cycle, and (C) the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Stocks and fluxes prior to human-influence are in black. Human-induced perturbations are in red. For stocks, the human-induced perturbations are the cumulative total through 2003. Human-caused fluxes are means for the 1990s (the most recent available data for some fluxes)" [20].**

### 3. Anthropogenic Influence

Since the Industrial Revolution in the 1800s, humans have had a significant effect on the C cycle by increasing the amount of C released to the atmosphere, mostly in the form of $CO_2$ [B,1]. This has occurred primarily due to the extraction and burning of fossil fuels for energy production, and land use change in the form of deforestation for agriculture, timber harvest, transportation and urban development [2,20]. Global atmospheric $CO_2$ has risen from 280 parts per million in the pre-industrial era to 380 parts per million in 2005 [1]. $CO_2$ concentrations in the atmosphere were predicted to reach 800 ppm by 2100 if that rate of increase remained constant [C]. In reality the rate of increase is becoming progressively faster with each passing decade [1], leading to conditions outside the known range of variability for atmospheric $CO_2$ on Earth during the last 20 million years [2].

Thus, it is certain that anthropogenic influences over the past several hundred years have increased the amount of C in Earth's atmosphere, while decreasing its presence in other pools such as geologic reservoirs [28]. The recent report by the Intergovernmental Panel on Climate Change states that it is "extremely likely" (there is a probability greater than 95%) that human activities have contributed to climate warming since 1750 [28]. Our understanding of element interactions and our ability to model them effectively are perhaps still insufficient to definitively predict the relationships between atmospheric C and processes such as the climate system and other nutrient cycles [B]. But a tremendous body of research, including the IPCC report, has been developed indicating that the increase in atmospheric C will lead to global climate warming, with difficult-to-predict but perhaps serious consequences.

Both $CO_2$ and two other common C compounds, methane ($CH_4$) and carbon monoxide (CO), are natural greenhouse gases that trap energy from the sun reflecting off the Earth's surface, warming the atmosphere [20]. Other gases also contribute to the greenhouse effect, including water vapor ($H_2O$), nitrous oxide ($N_2O$), sulphur dioxide

($SO_2$), ozone ($O_3$), and several industrial compounds that are purely anthropogenic in origin (for instance, hydrofluorocarbons and chlorofluorocarbons) [28]. The greenhouse warming process allows life as we know it to exist. However, scientists predict that the unprecedented increases in greenhouse gases may cause excessive warming, leading to more abnormal weather events, rising sea level due to the expansion of the oceans and the melting of the polar ice caps, and shifts in the natural ranges of plants and animals, possibly to the point of extinction [20]. $CO_2$ is thought to be the dominant radiative forcing agent, or potential mechanism of climate change, currently acting on the Earth [28].

Warming is not the only likely consequence of anthropogenic emissions. For instance, another common emission of the industrial era is aerosols, or small solid and liquid particles of various composition (e.g. organic carbon, soot, charcoal, nitrates and mineral dust) suspended in the atmosphere. These particles have exerted a cooling influence over time by reflecting sunlight. Sulphur dioxide ($SO_2$) in the atmosphere can also have a similar effect. These substances have not provided enough cooling, however, to reverse patterns of climate warming [28]. Some types of land use change can also act as cooling mechanisms by changing the albedo of the Earth's surface. Deforestation, for instance, can increase albedo in winter and spring through an increase in exposed snow cover [28].

Increased atmospheric $CO_2$ could also affect plant life in a variety of ways. The theory of progressive N limitation argues that plants living under conditions of increased atmospheric carbon will experience an initial spike in growth, but their carbon sequestration may eventually be inhibited by the lack of an equivalent availability of N [D]. Similarly, Loladze [E] theorizes that high atmospheric $CO_2$ will cause agricultural crops worldwide to grow well with plenty of available C for the creation of new biomass, but that C will be available in unexpected proportions compared to other nutrients crops require. Thus, plants will grow with low concentrations of those nutrients, perhaps becoming an “empty” food source that provides quantity, but not quality to its human and animal consumers. An increase in malnutrition around the globe could potentially result.

Because of the potential negative effects of increased atmospheric C, it is important to work towards a complete understanding of the C cycle and recent anthropogenic effects upon it. It is also important to identify ways to decrease anthropogenic C emissions and increase C sequestration.

## 4. Land Use, Energy and Carbon Cycling

As stated above, humans are contributing to the increase in atmospheric C primarily through the burning of fossil fuels and land use change in the form of deforestation and soil disturbance. Thus, it stands to reason that strategies to decrease atmospheric C begin with decreasing fossil fuel consumption and re-sequestering C in biomass and soils.

In this thesis, C emissions and sequestration in Chittenden County, Vermont are addressed from a land-use-based perspective. In particular, the project focuses on land use changes at a county scale. This is a very small geographic area in relation to the global cycles discussed so far, but the regional focus is important for several reasons.

From a broad perspective, northern temperate lands involved in reforestation (or a return to forest after clearing for some other land use), such as those in Chittenden County, are currently the largest terrestrial C sink in the world [20]. In North America, this reforestation is due to an historical movement away from agricultural land use as people chose to farm on more productive lands elsewhere or moved to urban centers [4,20].

Also, state, local and municipal governments and land owners are often the entities making the most immediate decisions about land use planning and energy investment. These decisions add up over time and space, so accurate regional-scale information for policymakers is important. Often the local level is the only place individual decision-making can make an immediate difference. This section describes the effects of land use and fossil fuel energy on C cycling, both globally and in the study area.

**4.1. Land Use**

Past studies have described in detail exactly how different land uses, and land use change over time, have an impact on C emissions and sequestration. These studies have taken place at a variety of spatial scales and geographic areas, from the national level to the individual forest stand or city.

Woodbury et al. [7] examined the historical relationship between land use and the C cycle in the Southern United States, with the intention of modeling future interactions. They found that tree biomass on forestland was a vulnerable C stock, increasing under land uses that encouraged afforestation and decreasing rapidly under land uses that encouraged deforestation. Forest soil stocks were also affected in a similar manner. The degree to which any component of the C cycle was affected by land use varied by topographical area within the larger region.

Woomer et al. [8] focused on land use change in Senegal. They found that deforestation and vegetation disturbance were responsible for over 95% of the loss of terrestrial C stocks in that country between 1965 and 2000. They also noted that programs to increase C sequestration through revegetation might decrease the rate of loss of those stocks. Similarly, Houghton and Hackler [9] found that reduction of forest area accounted for 90% of the total C flux in the United States. An Austrian study by Erb [5] determined that the conversion of forestland to agricultural and urban areas had contributed to 77% of the loss of aboveground C stocks in that country, with the remaining 23% attributed to forest management for young stands (which have less biomass and thus less C) with unnatural species composition. These results demonstrate that even though areas may vary remarkably in climate, topography and environment, human management has the potential to change C stocks and flux – whether by changing vegetative composition, disturbing soils, or decreasing overall biomass.

Jandl et al. [6] focused more specifically on the potential of forestland to sequester C with proper management. They found that incorporating fast-growing tree species into forest environments could increase the rate at which C is captured in biomass. Also, they determined that managing forests for maximum productivity (through thinning, fertilization, and other techniques) increased not only biomass sequestration, but also sequestration of C in soils. If minimum disturbance to the land surface was also achieved during management, C already in the soil would remain intact indefinitely into the future.

Harmon et al. [3], however, indicated that undisturbed old-growth forests in temperate regions store significant amounts of $CO_2$ because they contain high amounts of biomass in both live and dead vegetation. Actively harvested, younger forests grow faster, sequestering C at a higher rate than older forests, but still result in a net flux of C to the atmosphere due to decreased storage capacity. Often, harvested wood is converted to durable wood products, which also sequester carbon during their time in use and in landfills. Inefficiencies in the processing of wood products and other production-related emissions, however, can decrease the benefits of wood product sequestration [40].

Forests are not the only places where C can be sequestered. Agricultural lands do sequester some C – but not nearly as much as natural vegetation, as crops are harvested and removed annually and cultivated soil is constantly disturbed. In one study of the United States by Houghton and Hackler [9], agricultural cultivation of soils accounted for 25% of all soil C loss detected from 1700 to 1990. Agricultural land use can also detract from C sequestration efforts because some types of ruminant animals, such as cows, release significant amounts of methane while digesting their food [20].

Urban areas offer challenges as well, because they can detract from the sequestration potential of a landscape while $CO_2$ emissions from fossil fuels increase overall with increases in population. But, they can also offer unique opportunities. For instance, cities often have larger population densities and more efficient public transit than rural areas, thereby decreasing emissions in some sectors, such as transportation and individual petroleum use, due to economies of scale. Residents of New York City, a densely developed city with an extensive public transportation system, own cars at well below the national level and use significantly less energy than other cities per capita to heat, cool and light their buildings [18]. Also, while urban lands will never support as much biomass as forestland, Pataki et al. [13] indicated that urban trees do sequester some C, much more than would be captured if no urban greenspace existed at all. Trees and other plants also have indirect effects on energy savings, decreasing the need for heating and cooling energy when planted around buildings as shade and windblocks. These benefits can be decreased, however, if urban vegetation is heavily managed using fertilizers and fossil-fuel-burning machinery.

Pouyat et al. [14] showed that we cannot discount urban soils. They reported that soils in residential lawns can have high C densities – sometimes higher than forest soils in many areas of the United States. Cities also often include remnant areas of native vegetation (up to 10% of land area in some cases) that can increase sequestration potential. In addition, soil trapped under impervious surfaces creates a valuable sink.

Pouyat et al. [14] also emphasized that the regional potential vegetation and soil properties of an urban area can change its net effect on the C cycle. The transition to urban area from forestland across the United States, for example, may lead to an overall decrease in sequestration potential. On a city-by-city basis, however, results may be quite different. In an area where native soils do not naturally sequester much C, such as the Southwest, transition to an urban landscape may actually increase soil sequestration potential. In an area like the Northeast, where native soils are naturally C-rich, urban transition may bring a decrease in sequestration.

The study area of this project – Chittenden County, Vermont – is located in the Northeastern United States, where the historical potential vegetation is forest. Since European settlement in the 1600s, forests in the region were extensively harvested for timber and cleared for agriculture. In recent decades, however, forest area in the Northeast has been increasing as agricultural use and timber harvesting decrease. Albani et al. [4] examined the relationship between land use change and C fluxes in the Northeastern US, and found that most of the increase in C storage taking place in the area today is a result of reforestation. Eventually, however, a limit will be reached and no more forest area expansion will be possible (except for after timber harvest, forest fire, or other disturbance [20]). This emphasizes the need for a variety of mitigation strategies in the region.

### 4.2. Energy Use and Transportation

Fossil fuels such as petroleum, coal and natural gas are mined from within the Earth's crust, and usually contain C in various compounds with hydrogen. When these fuels burn, water ($H_2O$) and $CO_2$ are produced and released to the atmosphere [20]. Thus, as more fossil fuel is extracted from the belowground C pool, more $CO_2$ is emitted to the atmosphere (along with water vapor, also a greenhouse gas). This process is the basis for concern over the effect of humanity's increasing use of fossil fuels on atmospheric C concentrations.

In the United States, fossil fuel consumption has increased exponentially over the last century and is predicted to continue to rise in the future [1,2]. Petroleum is by far the most commonly used fuel across all sectors, with coal and natural gas coming in a far second. Other sources of energy such as nuclear, hydroelectric, and a variety of renewable sources are also utilized in much smaller quantities [F]. These fuels are used to heat buildings, generate electricity, manufacture products and power vehicles.

Land use is integrally related to fossil fuel consumption; how a land area is used determines its energy needs. Standing forests, for instance, tend to have very few C releases besides natural decomposition, fire and harvest activities [G]. Agricultural lands release significantly more C via ruminant digestion, soil disturbance and emissions from fossil-fuel-based energy use by mechanical equipment [9]. Areas of human development, especially urban areas, tend to have the most energy-based emissions due to the proliferation of buildings that need to be heated and lighted and vehicles that need to be powered and given an infrastructure. Within North America, about 40% of total fossil fuel emissions come from the residential and transportation sectors alone [13].

The structure of urban growth can determine C emissions. Pataki et al. [13] cite population growth and a disproportionate increase in number of households as factors that are contributing to increased emissions in North American urban and suburban areas. This means that more individuals and families are acquiring their own homes or second homes, and that those households are smaller, resulting in an increase in area of developed land and number of dwellings per capita. That extra home space per capita requires more energy to maintain.

Urban areas, especially those in developing countries, do not always follow that growth pattern.  In Mexico, for instance, population growth exceeds the rate of household growth, implying a decrease in number of dwellings per capita and an increased population density [13].  High population density often leads to low per capita emissions, as demonstrated by New York City [18].  Vermont has a relatively low population density (only about 270 people per square mile [21]),  its development patterns more closely match those described by Pataki et. al [13].

Transportation infrastructure also affects C emissions.  Urban sprawl, or a decrease in density of development and a separation of residential and commercial centers, often leads to auto-dependency and necessitates a large transportation network to span increased distances between buildings.  This large network increases forest and agricultural land lost to development, daily commuting distances for individuals, traffic congestion and  overall vehicle miles traveled in cars, trucks, and buses [11].  Since vehicles usually require refined fossil fuels to operate, energy used in transportation, the amount of C released to the atmosphere and dependence on fossil fuels for daily operations are increased [12].  Conversely, higher density development over smaller land areas may decrease C emissions and daily dependence on fossil fuels [13].

Every region has different energy providers and different patterns of development due to land use history, climate, topography, and geographic location. Vermont's electricity is generated by a variety of sources (Figure B), two thirds of which are already non-fossil fuel burning – the Vermont Yankee nuclear plant and HydroQuebec.  The remaining third of Vermont's power comes from a variety of independent power providers with varying C outputs, such as the McNeil biomass burning plant in Burlington, small wind power, and small hydro operations. Any remaining electricity needs are met by purchases from New England's wholesale energy market [64].

