The Vermont Integrated Land-use and Transportation Carbon Estimator

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Abstract

Land conversion to developed use is associated with changes in land-based fluxes of carbon (C). Changes in vehicular transportation to and from the new development may also result in additional emissions from the burning of fossil fuels. National Land Cover Database (NLCD) and regional C sequestration rates from published literature were used to create a software tool, the Vermont Integrated Land-use and Transportation Carbon Estimator (VILTCE) meant for use with widely used commercial geographic information systems (GIS) software (ESRI ArcGIS using .NET). The tool is intended for Metropolitan Planning Organizations (MPOs) and regional planners to calculate the spatial C sequestration and emissions from the combined land use and transportation sectors for their region of interest under current and future development scenarios.

For illustration, the VILTCE was applied to Chittenden County, Vermont as a case study. Under current conditions, the county's soils and biomass in all land types are estimated to sequester approximately 23,500 and 184,000 Mg C per year, respectively. The transportation sector results in approximately 217,800 Mg C (797,900 Mg CO_2) emitted per year. Overall, Chittenden County is a C source (net release of C), emitting 37,700 Mg CO_2 annually, even without taking electricity and heating into account, which would add even more anthropogenically caused emissions. The gap between C emitted and stored could increase with additional development.

INTRODUCTION

Carbon Emissions from Transportation and Land-use Change

Biomass and soils sequester carbon (C) (*1*) through biological processes such as photosynthesis (*2*) and accumulation of plant, animal and microbial residues (*3*). Forests are an especially important C sink; estimates show that between 1993 and 2003, the world's forests sequestered about 3,300 metric tons of carbon dioxide ($MtCO_2$ yr^{-1}), equaling about 900 Mg C yr^{-1}, not taking land-use change into account (*1*). Goodale *et al.* found that in the United States between 1990 and 1991 the net change in forest C, including live vegetation, forest products, dead wood, forest floor, and soil organic C, was approximately 0.28 Pg C yr^{-1} (10.26 $MtCO_2$ yr^{-1} or 2.80 x 10^8 Mg C yr^{-1}) (*4*). However, some land-use change, such as a new residential development, results in C emissions to the atmosphere. In the 1990s such land-use change resulted in approximately 5,800 $MtCO_2$ (1,600 Mg C) emitted per year (*1*). The loss of C to the atmosphere when forestland is cleared is compounded by the C sink capacity that is foregone as a result.

If the new land-use is residential, commercial, or industrial, then the land-use change also affects travel patterns in the surrounding area and vehicle miles traveled (VMT), which is likely to alter emissions from the transportation sector (*5*). Additionally, the new land cover sequesters a distinct amount of C per year depending on its current land-use (*6*), its prior land-use (*7*), and its climatic region (*8*). Changes in road networks and the spatial arrangements of destinations result in a feedback between land-use and travel patterns that produces more or less greenhouse gas emissions (*9*, *10*, *5*). Specifically, population size and density are the key factors relating to urban growth and structure that affect travel demand and fossil fuel emissions (*9*). Therefore, the two main factors that affect C sequestration are: 1) removing C sinks; and 2) adding new emissions.

Energy use by the transportation sector in Organisation for Economic Co-operation and Development (OECD) countries has been steadily increasing by slightly less than 1% per year since 1973, and the rate of increase is not expected to slow, given the ever-growing vehicle fleet (*11*). The transportation sector accounts for 20-30% of the final energy consumed by OECD countries, of which approximately 70% is used by personal vehicles (*11*). Globally, personal transportation accounts for about 66% of CO_2 emissions (*11*). In addition, development conditions such as "urban sprawl", defined as "dispersed development outside compact urban and village centers, along highways, and in rural countrysides" (*12*) and characterized by a larger consumption of land per person together with a de-centralization of city centers, generally result in more emissions (*9*). This type of development typically also results in longer commuting distances and increased reliability on personal vehicles, which in turn promotes more vehicles per capita and higher land-use change rates (*9*).

Although transportation and land-use change are critical and interlinked components of the C budget in human-dominated landscapes, almost all urban land-use models lack a calculation of the effects of urban development on C sources and sinks from biomass and soil (*9*). For example, the Clean Air and Climate Protection (CACP) software from ICLEI (www.icleiusa.org/action-center/tools/cacp-software) takes into account greenhouse gas emissions from fuel use, electricity, and waste disposal, but not land-use change (*13*). We are unaware of any existing tools quantify the comprehensive effect of land-use change on the C flux from the natural environment and transportation in urban systems. Furthermore, Vermont is part of the Regional Greenhouse Gas Initiative (RGGI), which is a market-based system that will attempt to reduce CO_2 emissions by 10% by 2018. This, along with increased pressure on all sectors, is motivation for regional planners to attempt to accommodate their decisions to reduce the impact of their decisions on C emissions.

Objectives

This work focuses on the development of a method for quantifying some of the major effects of land-use change on the C emissions from the integrated transportation and land-use system. By integrating land cover data with traffic demand data, a tool was developed that estimates C sequestration and emissions associated with vegetation and transportation for a particular landscape configuration. This Vermont Integrated Land-use and Transportation Carbon Estimator (VILTCE) is an accounting tool that can be used to assess some of the impacts of various development scenarios on the land-use and transportation-related C footprint for a region, and can thus be used in the planning process.

The geographical analysis adds to the understanding of transportation emissions by spatially illustrating the ways in which certain developments not only decrease the amount of C storage and sequestration by vegetation and soils, but also increase commuting and, therefore, C emissions from transportation. The VILTCE is an applied tool; it is an ArcGIS toolbar available free of charge for Metropolitan Planning Organizations (MPOs) and regional planners to download from the University of Vermont's Transportation Research Center (www.uvm.edu/~transctr/). This paper describes the development of the VILTCE and provides the results of an application of the VILTCE to Chittenden County, Vermont.