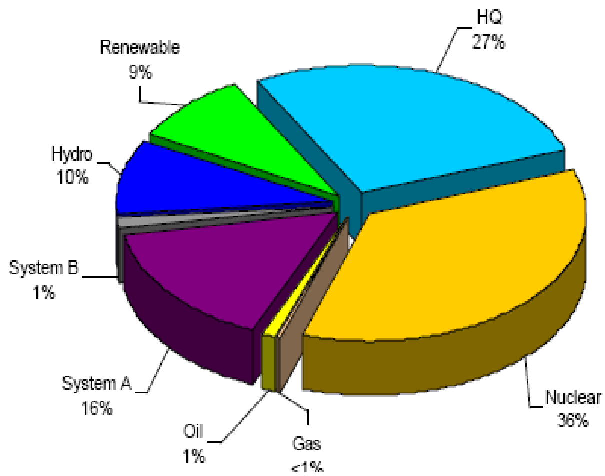


**Figure B: "2005 Vermont own load electric energy supply [64]." 'System A' refers to energy purchased from New England's wholesale energy market. 'System B' refers to renewable energy sold to other utilities as renewable energy credits. 'Hydro' indicates small hydro projects. 'Renewable' indicates other renewable resources in Vermont, such as the McNeil biomass plant. 'HQ' refers to HydroQuebec. 'Nuclear' refers to Vermont Yankee.**

Vermont's residential, commercial, and industrial heating needs are met primarily through distillate fuel oil, in varying degrees across the three sectors. Natural gas and propane are also common heat sources. Kerosene, wood, coal and other sources are utilized, but to a much smaller degree [H]. All of these fuels release C to the atmosphere in their production and consumption. Figure C demonstrates Vermont's fuel usage by fuel type, and Figure D breaks down that usage by sector.

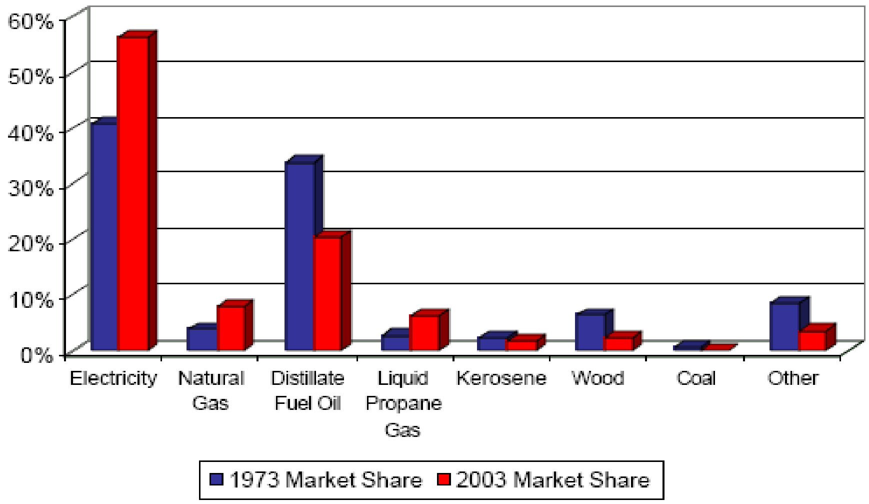


**Figure C: Percent of Vermont's total energy market share by fuel, 1973 and 2003 [H]. The 'electricity' bar demonstrates electricity's contribution to overall energy use, but specific fuel sources used to generate electricity are not included.**

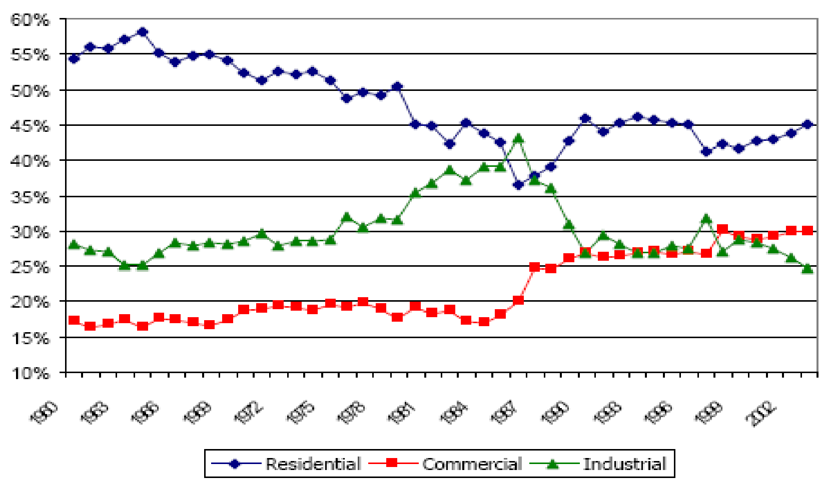


**Figure D: Percent of Vermont's total energy market share by sector over time [H].**

Vermont's transportation network includes roadways, railways, ferries and airports, all of which emit C to some degree, but vehicles traveling on roadways are by far the most common transportation-related C source. Vermont has almost 14,500 miles of roadway, on which over 7 billion vehicle miles were traveled in 2005 [I]. In Chittenden County alone, vehicle miles traveled are predicted to increase 60% by 2025, while traffic volume is predicted to increase 360% [J]. This may be due to Vermont's rural, low-density population distribution, coupled with a marked increase in development around urban areas in recent years.

Increases in energy use efficiency, along with developments in renewable, non-fossil-fuel-based energy sources and changes to transportation infrastructure, can drastically decrease atmospheric C emissions at the county scale. Vadas et al. [21] examined mitigation strategies for Tompkins County, New York, and found that significant decreases in emissions could be achieved at low cost by increasing the use of renewable energy sources such as wood and biomass heating, changing driving habits, converting lights and appliances to more efficient models, and adding insulation to buildings. These are only a few of the potential emissions mitigation options that exist, and many more have yet to be determined. Vermont will require its own unique portfolio of mitigation options, many of which have been addressed by the Vermont Governor's Commission on Climate Change [K].

## 5. Carbon Accounting Considerations

Many attempts have been made to quantify the complete C cycle at a variety of scales, especially in recent years as governments, businesses and individuals begin to focus on regulating C emissions. Often this process is called C accounting. Some C budgets focus only on natural systems, from the forest stand level [15] to the national level [17] to the hemispherical and global level [16]. Other budgets more explicitly incorporate anthropogenic emissions and land use change. Of these, most include only anthropogenic effects and are presented as greenhouse gas inventories. They are usually aligned with political boundaries, and can also occur at any scale, from the town and city [18] to the state [19] to the country [20] to the world [1].

This thesis considers C emissions and sequestration at the county scale and categorizes both in terms of land use. Anthropogenic emissions and land-based sinks are two realms of C analysis that are not often associated, but knowledge of both aspects of the C cycle is crucial in determining how mitigation should proceed. Emissions from energy used to create products imported across county boundaries are not included in the analysis.

C budgets vary widely by sources and sinks included, reporting units, and levels of error. Attempts have been made to standardize inventory methods, especially at the country level since the development of the Kyoto Protocol [L]. However, variation still exists among methods and care must be taken to make explicit and transparent all data sources, calculations, and assumptions in the development of each individual budget.

One of the most important considerations in carbon budgeting involves where to place responsibility for $CO_2$ emissions. Under the production accounting principle, entities which produce the energy or products that result in emissions are held responsible. Under the consumption accounting principle, entities which consume the energy or products that result in emissions are held responsible [49]. Making this determination in the initial stages of the budgeting process ensures that emissions will not be “double counted”, or added to more than one sector. Also, often results from the two types of budgets will differ, and this can have policy implications in terms of where mitigation strategies are applied.

The Chittenden County carbon budget used a consumption-based approach, with some exceptions in cases for which calculations were not feasible or relevant for policy and decision-making. Methodology is documented in detail in the article below.

# A land-use-based county-level carbon budget for Chittenden County, Vermont

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# Abstract

### Background

This project brings together the natural and anthropogenic sources and sinks of atmospheric carbon dioxide ($CO_2$) at the county scale. In collaboration with the Hubbard Brook Research Foundation's (HBRF's) Sciencelinks Carbon Group, we created a land-use-based carbon (C) budget for Chittenden County, Vermont.

The primary goal of the budget is to provide up-to-date and accurate decision-making information to planners and policy-makers in the county, allowing the most tangible benefits to be gained from mitigation efforts. This project also creates and tests a methodology that is replicable in any county in the United States. This methodology will facilitate the process of developing county-level C balance data beyond Vermont and the Northeast.

This work contributes to a larger ongoing study by the HBRF which compares C emissions and sequestration among seven counties representing different patterns of land use.

### Results

This study suggests that Chittenden County is a net sink for C; 1.12 Tg C accumulate per year in the county's biomass and soils while 0.418 Tg C are emitted each year through anthropogenic activity. The budget does not account for the energy used during manufacturing and transportation of products imported into the study area.

### Conclusions

Chittenden County is a net sink for C. Developed areas, however, are responsible for significantly more C emissions per hectare than forestland sequesters, and land dedicated to urban development in the county is increasing. As development encroaches on forest and agricultural land, the C balance may shift. Urban vegetation and soils have the potential to mitigate only a small portion of annual C emissions.

The difference between annual C sequestration and annual C emissions in Chittenden County is much larger than that calculated in a comparable Tompkins County, NY study. Tompkins County was found to be a source rather than a sink for $CO_2$.

Transportation emissions and residential petroleum emissions are two areas where mitigation programs might provide the most benefit for the least cost. Also, sequestration might be increased through forest preservation, manufacture of durable wood products, development of urban greenspace and promotion of no-till agriculture.

## Background

Since the beginning of the Industrial Revolution in the late 1800's, human activities have increased the amount of carbon dioxide ($CO_2$) in the atmosphere. Global atmospheric $CO_2$ has risen from 280 parts per million in the pre-industrial era to 380 parts per million in 2005 [1]. A drastic increase in the burning of fossil fuels for energy production is partially responsible for the trend. Also responsible are changes in land use, including deforestation, suburbanization and transportation development [2]. The rate of increase is becoming progressively faster with each passing decade [1], leading to conditions outside the known range of variability of atmospheric $CO_2$ on Earth for 20 million years [2]. If atmospheric $CO_2$ concentrations are not stabilized at around a doubling of pre-industrial values, irreversible and unpredictable changes to Earth's climate may result [1]. Emissions rates since 2000, however, have been far above the necessary stabilization trajectories [1].

A sizeable body of literature exists demonstrating that land use patterns can have a significant impact on $CO_2$ emissions and sequestration. Forests allowed to grow to old age uninhibited by human land use change, for example, can create a significant sink for C [3]. Deforestation can lead to a release of C to the atmosphere, while afforestation, reforestation and forest management can increase both the rate of C sequestration and the amount of C in forest pools [4-8]. Agricultural activity often leads to a net release of C to the atmosphere via both deforestation (clearing of forests for agriculture) and crop management practices [5,9]. Agricultural soils have the potential to store C, however, when tillage is decreased and cropping intensity is increased [10]. Urban development causes C release via deforestation and earth movement along with increased fossil fuel use [5, 11-13], but significant amounts of C can also be stored in urban vegetation and soils [13,14].

Studies of the C cycle at a variety of scales have typically focused on either patterns of sequestration [15-17] or anthropogenic emissions [18,19]. A small number have focused on both [20]. While those two realms of C analysis are not usually examined together, both are crucial in determining how mitigation should proceed. The ability to accurately quantify the intricacies of the C cycle, especially the components that are driven by the combined effects of human emissions and land-based sinks, is vital to the development of strategies for the reduction of anthropogenic C emissions.  Certain land uses may sequester more C than others, but if they also increase emissions then potential benefits are lost.  Urban land uses that have relatively low C emissions may be seen as beneficial, when in fact they end up replacing natural land types with higher capacities for C sequestration.  Consequently, knowing how land use affects the C cycle could lead to better policy and decision-making.  Concise, accessible emissions and sequestration data can be a valuable reference for decision-makers working  to obtain the most tangible benefits out of their mitigation efforts and policies.

This paper quantifies both the anthropogenic sources and natural sinks of atmospheric $CO_2$ on a county scale.  A net C budget was created for Chittenden County, Vermont, with key C sinks and emissions categorized in terms of land use.  The primary goal of the project was to make the results as clear, accessible, and widely distributed as possible to ensure that they will be available for future land management and development planning decisions.  The results of the project can also be used as a basis for choosing from an ever-growing portfolio of C mitigation options.  Policymakers and planners might use the information in this report to select a set of strategies that provide the most mitigation for the least cost.

The budget was based on a similar study already completed for Tompkins County, NY by researchers at Cornell University [21].  The two projects are as directly comparable as possible, enabling the data from each to be incorporated into a larger project by the Hubbard Brook Research Foundation's Sciencelinks Carbon Group.  That study will compare C emissions and sequestration in seven counties with different patterns of land use (Table 1).

The county scale was chosen because, while C budgets have been constructed at a variety of scales in the past, no complete analysis of both emissions and sequestration has yet been performed at the county level. While strong county government is not common in the Northeast, the county is often the scale at which various regional planning agencies (i.e. the Chittenden County Regional Planning Commission and the Chittenden County Metropolitan Planning Organization) operate, allowing for useful dissemination of results and effective use of information in the planning process.

# Methods

### 1. Study Area

The study area for this project is Chittenden County, located in the northwestern corner of Vermont, USA (Figure 1). Lake Champlain forms the county's western border. It is home to the Burlington-South Burlington Metro Area and has a population of about 150,000, a land area of 139,610 hectares and a population density of about 1 person per hectare [22]. The borders of Chittenden County extend into Lake Champlain, but only land area is included in this analysis. The county varies in elevation from 29 meters above sea level at the shores of Lake Champlain to 1339 meters on the summit of Mount Mansfield, Vermont's highest peak.

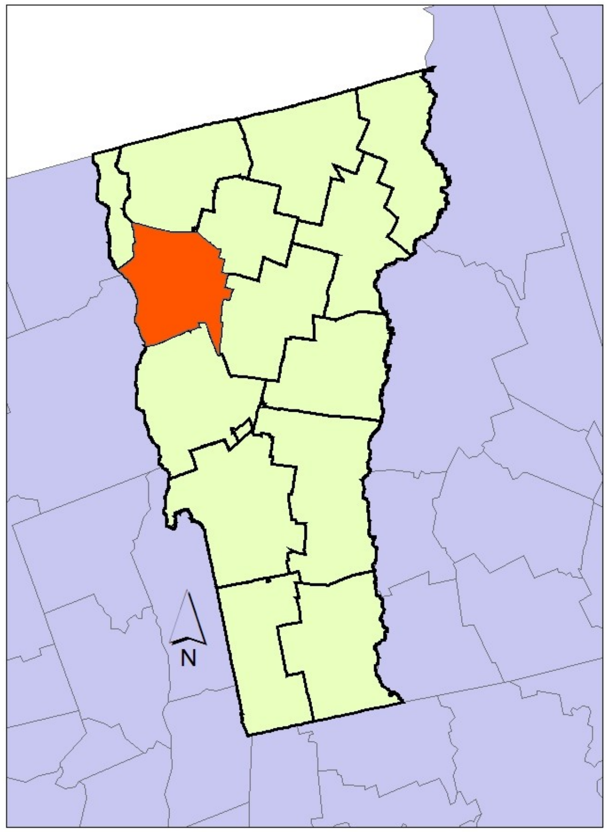


**Figure 1: Vermont, USA with Chittenden County highlighted.**

Chittenden County's climate is temperate, with a mean temperature of 21 ºC in July and -8 ºC in January. Annual precipitation averages about 97 cm, with high regional variability based on topography. One of the most notable aspects of Chittenden County weather is its changeability, a characteristic the county shares with the rest of New England [23]. Thus, variation around the means stated above is commonplace. Abnormal weather events (i.e. the ice storm of 1998, the drought of 2001-02 and the extreme temperature variations of spring 2001 [24]) can affect both C emissions and sequestration.

## 2. Land Use History

Chittenden County's land use has changed dramatically over time (Figure 2). During the past century, much of the county's former agricultural land has returned to forest and, in some cases, both have succumbed to urban development.

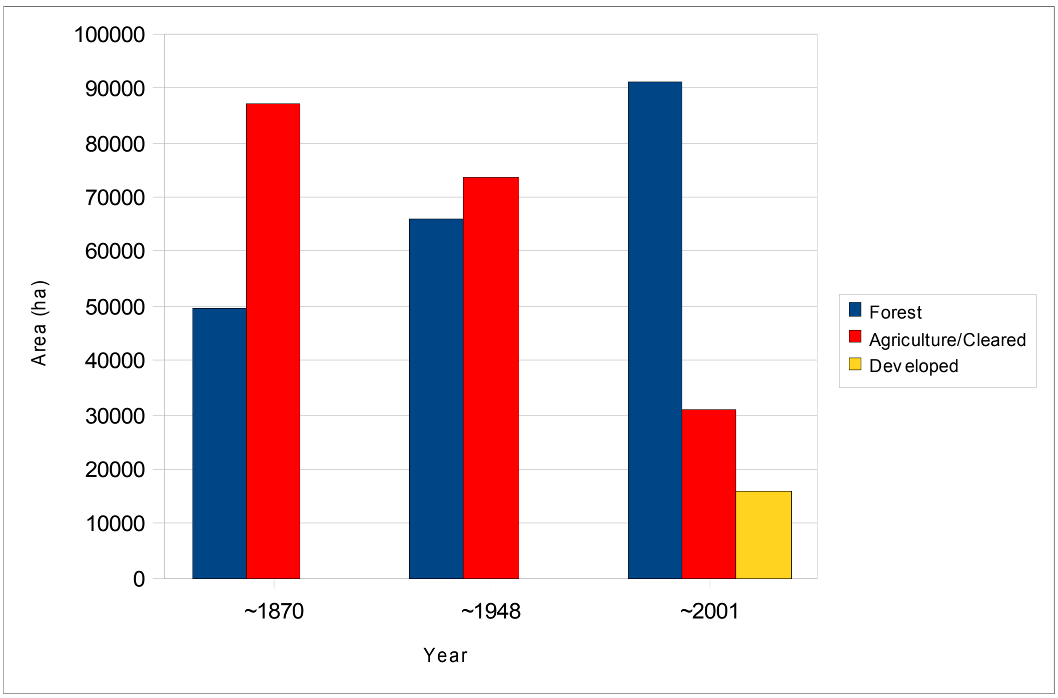


**Figure 2: Land use change over time in Chittenden County, Vermont.**

Figure 2 was created using a combination of historical documents. Land area in forest and agricultural use in 1870 was estimated from handwritten United States Census of Agriculture documents available on microfilm [25]. Acres of land cultivated (or "improved") on farms, acres of woodlot on farms and acres of other use on farms were totaled for all farms in the county. Unavoidable error existed in this data insofar as the census information relied on the estimations and surveys of individual landowners and was recorded by hand by census-takers. All remaining land in the county not accounted for in the census was assumed to be forest. This does not take into account towns and other developing urban areas, which were still small at the time when compared to areas of forest and agricultural land. For instance, the area of the city of Burlington was assumed to be insignificant in this coarse analysis, as it was still a relatively small population center at the time, with development concentrated along the water's edge.

Land area in forest and agricultural use in 1948 was calculated using ArcMap to georeference and digitize topographic maps of the county from within five years of 1948 [26]. Green areas on the historic topographic maps, traced by hand by the original mapmakers from aerial photographs, provided a coarse estimate of forest area. Other areas were assumed to be agriculture or some other form of cultivated open space. Urban areas, such as Burlington, were a slightly more significant land use at this time, but they were still a relatively small percentage of total county land area. Unavoidable error was introduced through the classification of the original aerial photographs and the hand-georeferencing and -digitizing of the topographic maps.

Land area in forest, urban and agricultural use in 2000 was calculated using the National Land Cover Database (NLCD), a nationally available classification of remote sensing imagery [27]. Three broad land cover classes, forest, agriculture and developed area, were compiled from the smaller classes represented in the NLCD dataset. Forest area included the evergreen, deciduous and mixed forest classes, as well as shrubland and woody wetlands. Agriculture included the pasture/hay, row crop, small grains, orchard and grassland/herbaceous classes. Developed area included the low-, medium- and high-density developed classes, as well as developed open space. Accuracy of NLCD land use classifications is discussed in Section 7 below.

Currently, Chittenden County is about 70% forested, 15% urban, and 15% agricultural land (Figure 3).

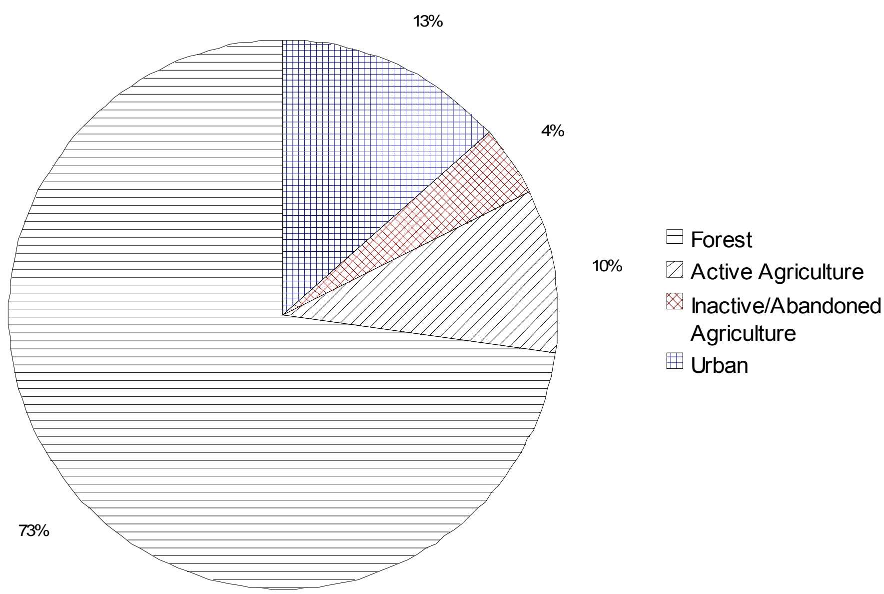


**Figure 3: Current land use in Chittenden County, Vermont. Data (from Tables 11 and 12) represents range of years from 1997-2002.**

## 3. Study Context

The ongoing HBRF Sciencelinks project involves in-depth case studies of C sequestration and emissions for five counties across the Northeastern US (Figure 4). Each county represents different dominant land uses as demonstrated in Table 1.

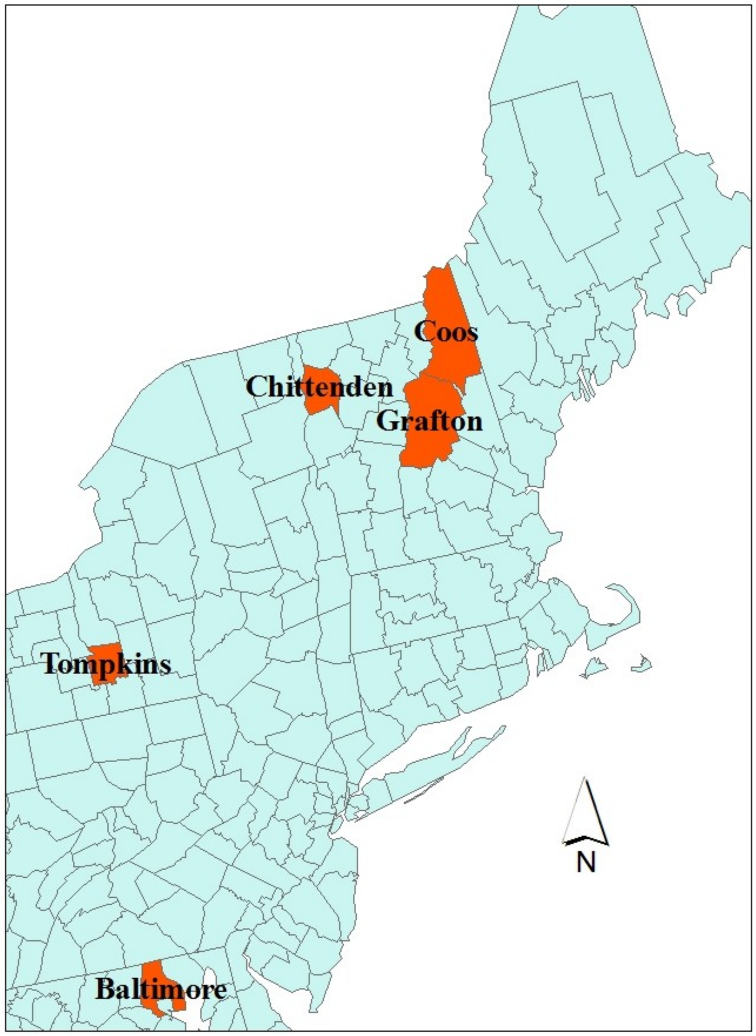


**Figure 4: United States counties involved in the Hubbard Brook Research Foundation's Sciencelinks C project.**

**Table 1: United States counties involved in the Hubbard Brook Research Foundation's Sciencelinks C project. All population and land area information from the US Census [22].**

| County | State | Population | Land Area (sq mile) | Population Density (people/sq mile) | Dominant Land Use |
|---|---|---|---|---|---|
| Baltimore County | Maryland | 790,000 | 682 | 1300 | large urban center |
| Chittenden County | Vermont | 150,000 | 620 | 270 | small, rapidly growing population center; forested |
| Tompkins County | New York | 100,000 | 476 | 200 | rural; mixed forest and farmland |
| Grafton County | New Hampshire | 85,000 | 1750 | 50 | rural forested; primarily recreational use |
| Coos County | New Hampshire | 34,000 | 1831 | 20 | rural forested; primarily industrial timber use |

The case study for Tompkins County, New York has already been completed [21]. Plum Island, Massachusetts and Harvard Forest, Massachusetts are potential future additions that have not yet been confirmed. Several of the methods described below were pioneered by the completed Tompkins County study [21], but many were developed specifically for Chittenden County.

One of the primary goals of this project was to develop methodology that would make the C budgeting process manageable for any county, or other political entity of similar scale. Thus, the data and methodology used for the calculation of both anthropogenic C emissions and natural C sinks in Chittenden County were chosen according to three criteria: accuracy, completeness of coverage, and accessibility of similar data to other counties. In the subsections below, every attempt is made to identify where useful data were found and describe the breadth of the data's availability.

The data utilized were from a variety of years, which are carefully noted in the text. Most of the emissions data center on the year 2000, a year that is representative of typical energy use and considered a baseline year for projections of future Vermont emissions [19]. The data collection periods for the remotely sensed data, census data, forest inventory data, and other sources varied as necessary. For that reason, this budget does not claim to be representative of a particular year, but is rather a general estimation of C flux at the turn of the 21st century in the county.

Several known greenhouse gases incorporate C, including $CO_2$, $CH_4$ and CO [28]. Other gases also contribute to the greenhouse effect, including water vapor ($H_2O$), nitrous oxide ($N_2O$), sulphur dioxide ($SO_2$), ozone ($O_3$), and several industrial compounds that are purely anthropogenic in origin (for instance, hydrofluorocarbons and chlorofluorocarbons) [28]. For the purposes of this report, however, only $CO_2$ was measured, since it has the highest potential as a climate change mechanism of any greenhouse gas [28]. In cases where data were presented in $CO_2$ equivalents, raw data were obtained that allowed for the breakdown of the data into each individual greenhouse gas such that only $CO_2$ would be reported. All $CO_2$ emissions and sequestration values were calculated in megagrams (Mg) C.

## 4. Land Area

Land area in Chittenden County was measured for forest, agricultural and urban uses. Urban areas were divided into impervious and pervious surfaces for C sequestration analysis, and divided into residential, commercial, industrial and transportation uses for C emissions analysis.

### 4.1. Forest Land Area

The forest types in Chittenden County and the land area of each (Tables 3 and 4) were determined using Forest Inventory Mapmaker version 3.0 [29]. Forest Inventory

Mapmaker searches the entire USDA Forest Service Forest Inventory and Analysis database [30] and creates custom tables based on the user's area of geographic interest and desired attributes. For this paper, Mapmaker was instructed to search the most recent complete FIA dataset (collected in 1997) to calculate area of forest land in Chittenden County categorized by forest type.

When compared with NLCD data [27] and another Landsat TM satellite image from 2002 classified by the University of Vermont's Spatial Analysis Laboratory [31], Mapmaker fell between the two remotely sensed values in estimation of forest area. The NLCD found the total area of forest land in Chittenden County to be about 92,189 ha, and the SAL dataset found the total area to be 75,307 ha. Mapmaker calculated a forest area of 85,891 ha. Given the potential for error in the remotely sensed datasets (addressed below), Mapmaker appears to produce comparable estimates of land area.

Area of wood product harvest was assumed to be the same as area of forestland. In actuality, some forest areas might not be harvested due to topography, tree health, or species composition.

**4.2. Agricultural Land Area**

The 2002 US Census of Agriculture [32] was used to determine agricultural land area. Table 2 outlines each 2002 Census of Agriculture land use category and its associated area in Chittenden County.

**Table 2: Land in agricultural uses in 2002 in Chittenden County, Vermont [32].**

| Farm Land Use Type | Area in Chittenden (ha) |
|---|---|
| Harvested cropland | 11,189 |
| Cropland used only for pasture and grazing | 2,010 |
| Cropland idle | 555 |
| Cropland on which all crops failed or were abandoned | 141 |
| Cropland in cultivated summer fallow | 113 |
| Pastureland and rangeland | 2,261 |
| Land enrolled in Conservation Reserve or Wetlands Reserve programs | data not disclosed – only 1 farm enrolled |
| Total | 16,268 |

Land area in active agriculture was calculated as a summary of the county-level land-use categories 'harvested cropland' and 'cropland in cultivated summer fallow.' Area of active agricultural vegetation and soil were assumed to be the same. Area of inactive cropland and Conservation Reserve Program soils were considered a summary of the county-level land-use categories 'cropland used only for pasture and grazing,' 'cropland idle,' 'pastureland and rangeland,' and 'land enrolled in Conservation Reserve or Wetland Reserve programs.' Cropland that is idle one year may not be idle the next year, but this analysis assumes that equivalent amounts of active land convert to idle status each year, balancing the area calculations. Land area in abandoned agriculture was the land-use category 'cropland on which all crops failed or were abandoned.' Area of abandoned agricultural vegetation and soil were assumed to be the same.

### 4.3. Urban Land Area

Urban vegetation and soil area for C sequestration analysis was determined using the National Land Cover Database (NLCD) [27]. Regionally-produced land use classifications of similar satellite imagery can also be used for this purpose, but were not used here. The classifications of urban land in the NLCD dataset were more useful than any other available classifications for this sequestration analysis, as they incorporated impervious surface data. Land use classifications considered urban were based on cover by impervious surfaces and included: developed open space (less than 20% of total cover impervious), developed low intensity (20-49% of total cover impervious), developed medium intensity (50-79% of total cover impervious) and developed high intensity (80-100% of total cover impervious).

As plants can only grow on pervious soil and not roads and sidewalks, impervious area had to be separated from pervious area. Pixels in each urban category were converted to hectares, and the average percentage of impervious surface in each category was multiplied by the total area in that category to find an estimate of total impervious area. The sum of impervious areas for each category was then subtracted from the total urban land area to find area of urban vegetation, pervious urban soil and urban soil under impervious surfaces.

### 4.4. Residential, Commercial and Industrial Land Area

For C emissions analysis, land area dedicated to residential, commercial, industrial and transportation uses in the state was determined from number of pixels as described above. Landsat TM satellite imagery for 2002 classified for land use and land cover by the University of Vermont's Spatial Analysis Laboratory (SAL) was used [31]. The National Land Cover Database [27], mentioned above, can also be used for this purpose, but was not used here – the classifications of urban land in the SAL dataset (residential, commercial, industrial and transportation) were more useful for this emissions analysis than the urban categories in the NLCD (low-density, medium-density and high-density developed), and the NLCD's focus on impervious surfaces was not necessary.

A third remotely sensed data source was available for Chittenden County, also created by the UVM SAL [33]. It was an improvement upon the 2001 NLCD data for the Lake Champlain Basin utilizing information from other data sources and manual error assessment and correction. Although more accurate than either of the other land use classifications mentioned above, the dataset was not used for this paper as its classifications were very general. Only a single, broad 'urban' category was identified, making C emissions and sequestration analysis by urban land use type difficult.

Total land area in Chittenden County, according to the US Census, is 139,610 ha [22]. The land areas calculated using the methods described above add up to only about 119,000 ha, as several land use categories were not taken into account for this analysis. Water, barren land, bare rock, non-forested wetlands and land in sand and gravel pits, for instance, were not considered. Error in each dataset (Section 7) could also be partially responsible for the difference.

## 5. Carbon Pools and Sequestration

Eleven C pools were measured in Chittenden County. These included forest biomass, forest soil, wood products, active agricultural biomass, active agricultural soil, inactive cropland and CRP soils, abandoned agricultural biomass, abandoned agricultural soil, urban biomass, pervious urban soil and urban soil under impervious surfaces. For each pool, five values were calculated: C pool (Mg C), C density (Mg C/ha), county C accumulation (Mg C/year), net C accumulation (Mg C/ha/year) and % of total C sequestration.

### 5.1. Forest Vegetation

Carbon stored in the forest vegetation pool was quantified in live tree, standing dead tree, understory plant, down dead wood and forest floor biomass. Live-tree biomass was calculated from forest inventory data, and the rest of the pools were calculated together using reference tables.

C storage and flux in live tree biomass was quantified using tree-level USDA Forest Service Forest Inventory and Analysis (FIA) measurements [30] aggregated to the plot scale, following methods described by Hicke et al. [34]. In Northern Vermont (Caledonia, Essex, Franklin, Grand Isle, Lamoille, Orange, Orleans, and Washington counties), 378 plots were measured in the most recent inventory, performed between 1996 and 1998. Twenty-seven of those plots were located in Chittenden County. To increase the total number of plots available for estimation of large-scale trends in biomass and net primary production by forest type, plots in Chittenden County and the rest of the Northern Vermont region were used together in this analysis.

For all the Northern Vermont counties, biomass and wood net primary production were calculated using allometric equations as described in Hicke et al. [34], averaged for each existing forest type. Average C density and average C accumulation for each forest type were then calculated by assuming that C is one-half biomass [35].

The C pool (Mg) in live tree biomass in the county was calculated by multiplying land area in each forest type by average C density (Mg C/ha) for that type and adding the results (Table 3). Since land area data was extrapolated from a plot-level inventory, this calculation assumes that the C density value from FIA data is an accurate average of values for all forest age and size classes present in Chittenden County.

**Table 3: Live tree C density and total C by forest type in Chittenden County, Vermont.**

| Forest Type | Average Biomass [calculated from all N. VT counties] (Mg/ha) [34] | Average C Density (Mg/ha) | Land Area in Chittenden (ha) [29] | Total C in Chittenden (Mg) |
|---|---|---|---|---|
| Eastern White Pine | 147 | 73 | 5,509 | 403,815 |
| White Pine/Hemlock | 234 | 117 | 8,263 | 966,481 |
| Eastern Hemlock | 223 | 112 | 2,549 | 284,754 |
| Black Ash/American Elm/ Red Maple | 196 | 98 | 2,856 | 280,475 |
| Sugar Maple/Beech/Yellow Birch | 200 | 100 | 55,475 | 5,560,225 |
| Red Maple/Upland | 175 | 87 | 11,239 | 982,906 |
| County Totals | | | 85,891 | 8,478,656 |

Net annual C accumulation (Mg C/ha/yr) in live tree biomass in the county was calculated by multiplying land area in each forest type by average C accumulation for that type, then adding the results. Total county C accumulation (Mg C/yr) was then determined by multiplying net annual C accumulation by total forest area (Table 4). This calculation assumes that the C accumulation value from FIA data is an accurate average of all forest age and size classes present in Chittenden County as described above.

**Table 4: Live tree C accumulation by forest type in Chittenden County, Vermont.**

| Forest Type | Average Wood NPP [calculated from N.VT counties] (Mg/ha/yr) [34] | Average C Accumulation in N. VT Counties (Mg/ha/yr) | Land Area in Chittenden (ha) [29] | Total C Accumulation in Chittenden (Mg/year) |
|---|---|---|---|---|
| Eastern White Pine | 4 | 2 | 5,509 | 9,798 |
| White Pine/Hemlock | 5 | 3 | 8,263 | 20,759 |
| Eastern Hemlock | 4 | 2 | 2,549 | 5,401 |
| Black Ash/American Elm/ Red Maple | 4 | 2 | 2,856 | 6,012 |
| Sugar Maple/Beech/Yellow Birch | 4 | 2 | 55,475 | 105,214 |
| Red Maple/Upland | 3 | 2 | 11,239 | 19,429 |
| County Totals | 24 | 12 | 85,891 | 1,042,727 |

To quantify C density and accumulation in standing dead tree, understory, down dead wood and forest floor biomass, an average stand age for each of two broad forest type categories in the county was determined from FIA plot-level data. The maple-beech-birch category contained all hardwood categories found in the tables above and had an average stand age of 45 years. The pine category contained all softwood categories found in the tables above and had an average stand age of 65 years. C stock tables (A2 and A6) for reforestation for those broad forest types were available in Smith et al. [36]. C density values were found in the tables for the average stand age for each forest type. These values were then added together and multiplied by the area of each forest type in the county to find the C pool in standing dead tree, understory, down dead wood and forest floor biomass (Table 5).

**Table 5: C density [36], land area [29] and total C for non-live-tree forest biomass components in Chittenden County, Vermont.**

| Biomass Component | C Density at Avg Stand Age (Mg C/ha) | Land Area in Chittenden (ha) | Total C Pool (Mg) |
|---|---|---|---|
| Maple-Beech-Birch Forests: | | | |
| standing dead | 6.6 | 69,569 | 459,158 |
| understory | 1.7 | 69,569 | 118,268 |
| down dead wood | 7.0 | 69,569 | 486,986 |
| forest floor | 23.0 | 69,569 | 1,600,096 |
| | | | |
| Pine Forests: | | | |
| standing dead | 5.0 | 16,321 | 81,606 |
| understory | 1.6 | 16,321 | 26,114 |
| down dead wood | 5.3 | 16,321 | 86,502 |
| forest floor | 13.7 | 16,321 | 223,600 |
| | | Total | 3,082,331 |

This value was added to the value calculated for live trees. C density in the county was then determined by dividing county C storage by total forest area.

According to the tables in Smith et al. [36], the addition to net annual C accumulation from standing dead tree, understory, down dead wood and forest floor biomass was minimal (Table 6). Thus, only the net annual C accumulation in live trees was considered in this report.

**Table 6: Net C accumulation in non-live-tree forest biomass components in Chittenden County, Vermont [36]. Negative values indicate emissions to the atmosphere.**

| Year Interval After Harvest | C Accumulation, Pine Forest (Mg/ha/10 years) | C Accumulation, Maple-Beech-Birch Forest (Mg/ha/10 years) |
|---|---|---|
| 5-15 | -5 | -11.9 |
| 15-25 | -1.1 | -0.04 |
| 25-35 | -0.1 | 2.5 |
| 35-45 | 0.7 | 3.2 |
| 45-55 | 0.7 | 3.4 |
| 55-65 | 1 | 3 |
| 65-75 | 0.8 | 2.8 |
| 75-85 | 0.9 | 2.3 |
| 85-95 | 0.7 | 2.1 |
| 95-105 | 0.7 | 1.9 |
| 105-115 | 0.6 | 1.7 |
| 115-125 | 0.6 | 1.3 |
| Avg C Accumulation (Mg/ha/10 years) | 0.04 | 1.02 |
| Avg C Accumulation (Mg/ha/yr) | 0.004 | 0.1 |

Mortality and harvest are included in this analysis implicitly due to the determination of C accumulation via the stock change method described above. In this method of calculation, forest stock at one time period was compared to forest stock at another, which provided an estimate of net change. This automatically accounted for mortality and harvest at the county scale within each time increment.

## 5.2. Wood Products

Net annual accumulation in wood products, both in the product stream and in landfills, was calculated using the methods described in a report prepared for the state of Pennsylvania by the Center for Climate Strategies [37], which utilize tables in Smith et al. [36].

The 2006 US Census [38] provided the annual amount of hardwood and softwood harvested in Vermont, which was adjusted based on proportion of Vermont forestland in Chittenden County to find the county's annual harvest. Table 4 in Smith et al. [36] provided the fraction of growing stock volume of hardwood and softwood that occurred in the sawtimber and pulpwood size classes. The percentage of timber in each of two broad forest types (maple-beech-birch and pine) in the county used in the forest biomass analysis was determined using the area information in Table 5 above.

From this information, the total harvest in board feet of hardwood sawtimber, hardwood pulpwood, softwood sawtimber and softwood pulpwood in the county was determined. Each of those numbers was multiplied by average specific gravity as listed in Table 4 in Smith et al. [36] to find biomass harvested, and divided by 2 [35] to find the total C harvested. As calculated by Ingerson [39] using data from Smith et al. [36] and Gower et al. [40], 35.2% of total C harvested was assumed to be incorporated into wood products and thus added to the wood product C pool annually.

Total C pool and density for wood products were not determined because they were not relevant to this paper. Thus, the amount of time C remained in the wood product pool based on product type (i.e. pulp versus lumber) was not calculated.

It is important to note that some of the wood harvested in Chittenden County does not go into durable wood products, but is burned for heat energy. Much of this occurs on the scale of individual small landowners and was not incorporated into the harvest calculations above. Burlington, Vermont is also home to the Joseph C. McNeil Generating Station, which uses woody biomass to provide electricity [41]. Since the electricity generated at McNeil goes into Vermont's electric grid and does not power Chittenden County specifically, this emissions source was included implicitly in the electricity emissions calculations described below and was not addressed here.

**5.3. Other Sequestration Pools**

Table 7 shows C density and net C accumulation values found in the literature for the remaining C sequestration pools. Literature values were used because quantitative C data for Chittenden County were not available. C pool size and total county-level C accumulation rates for each pool were calculated using area measurements.

The papers cited in the table were chosen for a variety of reasons. Forest soil C density and active agricultural soil C density were estimated from Table 5 of Ellert and Gregorich [42], a paper which reported quantitative soil C measurements in forested soils and adjacent agricultural lands in Ontario, Canada. This area was one of the closest in physical proximity to Vermont for which soil C density measurements could be found. That Ellert and Gregorich data could provide both forest and active agricultural soil C density values also added to data consistency.

Annual forest soil C accumulation was considered negligible, as demonstrated by Smith et al. [36]. C stock tables for reforestation in maple-beech-birch and pine forests (A2 and A6) indicate that soil organic matter stays constant for at least 125 years after harvest.

Net annual C accumulation in active agricultural soil was estimated from Table 9 of West and Marland [43]. This paper compiled the results of 76 long term agricultural soil C experiments across the United States, including a complete analysis of fossil fuel inputs. Both conventional till and no-till values were reported, but conventional till was assumed for this analysis. Active agricultural biomass is harvested annually, so net C accumulation and C pool size were assumed to be negligible.

The Conservation Reserve Program (CRP) reimburses farmers for taking agricultural land temporarily out of production. C density of inactive cropland and CRP soils was estimated from Table 4 in Paul et al. [44] as an average of all afforested plot pools. Paul et al. examined inactive agricultural land in Ontario and Ohio, covering a geographic location consistent with Ellert and Gregorich [42]. Net C accumulation was estimated from Gebhart et al. [45], a paper chosen because it quantified plots specifically on CRP lands in the United States.

C density of vegetation on abandoned agricultural lands was estimated from Table 1 in Hooker and Compton [46] as half the biomass of the youngest study plot. This paper was the only study found that specifically addressed forest regeneration after agricultural abandonment in the Northeastern United States. Net annual C accumulation was estimated from Table 3 in Hooker and Compton [46] as the sum of values for plant biomass, woody debris, and the forest floor.

The C density of abandoned agricultural soil was assumed to be the same as that of inactive cropland and CRP soils – the dynamics of the initial stages of regeneration on a field in the absence of active agriculture are likely to be similar at first, regardless of whether the land is defined as temporarily inactive or permanently abandoned. Net annual C accumulation was estimated from Post and Kwon [47], using an average of values in Table 1 for succession from old field/agriculture to cool temperate moist forest.

This paper provided a valuable summary of studies measuring soil C accumulation post-agriculture and allowed for the easy aggregation of values from those studies.

C density of urban vegetation was estimated from Figures 1 and 2 of Jo and McPherson [48], using an average of two plots. Net annual C accumulation was also estimated from Jo and McPherson [48]. This paper was an examination of two plots in Chicago, Illinois which included the effects of management and is one of the pioneering analyses of C cycling in urban areas.

C density of urban soil was estimated both in pervious areas and under impervious surfaces from Pouyat et al. [14]. This paper brought together urban soil C information from a variety of sources to create C density estimates specific to geographic regions of the United States. The values for residential and impervious/commercial-industrial-transportation areas in the Northeast region in Table 5 were used. Net annual C accumulation in urban soils was estimated in pervious areas and under impervious surfaces from Jo and McPherson [48] using an average of two plots.

**Table 7: C density and net C accumulation values from the literature by data type and geographic region.**

| Data Type | Value | Data Source | Geographic Area |
|---|---|---|---|
| Forest soil C density | 107 Mg/ha | Ellert and Gregorich 1996 | Ontario |
| Forest soil C accumulation | negligible | Smith et al. 2006 | Northeast US |
| Active agricultural biomass C density | negligible | n/a | n/a |
| Active agricultural biomass C accumulation | negligible | n/a | n/a |
| Active agricultural soil C density | 70 Mg/ha | Ellert and Gregorich 1996 | Ontario, CA |
| Active agricultural soil C accumulation | 0 Mg/ha/yr | West and Marland 2002 | United States |
| Inactive cropland and CRP soils C density | 82 Mg/ha | Paul et al. 2003 | Eastern North America |
| Inactive cropland and CRP soils C accumulation | 1 Mg/ha/yr | Gebhart et al. 1994 | US Great Plains |
| Abandoned agricultural biomass C density | 4 Mg/ha | Hooker and Compton 2003 | Rhode Island, US |
| Abandoned agricultural biomass C accumulation | 2 Mg/ha/yr | Hooker and Compton 2003 | Rhode Island, US |
| Abandoned agricultural soil C density | 82 Mg/ha | Paul et al. 2003 | Eastern North America |
| Abandoned agricultural soil C accumulation | 0.24 Mg/ha/yr | Post and Kwon 2000 | Worldwide cool temperate moist forests |
| Urban biomass C density | 41 Mg/ha | Jo and McPherson 1995 | Chicago, IL, US |
| Urban biomass C accumulation | 4 Mg/ha/yr | Jo and McPherson 1995 | Chicago, IL, US |
| Urban soil C density | 144 Mg/ha pervious, 33 Mg/ha under impervious | Pouyat et al. 2006 | Northeast US |
| Urban soil C accumulation | 2 Mg/ha/yr pervious, negligible under impervious | Jo and McPherson 1995 | Chicago, IL, US |

The values for soil C density and net soil C accumulation listed in Table 7 above come from studies that used a variety of methodologies, each incorporating different soil sampling depths. Often larger sampling depths lead to larger C density and C accumulation values, and the closer a sample stays to the soil surface the larger the value will be, as soil is more C dense closer to the surface. Thus, it is important to be aware of sampling depth when considering soil C values. Table 8 shows the sampling depth of each study from which soil C density and C accumulation values were estimated for this paper.

**Table 8: Sampling depths from the soil C density and C accumulation literature listed in Table 7.**

| Study | Land Type | Sampling Depth (cm) | C Density (Mg/ha) | C Accumulation (Mg/ha/yr) |
|---|---|---|---|---|
| Ellert and Gregorich 1996 | Forest soil | 32.2 | 107 | |
| Ellert and Gregorich 1996 | Active agricultural soil | 26.4 | 70 | |
| West and Marland 2002 | Active agricultural soil | 30 | | 0 |
| Paul et al. 2003 | Inactive cropland and CRP soils | 100 | 82 | |
| Gebhart et al. 1994 | Inactive and abandoned agricultural soil | 40 | | 1 |
| Post and Kwon 2000 | Abandoned agricultural soil | 33 | | 0.24 |
| Pouyat et al. 2006 | Urban soil, pervious | 100 | 144 | |
| Pouyat et al. 2006 | Urban soil, under impervious surface | 100 | 33 | |
| Jo and McPherson 1995 | Urban soil, pervious | 60 | | 2 |
| Jo and McPherson 1995 | Urban soil, under impervious surface | 60 | | 0 |

## 6. Carbon Emissions

Seven C emissions sources were measured in Chittenden County. These included residential electricity use, residential petroleum use, commercial electricity use, commercial petroleum use, industrial electricity use, industrial petroleum use (including agriculture) and petroleum use for transportation. For each source, three values were calculated: total C emissions (Mg/yr), C flux density (Mg/ha/yr) and % of total C emissions. Residential, commercial and industrial emissions came from point sources, but were expressed as densities under the assumption that land use controls the presence and distribution of sources.

One of the most important considerations in carbon budgeting involves where to allocate $CO_2$ emissions. Under the production accounting principle, emissions are allocated to the entities which produce the energy or products that result in the emissions. Under the consumption accounting principle, emissions are allocated to the entities which consume the energy or products that result in the emissions [49]. Making this determination in the initial stages of the budgeting process ensures that emissions will not be "double counted", or added to more than one sector. Also, often results from the two types of budgets will differ, and this can have policy implications in terms of where mitigation strategies are applied. This budget uses the consumption principle, and attributes responsibility for emissions to the demand side.

It is important to note, however, that not all C emissions due to consumption were counted – only those related to direct transportation, electricity, and petroleum use. Other emissions due to demand, such as emissions from energy used to create products imported across county borders, were not counted. Chittenden County has relatively little industry, so the amount of imported goods is high. Production of such material goods that occurs within the county was counted implicitly in the calculation of industrial electricity and petroleum use. Emissions from external food production and associated transportation of food into the county were also not included.

Cement production emits $CO_2$ not only from the burning of fossil fuels, but also in the chemical reactions required to form the cement material [28]. That process was not considered as there is no cement manufacturing in Chittenden County.

In the course of the analysis, two systems were determined for calculating emissions data. One was the “bottom-up” method, which involved energy use data collected at the county level or below. Town level or small regional level data can often be aggregated easily up to the county level. Because it relies on local reporting, this method is potentially the most accurate, and most likely to capture specific nuances of county emissions.

The other option was the “top-down” method, where data collected above the county level (i.e. state level data) was proportionally adjusted to the correct scale. This method provided a more generalized result, but was often necessary when data at the local level did not exist or were difficult to access. State-level data on C emissions for this report was acquired from a greenhouse gas inventory performed for the Vermont Governor's Commission on Climate Change (VGCCC) [19]. Similar greenhouse gas reduction plans have been prepared for many states [50]. Greenhouse gas inventories have also been prepared at the county level and below by planners and citizen groups [51].

**6.1. Transportation**

Fossil fuel use for transportation was determined using both the “top-down” and the “bottom-up” methods for the purposes of comparison.

The bottom-up method began with data on vehicle miles traveled (VMT) in the county in 2004 from the Vermont Agency of Transportation (VTrans) [52]. These data were broken down by road type. In 2006 VTrans released data on vehicle distribution by similar road types [53], which were used to determine what kind of vehicle drove each 2004 vehicle mile. Average fuel efficiencies (in miles per gallon) for each vehicle type were found in the Oak Ridge National Laboratory Transportation Data Book [54]. Miles traveled by each vehicle type divided by its fuel efficiency equaled the gallons of fuel used in the county in that year by that vehicle type (Table 9).

**Table 9: Fuel used for automobile transportation in Chittenden County, Vermont. Vehicle type codes refer to truck types by number of axles and tonnage. Fuel efficiencies from ORNL [54], VMTs and vehicle type distribution from VTrans [52,53].**

| Vehicle Type | Fuel Efficiency (miles/gal) | Vehicle Miles Traveled in Chittenden on All Road Types | Gallons of Fuel Used |
|---|---|---|---|
| Motorcycles | 22.5 | 11,547,089 | 513,204 |
| Passenger cars | 22.5 | 1,103,273,997 | 49,034,400 |
| Pickup truck/SUV | 16.2 | 299,746,992 | 18,502,901 |
| School/transit buses | 8.8 | 11,093,910 | 1,260,672 |
| 2A-6T | 8.8 | 43,502,890 | 4,943,510 |
| 3A-SU | 8.8 | 9,518,117 | 1,081,604 |
| 4A-SU | 8.8 | 1,632,501 | 185,511 |
| 4A-ST | 5.9 | 15,180,455 | 2,572,958 |
| 5A-ST | 5.9 | 27,065,044 | 4,587,296 |
| 6A-ST | 5.9 | 3,173,966 | 537,960 |
| 5-MT | 5.9 | 472,640 | 80,108 |
| 6A-MT | 5.9 | 255,109 | 43,239 |
| 7A-MT | 5.9 | 1,193,781 | 202,336 |
| | | Total | 83,545,699 |

The US Energy Information Administration (EIA) provided state energy data [55], which included the percentage of gasoline versus diesel fuel used in the state. This was applied to the total fuel consumption to determine how much fuel burned was gasoline and how much was diesel. Then standard conversion factors [56] were applied for each of the two fuel types to determine how much C was emitted in the county per gallon of fuel burned (2332 g C/gal gasoline and 2716 g C/gal diesel fuel). C emissions were divided by land area dedicated to transportation to calculate C flux density for transportation petroleum use.

For the top-down method, the 2004 vehicle miles traveled for both the state of Vermont and Chittenden County [52] were used to determine what percentage of state miles the county miles represented. That percentage was then applied to state C emissions due to transportation in 2000 [19] to determine the C emissions due to transportation in the county, using the following equation:

$$\text{County Transportation Emissions} = \text{Total Vermont Transportation Emissions} \\ * \text{ \% of Total Vermont Vehicle Miles Traveled in the County} \quad (1)$$

The state C emissions values [19] were originally calculated using the US Environmental Protection Agency's State Greenhouse Gas Inventory Tool software [57], with default values replaced by state-specific information from the Vermont Department of Environmental Conservation and the Vermont Agency of Transportation. This method assumed that traffic congestion, which increases emissions, is similar across Vermont. Since Chittenden County is home to Vermont's largest city, however, it is possible that more congestion occurs in Chittenden County than elsewhere in the state, affecting the accuracy of these calculations.

Unlike the bottom-up method, this calculation included non-highway fuel consumption such as that by aircraft, boats and trains. Chittenden County is home to the only international airport in Vermont. However, using the top-down method, the emissions from this major hub are distributed proportionally throughout the state and not attributed only to Chittenden County.

A third method existed for the calculation of transportation emissions in the county that, in the end, was not used. The Chittenden County Metropolitan Planning Organization developed a detailed county-level transportation model that accurately assessed vehicle miles traveled and took into account traffic congestion [58]. The model only worked for peak driving hours, however, and was not capable of estimating conditions at other times of day. Thus, while the model was more accurate than both the top-down and bottom-up methods described above for the time periods it covered, it was not chosen as it could not represent all daily traffic conditions in the county.

### 6.2. Electricity

Electricity emissions were calculated using only the top-down method, as complete electricity consumption data from individual electric utilities operating in the county were not available. $CO_2$ emissions due to electricity consumption at the state level were taken from the VGCCC report [19] . That report utilized information on electricity sales to individual utilities and the mix of fuels used in electricity generation from the Vermont Department of Public Service. To determine the land-use-based contributions of residential, commercial and industrial activity to overall C balance, emissions in each sector (found using methods described below) were divided by the land in each land use type within the county. Electricity sales in each sector were assumed to represent actual electricity use.

To determine the amount of state electricity use attributed to Chittenden in the residential sector, the following equation was used:

County Residential Electricity Emissions = Total Vermont Electricity Emissions * % of Total Vermont Households in the County * % of Vermont Electricity Sales in the Residential Sector (2)

Percentage of state electricity sales in the residential sector was found using EIA data from 2000 [59]. Percentage of Vermont households in the county was calculated from the 2000 US Census [60,61]. For this report, households were classified as number of Census-defined households plus number of second-home housing units (calculated as the total number of households subtracted from total number of housing units, divided by two as an assumption of second-home status and thus half-time occupancy and resource use). This method assumed that individual households across the state use a relatively similar amount of electricity per year.

To determine the amount of state electricity use attributed to Chittenden in the commercial sector, the following equation was used:

County Commercial Electricity Emissions = Total Vermont Electricity Emissions * % of Vermont Employment in the Commercial Sector in the County * % of Vermont Electricity Sales in the Commercial Sector (3)

Percentage of state electricity sales in the commercial sector were found using EIA data from 2000 [59]. Percentage of Vermont employment in the county and the state were calculated from the 2002 US Economic Census [62,63]. A key assumption in this equation, and for all equations in this section addressing the commercial and industrial sectors, was that commercial and industrial activity, and thus emissions, are proportional to the number of individuals employed in each sector. The accuracy of this assumption probably varies by degree based on specific businesses and industries. For example, some industries may require large amounts of energy but require very few employees to run the industrial processes, while some businesses may have many employees that do not work from a central location and thus do not use much energy in the commercial sector.

To determine the amount of state electricity use attributed to Chittenden in the industrial sector, the following equation was used:

County Industrial Electricity Emissions = Total Vermont Electricity Emissions * % of Vermont Employment in the Industrial Sector in the County * % of Vermont Electricity Sales in the Industrial Sector (4)

Percentage of state electricity sales in the industrial sector were found using EIA data from 2000 [59]. Percentage of Vermont employment in the county and the state were calculated from the 2002 US Economic Census [62,63]. C emissions were divided by land area to calculate C flux density. An assumption implicit in all equations addressing the industrial sector is that all sizes and types of industrial production have similar emissions levels. In reality Chittenden County contains the state's largest industrial producers and thus most of the state's industry, whose emissions may vary in C density and thus affect the accuracy of the method by introducing a discontinuity in scaling.

**6.3. Petroleum**

Petroleum emissions were calculated using only the top-down method, as petroleum consumption data at the county level or below did not exist for Chittenden County. $CO_2$ emissions due to petroleum consumption in the state for space heating and cooling, process heating, and other energy applications not including electricity were taken from the VGCCC [19]. That report utilized the Environmental Protection Agency's State Greenhouse Gas Inventory Tool software [57], with default data replaced by the most up-to-date information from the Energy Information Administration's state energy data reports. Petroleum included natural gas, oil products and coal (placed in this category for analytical purposes). State petroleum emissions were allocated to the residential, commercial and industrial sectors, and emissions from agricultural energy use were included in industrial emissions [19].

To determine the amount of state petroleum use attributed to Chittenden County in the residential sector, the following equation was used:

$$\text{County Residential Petroleum Emissions} = \text{Total Vermont Residential Petroleum Emissions} * \text{\% of Total Vermont Households in the County} \quad (5)$$

Percentage of Vermont households in the county were calculated with adjustment for half-time occupancy as described above, with similar assumptions included.

To determine the amount of state petroleum use attributed to Chittenden County in the commercial sector, the following equation was used:

County Commercial Petroleum Emissions = Total Vermont Commercial Petroleum Emissions * % of Vermont Employment in the Commercial Sector in the County (6)

Percentage of Vermont employment in the county and the state were calculated from the 2002 US Economic Census as described above, with similar assumptions included.

To determine the amount of state petroleum use attributed to Chittenden County in the industrial sector (including agriculture), the following equation was used:

County Industrial Petroleum Emissions = Total Vermont Industrial Petroleum Emissions * % of Vermont Employment in the Industrial Sector in the County (7)

Percentage of Vermont employment in the county and the state were calculated from the 2002 US Economic Census, and area dedicated to residential, commercial and industrial activity in the county was used to calculate C flux density as described above, with similar assumptions included.

The individual emissions calculations described above can be aggregated and analyzed as individual point sources contributing to total C emissions in the county, or they can be analyzed on an 'emissions per area of land use' basis using the C flux density calculation.

**6.4. Land Use Change**

Land use change often involves deforestation and soil disturbance, both of which emit C to the atmosphere. Every year in Chittenden County, forest and agricultural land are converted to developed uses, contributing to the county's total C emissions. Quantifying the flux associated with land use change is difficult, however, as it requires data detailed enough that significant change over short periods of time can be detected. Land use change emissions were not explicitly measured in this budget because appropriate spatial data for the entire county was not available. The National Land Cover Database [27] and other satellite data classified by UVM's SAL [31,33] show land use changes between 1992 and 2001-2, but the resolution of the data is not high enough to provide measures of change outside the range of classification error. In future studies, the development of a method to quantify land use change would be valuable. Concentrating on smaller areas within counties for land use change analyses may increase the availability of accurate, high-resolution data.

## 7. Sources of Error

Some of the data sources used to calculate Chittenden County's C budget had greater accuracy than others. Error in each individual dataset can compound potential error of the budget as a whole, or it can counteract other sources of error. While no statistical error analysis was done for this paper, this section presents an explanation of some of the most prominent sources of error in the budget, and what was done to control them.

Forest Inventory Mapmaker version 3.0 [29] was used to calculate land area in forest in Chittenden County. These estimations were performed with plot-level data, one plot placed every 2500 ha across the county, so there is potential for error in the results based on number of plots and the location of those plots. If a unique forest type existed within the county, for instance, but never happened to occur in an area containing an FIA plot, that forest type may have been left out of the analysis.

Land use classifications of remote sensing imagery have two types of error: errors of omission (when pixels are not recognized) and errors of commission (when pixels are classified as an incorrect class). The National Land Cover Database [27], used in this study to determine urban land area for C sequestration, calculated both types of error for each individual classification (Table 10). Accuracy varied drastically among categories, with low intensity developed areas being the least reliable classification.

**Table 10: Accuracy of urban land use classifications in the National Land Cover Database 2001 [27].**

| NLCD Land Use Classification | % Accuracy, Errors of Omission | % Accuracy, Errors of Commission |
|---|---|---|
| Developed, Open Space | 50 | 100 |
| Developed, Low Intensity | 25 | 41 |
| Developed, Medium Intensity | 79 | 52 |
| Developed, High Intensity | 50 | 73 |

The accuracy assessment of the Spatial Analysis Lab's land use dataset [31] was also divided into errors of omission and errors of commission. Accuracy was calculated for all urban categories together rather than for individual sectors (residential, commercial, industrial and transportation). The accuracy for urban categories in terms of errors of omission was 96.67%, and the accuracy for urban categories in terms of errors of commission was 84%. This locally-produced dataset was much more accurate than the NLCD, possibly because a classification covering a smaller area can be more readily checked against other data sources and verified on the ground.

Assumptions made to scale data from one spatial level to another can also add to error, as every assumption has the potential to bias the final result. The assumptions made in this budget are outlined where they appear in the methodology above. Potential for error from some of the larger assumptions are specifically discussed here.

To estimate the average biomass and net primary production in live trees in the county, plot-level data from all Northern Vermont counties was used. This method introduced potential for bias, however, as it assumed that all Northern Vermont counties were similar to Chittenden County in terms of forest conditions such as site quality and climate. Chittenden County's position on the shores of Lake Champlain may lead to differences in these conditions, as the rest of Northern Vermont is landlocked. Also, depending on the number and location of plots measured in the county and across northern Vermont, the calculated average may not represent all forest types – similar to the potential for error in Mapmaker's forest area calculations.

Scaling residential data from the state-level to the county-level required the assumption that number of households in the county was equivalent to energy use. In reality this may vary according to individual home energy efficiency and conservation. Scaling commercial and industrial data from the state-level to the county-level required the assumption that employment in each sector was equivalent to the sector's emissions. This may not always be the case, however, especially in industry, where a process may be energy-intensive but require few employees. Using vehicle miles traveled in the county to calculate transportation emissions may also cause error, as VMT's do not take into account traffic congestion during peak hours on each roadway.

These sources of error are important to keep in mind while viewing the results of the C budget, but do not make the results insignificant. In all cases, assumptions were made and datasets with error were utilized because no other data was available. At every point in the creation of the budget, the best possible available data was found following the three selection criteria: accuracy, completeness of coverage and accessibility. Despite small sources of error, the scale of the budget is such that useful estimations for county-level decision-making can still be made.

# Results

### 1. Carbon Sequestration

The majority of the stored C in Chittenden County is found in forest biomass (11,560,987 Mg C) and forest soils (9,190,294 Mg C). Urban biomass and soils are also important C pools (441,202 Mg C and 1,719,864 Mg C respectively). The total amount of C currently stored in the county is 24,109,047 Mg C. C density is highest in forest biomass (135 Mg C/ha) and forest soils (107 Mg C/ha), as well as pervious urban soil (144 Mg C/ha).

**Table 11: Area, C density and C pool size of land types in Chittenden County, Vermont.**

| Land type | Area (ha)[a] | C density (Mg C/ha) | C pool (Mg C) | % of Total C Pool |
|---|---|---|---|---|
| Forest biomass[b] | 85,891 | 135 | 11,560,987 | 48 |
| Forest soil[c] | 85,891 | 107 | 9,190,294 | 38 |
| Wood products[d] | 85,891 | not calculated | not calculated | 0 |
| Active agricultural biomass[e] | 11,301 | negligible | negligible | 0 |
| Active agricultural soil[f] | 11,301 | 70 | 791,088 | 3 |
| Inactive cropland and CRP soils[g] | 4,826 | 82 | 393,502 | 2 |
| Abandoned agricultural biomass[h] | 141 | 4 | 627 | 0.003 |
| Abandoned agricultural soil[i] | 141 | 82 | 11,483 | 0.05 |
| Urban biomass[j] | 10,772 | 41 | 441,202 | 2 |
| Urban soil, pervious[k] | 10,772 | 144 | 1,551,102 | 6 |
| Urban soil, under impervious surface[k] | 5,114 | 33 | 168,762 | 1 |
| | | **TOTAL:** | **24,109,047** | |

a) Forest land area calculated with Forest Inventory Mapmaker version 3.0 [29]. Active agricultural land area, inactive cropland and CRP area and abandoned agricultural land area from the 2002 US Census of Agriculture [32]. Urban area from the National Land Cover Database [27].

b) Forest biomass C density calculated from Forest Inventory and Analysis data [30] and Smith et al. [36].

c) Forest soil C density from Table 5 of Ellert and Gregorich [42].

d) Wood products C pool and density not calculated for this report.

e) No net C is stored in annually harvested agricultural biomass.

f) Active agricultural soil C density from Table 5 of Ellert and Gregorich [42].

g) Inactive cropland and CRP soils C density from Paul et al. [44].

h) Abandoned agricultural biomass C density from Table 1 of Hooker and Compton [46].

i) Abandoned agricultural soil C density assumed to be the same as that of inactive cropland and CRP soils.

j) Urban biomass C density from Figures 1 and 2 of Jo and McPherson [48].

k) Urban soil C density from Table 5 in Pouyat et al. [14].

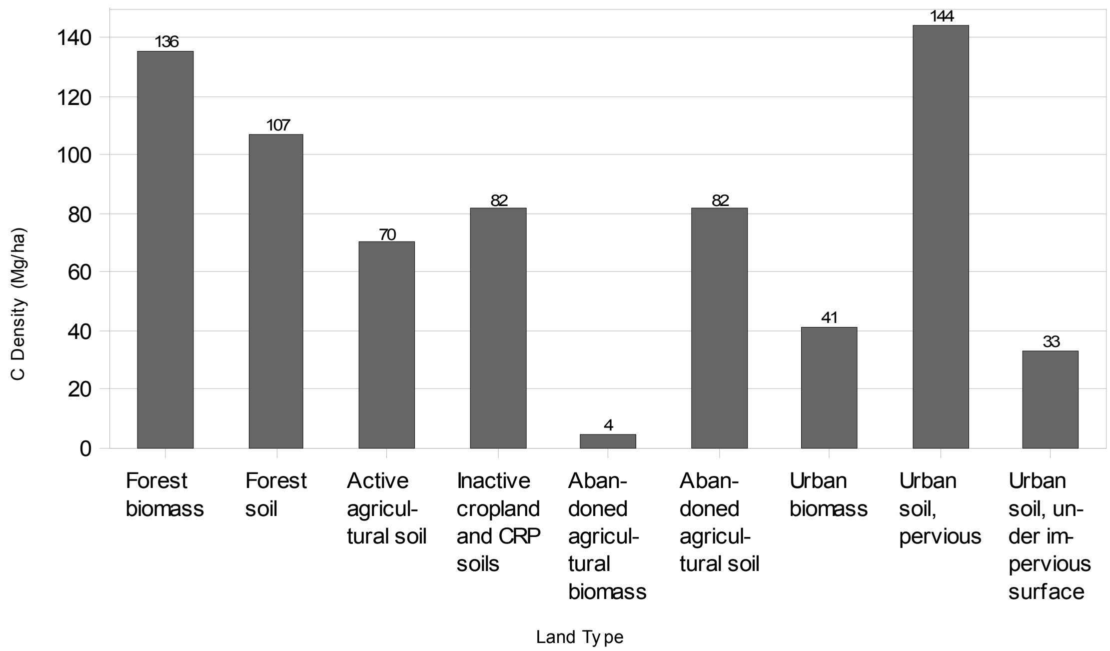


**Figure 5: C density by land type in Chittenden County, Vermont.**

Net annual C accumulation is largest in forest biomass (12 Mg C/ha/year), by a wide margin. Urban vegetation also experiences a high rate of net annual accumulation (4 Mg C/ha/year). Annual county accumulation is dominated by forest biomass (1,042,727 Mg C/year). Urban biomass and soil also contribute in relatively large amounts (46,318 Mg C/year and 20,466 Mg C/year respectively). The total amount of C sequestered in the county annually is about 1,116,652 Mg C/year.

**Table 12: Area, net C accumulation and total C accumulation of land types in Chittenden County, Vermont.**

| Land type | Area (ha)[a] | Net accumulation (Mg C/ha/year) | County accumulation (Mg C/year) | % of Total C Sequestration |
|---|---|---|---|---|
| Forest biomass[b] | 85,891 | 12 | 1,042,727 | 93 |
| Forest soil[c] | 85,891 | negligible | negligible | 0 |
| Wood products[d] | 85,891 | 0.02 | 1,524 | 0.14 |
| Active agricultural biomass[e] | 11,301 | negligible | negligible | 0 |
| Active agricultural soil[f] | 11,301 | negligible | negligible | 0 |
| Inactive cropland and CRP soils[g] | 4,826 | 1 | 5,308 | 0.48 |
| Abandoned agricultural biomass[h] | 141 | 2 | 275 | 0.02 |
| Abandoned agricultural soil[i] | 141 | 0.24 | 34 | 0.003 |
| Urban biomass[j] | 10,772 | 4 | 46,318 | 4 |
| Urban soil, pervious[k] | 10,772 | 2 | 20,466 | 2 |
| Urban soil, under impervious surface[k] | 5,114 | negligible | negligible | 0 |
| | | **TOTAL:** | **1,116,652** | |

a) Forest land area calculated with Forest Inventory Mapmaker version 3.0 [29]. Active agricultural land area, inactive cropland and CRP area and abandoned agricultural land area from the 2002 US Census of Agriculture [32]. Urban area from the National Land Cover Database [27].

b) Forest biomass net C accumulation calculated from Forest Inventory and Analysis data [30] and Smith et al. [36].

c) Forest soil net C accumulation from Smith et al. [36].

d) Wood products net C accumulation calculated from the PA DCNR CMAG report [37].

e) No net C is stored annually in harvested agricultural biomass.

f) Active agricultural soil net C accumulation from Table 9 of West and Marland [43].

g) Inactive cropland and CRP soils net C accumulation from Gebhart et al. [45].

h) Abandoned agricultural biomass net C accumulation from Hooker and Compton [46].

i) Abandoned agricultural soil net C accumulation from Post and Kwon [47].

j) Urban biomass net C accumulation from Jo and McPherson [48].

k) Urban soil net C accumulation from Jo and McPherson [48].

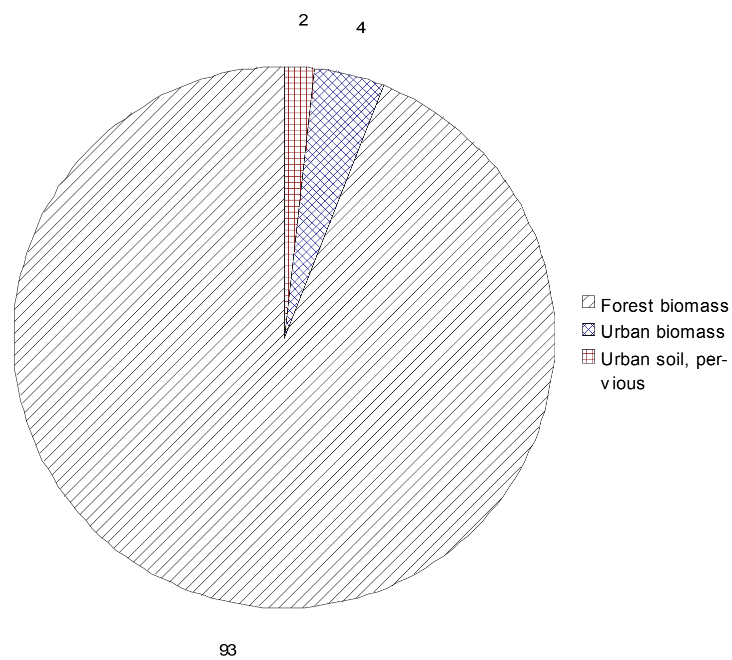


**Figure 6: Percent of total annual C accumulation by land type in Chittenden County, Vermont. Land uses contributing to less than 2% of annual accumulation not included.**

## 2. Carbon Emissions

Almost half (47%) of the $CO_2$ emitted to the atmosphere annually in Chittenden County is due to transportation (197,754 Mg C). That is comparable to the state of Vermont as a whole, where 44% of total C emissions come from transportation [19]. Also significant is petroleum burned in the residential sector for heating (95,298 Mg C). Electricity contributes minimally to the county's emissions. The largest C flux density, or C emitted per unit area devoted to a given land use type, is in the commercial petroleum sector (48 Mg C/ha). Transportation also has high C flux density (36 Mg C/ha). The total amount of C emitted annually in the county is 417,820 Mg C/ha/yr. The difference between net annual C sequestration and annual C emissions is 698,832 Mg C/yr.

**Table 13: Annual C emissions by sector in Chittenden County, Vermont.**

| Sector | Energy type | Area (ha)[a] | C flux density (Mg C/ha/yr) | County emissions (Mg C/yr) | % C emissions |
|---|---|---|---|---|---|
| Residential | Electricity[b] | 5,761 | 2 | 8,925 | 2 |
| | Petroleum[c] | 5,761 | 17 | 95,298 | 23 |
| Commercial | Electricity[d] | 1,097 | 10 | 11,127 | 3 |
| | Petroleum[e] | 1,097 | 48 | 52,700 | 13 |
| Industrial | Electricity[f] | 467 | 22 | 10,081 | 2 |
| | Petroleum[g] | 467 | 4 | 41,936 | 10 |
| Transportation | Petroleum[h] | 5,509 | 36 | 197,754 | 47 |
| | | | **TOTAL:** | **417,820** | |

a) Area devoted to each land use type calculated from 2002 Landsat TM imagery classified by the University of Vermont Spatial Analysis Laboratory [31].

b) Residential electricity emissions calculated from VGCCC [19], EIA [59] and US Census [60,61] data.

c) Residential petroleum emissions calculated from VGCCC [19] and US Census [60,61] data.

d) Commercial electricity emissions calculated from VGCCC [19], EIA [59] and US Economic Census [62,63] data.

e) Commercial petroleum emissions calculated from VGCCC [19] and US Economic Census [62,63] data.

f) Industrial electricity emissions calculated from VGCCC [19], EIA [59] and US Economic Census [62,63] data.

g) Industrial petroleum emissions calculated from VGCCC [19] and US Economic Census [62,63] data.

h) Transportation petroleum emissions calculated from VGCCC [19] and VTrans [52] data.

Refer to text for methodology used to calculate emissions in each sector. Petroleum consists of natural gas, oil products and coal (placed in this category for analytical purposes).

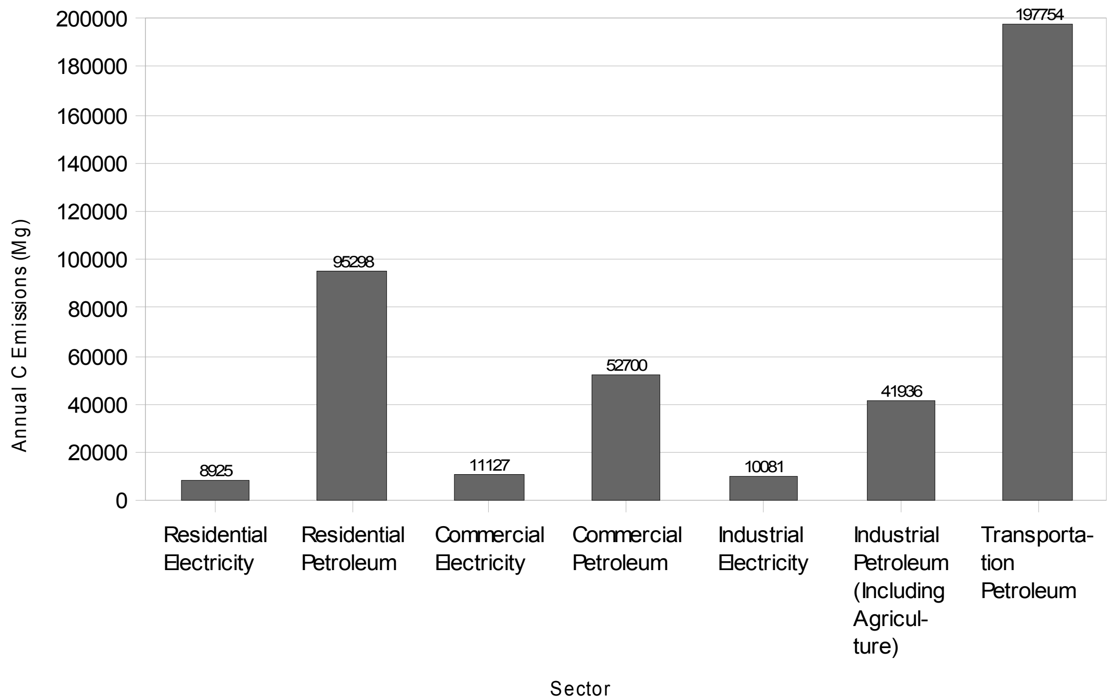


**Figure 7: Annual C emissions by sector in Chittenden County, Vermont.**

When top-down and bottom-up calculations of transportation emissions were compared, they produced similar results. Using the top-down method, it was estimated that the county emitted 197,754 Mg C annually due to transportation. Using the bottom-up method, the results suggested 201,245 Mg C were emitted annually. These numbers are quite similar given the differences in data sources and assumptions between the two methods.

# Discussion

### 1. Carbon Balance

The results above indicate that Chittenden County is a net sink for $CO_2$. In other words, within the county's borders more than twice as much carbon is likely stored annually in biomass and soils than is emitted due to anthropogenic activity.

Along with the potential sources of error for each individual data source explained in detail above, fundamental differences exist between methods of measuring emissions and sequestration that may lead to further uncertainty. For instance, emissions due to electricity and petroleum use are often calculated “at the stack”, or at the point source, while biomass and soil sequestration are estimated over a land area from literature values. These discrepancies may have unknown effects, especially on the calculation of C densities. Calculating C densities for both emissions and sequestration analyses, however, still yields interesting comparative results.

Despite the fact that the direct impacts of land use change were not considered in this analysis, the difference between C flux density on urban land and net C sequestration on forest land sheds light on the potential effects of future population growth and development in Chittenden County. The current land use patterns in the county show a decrease in farmland and forestland and an increase in urban and suburban development (Figure 2). Urban biomass and soils do sequester C, but not as effectively as forestland, and development is often accompanied by an initial C release when biomass is cleared from the landscape [3,5,13]. Thus, it is important to acknowledge that development pressures may decrease the significance of other C sinks in the county in coming years.

A hectare of forest in the county stores about 12 Mg C in biomass and soils annually. At the same time, each hectare of developed land dedicated to residential use emits about 17 Mg C/yr. Industrial and commercial land uses release even more annually (26 and 58 Mg C/yr respectively). Currently, 78,566 more hectares of Chittenden County are in forest than in residential, commercial and industrial uses combined, so forest sequestration still outweighs urban emissions. However, these data demonstrate that developed areas emit significantly more C per hectare than surrounding forestland sequesters, and land dedicated to urban development in the county is increasing. Each hectare of forest cleared for development also decreases the sequestration potential of the total land area. Thus, as development encroaches on forestland, the C balance will inevitably shift. For example, an increase in residential, commercial and industrial land of 10,124 ha (slightly less than double the current developed area in the county) would set annual C emissions equal to current annual sequestration capacity.

Urban vegetation is a large C pool in Chittenden County which could potentially help alleviate the emissions associated with developed land. Urban biomass sequesters 4 Mg C/ha annually, and urban soil sequesters 2 Mg C/ha annually. Those values are similar to the annual C flux density of industrial petroleum (including emissions from agriculture), but are much smaller than the flux density of the other developed land uses. Thus, urban biomass has the potential to mitigate only a small portion of the annual C emissions from the residential, commercial, industrial and transportation sectors.

For future planning considerations in Chittenden County, an analysis of the annual C emissions and sequestration potential of land uses could be a useful metric by which to determine development priorities.

**2. Other Considerations**

It is important to note that, while Chittenden County's forests are its most valuable C sink, the forest will not always sequester C at the same rate. The entire Northeast is currently recovering from a near-complete loss of forestland which began in the mid-1800s as farms were abandoned and people moved to urban centers [4]. Chittenden County follows that trend (Figure 2). The increase in forest area due to agricultural abandonment and the fact that young forests grow quickly and thus sequester C at relatively high rates [3] contribute to the current strength of the county's forest sink. Eventually the county's forests will reach maturity and the annual rate of C uptake will slow, increasing again only temporarily after stand level disturbances such as timber harvest or fire. Sustainable forest management and the efficient manufacture of durable wood products are thus crucial for continued forest C sequestration. This study demonstrates, however, that wood products currently add only small amounts to Chittenden County's annual C sequestration. Thus, the strong forest sink cannot be counted on to continue in coming years.

It is also worth noting that this C budget, although consumption based, does not take into account products manufactured outside of Chittenden County and transported to within the county's borders (the Tompkins County study did not take into account manufactured products either). Food grown outside of the county is also not included. Emissions from the creation and transportation of these products would be difficult to quantify and would be not be as useful as other emissions calculations to county planners and policy makers, so they were not included. However, since manufacturing within the county is quite low, they would probably significantly tip Chittenden County's C balance. Decreasing demand for products and food from out-of-state would help mitigate this effect.

The methodology used in this analysis focused heavily on the scaling of state-level data down to the county level. The assumptions and potential errors involved in that scaling are described in the Methods section. It is important to consider, however, that the effectiveness of such scaling methods is contingent on the size of the state. In a relatively small state such as Vermont, a small geographic area is covered, and relatively consistent climatic and cultural conditions are present. In a larger state, variation in climate, industry, commerce, and population might be more pronounced, and make scaling from the state-level to the county-level more difficult.

### 3. Comparisons to Vermont

The distribution of C emissions in Chittenden County is somewhat proportional to the distribution of C emissions in Vermont as a whole, according to the Vermont Governor's Commission on Climate Change Greenhouse Gas Inventory [19] (Table 14).

**Table 14: C emissions as a percentage of the total in Chittenden County, Vermont and Vermont as a whole by sector. Vermont's emissions do not add up to 100, as only those sectors addressing $CO_2$ specifically and also calculated for Chittenden County were included.**

| Sector | % of Total Annual C Emissions in Chittenden County | % of Total Annual C Emissions in Vermont [19] |
|---|---|---|
| Transportation Petroleum | 47 | 44 |
| Residential and Commercial Petroleum | 36 | 27 |
| Industrial Petroleum | 10 | 6 |
| Electricity | 7 | 5 |

Annual C emissions from transportation and electricity are quite similar. Differences in residential, commercial and industrial petroleum use between the two entities potentially demonstrate the concentration of Vermont's population and industry in Chittenden County, home to the state's only metro area. This study assumed that using number of households and levels of employment to scale Vermont state-level emissions data to county-level data provided accurate results. These comparisons seem to demonstrate a reasonable basis for those assumptions, considering the potential for error involved.

Annual C sequestration in Vermont's forestland was found by the Vermont Governor's Commission to be about 35 million Mg/yr [19]. Annual C sequestration in Chittenden County was found in this analysis to be about 1 million Mg/yr. Thus, about 3% of the total annual C sequestration in the state happened in Chittenden County. According to Forest Inventory and Analysis data [30], about 4.5% of Vermont's forest land is in Chittenden County. The similarity of those proportions, along with those in the emissions sectors compared above, again implies consistency and reasonable accuracy in scaling.

### 4. Comparisons to Tompkins County, NY

The difference between annual C sequestration and annual C emissions in Chittenden County, Vermont (698,832 Mg C/yr) was much larger than the difference between C sequestration and emissions calculated in the comparable Tompkins County, NY study (219,000 Mg C/yr) [21]. Additionally, Tompkins County was found to a source rather than a sink for $CO_2$ [21], despite its lower population density. Potential reasons for this discrepancy and a comparison of the C density of various sectors within each county will be explored below.

Electricity in Chittenden County and the state of Vermont is currently provided by a variety of sources, few of which are C intensive. These include the Vermont Yankee nuclear plant, HydroQuebec, the McNeil biomass plant in Burlington, and several small wind and hydro operations [64]. This gives Vermont an advantage over other states in terms of C emissions from electricity. Consequently, the total C density of electricity in Tompkins County was found to be 46 Mg C/ha/yr, while the total C density of electricity in Chittenden County was 34 Mg C/ha/yr – consistently lower across each sector. Vermont's contract with Vermont Yankee ends in 2012, however, and contracts with HydroQuebec begin to phase out in 2020 [19]. This leaves the future of Chittenden's electricity production open and vulnerable. Figure 8 shows how $CO_2$ emissions might increase if nuclear and large hydro are no longer parts of the state's electricity portfolio in the future.

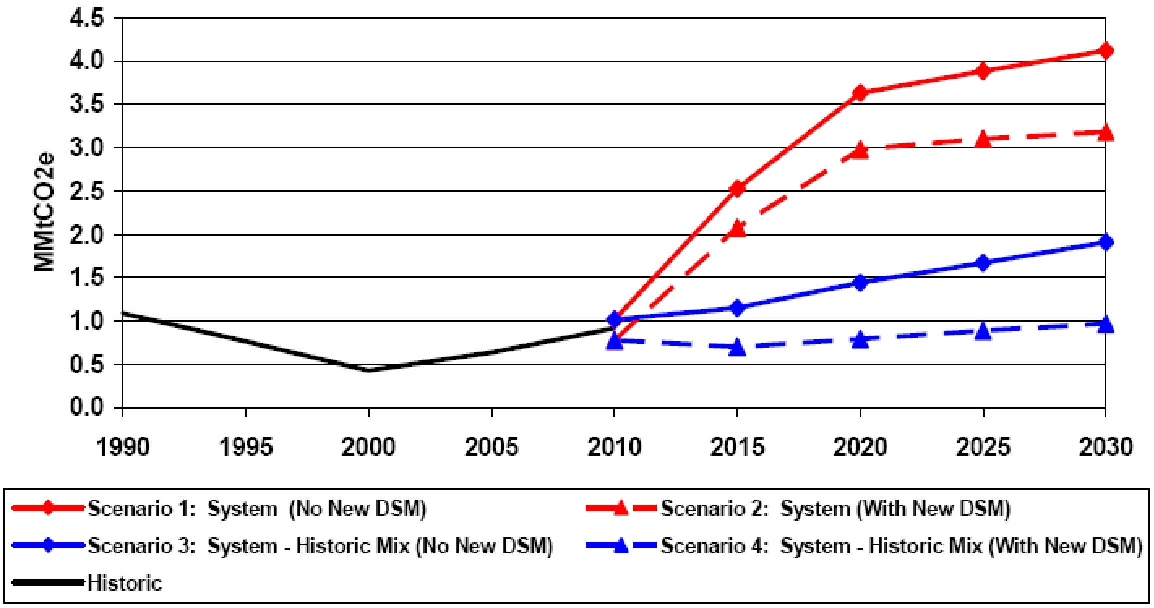


**Figure 8: Electricity-consumption-based greenhouse gas inventory and forecast for Vermont [19]. DSM is Demand-Side Management programs designed to decrease consumption. Scenarios 3 and 4 include nuclear and hydro; Scenarios 1 and 2 do not.**

The inclusion of urban biomass and soils as C sinks is potentially responsible for the magnitude of the annual sequestration in Chittenden County. The Tompkins County analysis [21] calculated significantly lower numbers for annual C sequestration, and did not quantify urban vegetation as a potential C pool. Recalculating Chittenden's total annual C sequestration without urban biomass and soils, however, yields 1,049,868 Mg/year – still significantly higher than the total annual sequestration of Tompkins County (121,000 Mg/year). Chittenden County is also extensively forested – about 70% -- while Tompkins County is only 40% forest. This may help account for the rest of the difference between the two counties, and demonstrate the effectiveness of forestland in balancing C.

According to the Tompkins County report [21], significantly more C is sequestered annually in all agricultural biomass and soils (46,000 Mg C/yr) than in the same pools in Chittenden County (only 5617 Mg C/yr). Thirty percent of the total land area in Tompkins County is dedicated to agriculture, while only 14% of the total land area is agriculture in Chittenden County, accounting for the difference. Both studies found that agricultural biomass and soils are significantly less C-dense than forest biomass and soils. Thus, Chittenden County still sequesters significantly more total C annually.

The difference in C density between agricultural land and forest has interesting implications in terms of development for the two counties. All other factors being equal, urban development resulting in a loss of farmland may lead to a slightly smaller decrease in annual C sequestration than urban development resulting in a loss of forestland. In Chittenden County, for example, if inactive cropland was converted to residential development only 1 Mg C/ha/yr of sequestration would be lost, compared to 12 Mg C/ha/yr if the developed land had been forest. In Tompkins County, where land under development pressure is more likely to be agricultural, urbanization may lead to a smaller net loss of C sequestration potential than in the primarily forested Chittenden County. Also, urban biomass and soils sequester on average 6 Mg C/ha/yr, potentially leading to a net increase in sequestration when development occurs on agricultural land. Residential areas emit 19 Mg C/ha/yr, however, an amount significantly larger than the C sequestered, demonstrating the importance of analyzing C sources and sinks together.

These comparisons between the two counties demonstrate that differences in agricultural and forest land area, along with the impact of development, have the potential to affect differences in C balance more than any other factors. As further case studies are completed, the intricacies of the relationship between these two land uses and the C cycle at the county level will be explored in more detail.

## 5. Carbon Mitigation

Acknowledging the issues described above, this C budget gives planners and policymakers the tools they need to choose the most effective C mitigation strategies at the county level. According to the budget, C emissions due to transportation are the most important C source in the county. Thus, policy and planning directed at decreasing transportation emissions would have a significant effect. Programs to address transportation might include vehicle fuel efficiency research, promotion of locally-produced biofuels, improved public transportation systems (in both the Burlington-South Burlington metro area and more rural parts of the county), carpooling incentives and compact development incentives.

Residential petroleum emissions were also important in the county. Programs to decrease C emissions in this sector might incentivize household energy efficiency (i.e. installation of efficient windows and doors, Energy Star appliances, additional insulation) and the building of homes that use construction design to decrease heating and cooling needs.

Forest sequestration is one of the most effective ways the county removes C from the atmosphere. Thus, planners and policymakers could also strive to keep forest as forest and not let it succumb to development pressure, which would ensure the existence of the forest sink for many years into the future. This budget shows explicitly how significant the effects of land use change can be on C dynamics. Sustainable forest management that encourages maximum forest growth, along with incentives for the manufacture of durable wood products, could also be encouraged.

Urban vegetation was also an important C sink. Thus, urban tree planting and gardening programs could be encouraged to maximize urban C sequestration. Incentives could be provided for urban greenspace to be included in development plans and disturbance to existing vegetation and soils minimized. No-till agriculture and other farming methods that increase C sequestration could also be emphasized.

## Conclusions

Chittenden County, Vermont is a net sink for $CO_2$. More than twice as much carbon is likely stored annually in biomass and soils in the county than is emitted due to anthropogenic activity. Developed areas emit significantly more C per hectare than forestland sequesters, and land dedicated to urban development in the county is increasing. Each hectare of forest cleared for development also decreases the sequestration potential of the total land area. Thus, as development encroaches on forestland, the C balance will inevitably shift. Urban greenspace has the potential to mitigate only a small portion of annual C emissions.

Chittenden County, Vermont is currently recovering from a near-complete loss of forestland which began in the mid-1800s. Eventually the county's forests will reach maturity and the annual rate of C uptake will slow. This may cause the county's C balance to change.

The difference between annual C sequestration and annual C emissions in Chittenden County, Vermont was much larger than the difference between C sequestration and emissions in the comparable Tompkins County, NY study. Tompkins County was also found to a source rather than a sink for $CO_2$. Chittenden County's portfolio of electricity providers is not C-intensive, leading to lower C emissions in that sector. Also, Chittenden County is more forested than Tompkins County, leading to greater sequestration. Tompkins County has more agricultural land than Chittenden County, but agricultural biomass and soils are not as C-dense as forest biomass and soils. Tompkins County did not calculate sequestration in urban biomass and soils, which could increase their estimate of county sequestration. The conversion of agricultural land to development may have less impact on C sequestration potential of the landscape than the conversion of forest land to development, but urban land emits significantly more C than both agriculture and forest.

This C budget gives planners and policymakers the tools they need to choose the most effective C mitigation strategies at the county level. Transportation emissions and residential petroleum emissions are two areas where mitigation programs might provide the most benefit for the least cost. To increase sequestration most effectively, forest could be preserved and sustainably managed and manufacture of durable wood products could be encouraged. Urban greenspace and area involved in no-till agriculture could also be maximized.

## Competing interests

The author(s) declare that they have no competing interests.

## Authors' contributions

EQ acquired the data, developed some of the methods, performed all calculations and drafted the manuscript. JJ developed forest sequestration and wood products methods and provided other assistance as necessary. TF developed emissions and sequestration methods and is instrumental in the development of the larger study, of which this manuscript is only a part. SH developed land use change and top-down emissions calculation methods and is also involved in the larger study.

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