Case Study

Chittenden County is the most populated county in Vermont with 152,782 people (25% of the state's population) (*14*). Burlington, the most populated city in Vermont, has about a quarter of Chittenden County's population (*14*). In 2001, Chittenden County's land cover (not including water) was approximately 139,400 ha, of which 60.98% was forestland (*15*). Following deforestation in the 19th century that resulted from intensive harvesting and agriculture practices, forestland area in Vermont has been increasing over the last 70 years (*16*). Cropland was the second most abundant land cover, occupying 22.08% of the total land in the county (*15*).

Historically, Vermont has been a net C sink, meaning that its soils and biomass take up more C than is released from human activities (*17*). In 2005, transportation emissions from Vermont were 4.02 $MtCO_2$ equivalent ($MtCO_2e$), accounting for approximately 44% of the state's greenhouse gas emissions (*17*). On the other hand, forestry and land-use resulted in a net sink of 9.70 $MtCO_2e$ in 2005 (*17*). In the same year, Vermont's total emissions were only 0.13% of the entire United States' greenhouse gas emissions (*17*) even though the total population of the state was approximately 0.21% of the country's total population (*14*). Furthermore, Vermont's emissions appear to be increasing at a slower rate compared to the rest of the nation (*17*). However, within Vermont, Chittenden County is a net source of emissions (*18*); the total emissions from the county for transportation as well as residential/commercial/industrial petroleum and electricity use have been previously estimated at approximately 418,000 Mg C yr^{-1} while the amount sequestered by biomass and soils is only 241,000 Mg C yr^{-1} (*18*). This comparison of the relatively highly populated county to the remainder of the state underlines the importance of conducting C budgets at various spatial scales.

This paper describes the development of the VILTCE using data specific to Chittenden County. Datasets were chosen to be as widely-applicable as possible and the VILTCE was designed to be expanded to other regions. It was constructed so that it can be applied to any region of any size, for which comparable data are available. This would require parameterization of the existing Tables using readily available data for each additional climate zone, land use type, and forest type/stand age combination. For large-scale data requirements such as national land cover and forest C sequestration rates, additional data for new regions can be acquired from the same databases as used for Chittenden County. More region-specific C sequestration rates for non-forested land can be acquired from the literature (such as Pouyat *et al.* (*8*)).

METHODS

Part I: Land-use Carbon Sequestration

The Multi-Resolution Land Characteristics Consortium (*15*) National Land Cover Database (NLCD; http://www.mrlc.gov/nlcd_multizone_map.php) was used to measure areas of specific land uses in the county. This database was chosen because it is a publicly accessible source of land cover data with comprehensive coverage for all of the United States. The NLCD data for the full United States are available in raster format, which was converted to vector format for use in the VILTCE. In order to quantify C fluxes (i.e. overall change) using standard methodology, the 36 land categories from the 2001 NLCD data were grouped to the land cover classifications used for estimating C fluxes created by the Intergovernmental Panel on Climate Change (IPCC) and used for national-scale reporting (Table 1). In order to obtain the amount of pervious (urban green space) and impervious (paved) land cover from the 4 NLCD categories of 'Developed' land, the middle of the range of impervious cover was taken and the rest was assumed to be pervious surface. The NLCD 'Developed' land categories are: 'Open Space' (<20% impervious surface); 'Low Intensity' (20-49% impervious surface); 'Medium Intensity' (50-79% impervious surface); and 'High Intensity' (80-100% impervious surface) (*15*). For example, to calculate the amount of impervious and pervious surface using the 'Low Intensity' category, it was assumed that, on average, 35% is impervious and the remainder, 65%, is pervious surface.

TABLE 1 The land classifications in this study from the National Land Cover Database (NLCD; *15*) land classifications grouped into Intergovernmental Panel on Climate Change (IPCC) land classes

NLCD 2001 Land Classification	IPCC Land Types	
10. Water	Not used	
11. Open Water		
12. Perennial Ice/Snow		
20. Developed	Settlements - Impervious Surface	Settlements - Pervious Surface
21. Developed, Open Space	10%	90%
22. Developed, Low Intensity	35%	65%
23. Developed, Medium Intensity	65%	35%
24. Developed, High Intensity	90%	10%
30. Barren	Other Land	

31. Barren Land	
32. Unconsolidated Shore	
40. Forested Land	By Age and Species Group (See Table 3)
41. Deciduous Forest	
42. Evergreen Forest	
43. Mixed Forest	
50. Shrubland	Grassland
51. Dwarf Scrub	
52. Shrub/Scrub	
70. Herbaceous Upland	Grassland
71. Grassland/Herbaceous	
72. Sedge/Herbaceous	
73. Lichens	
74. Moss	
80. Planted/Cultivated	Cropland
81. Pasture/Hay	
82. Cultivated Crops	
90. Woody Wetlands	Wetlands (Woody Wetlands)
91. Palustrine Forested Wetland	
92. Palustrine Scrub/Shrub Wetland	
93. Estuarine Forested Wetland	
94. Estuarine Scrub/Shrub Wetland	
95. Emergent Herbaceous Wetlands	Wetlands (Emergent Herbaceous Wetlands)
96. Palustrine Emergent Wetland (Persistent)	
97. Estuarine Emergent Wetland	
98. Palustrine Aquatic Bed	
99. Estuarine Aquatic Bed	

The C sequestration rates per unit land area were calculated as the sum of two distinct pools: biomass C (all aboveground plant material) and soil C (all belowground root plant matter and other organic material; *3*). For all land use types except forestland, C sequestration rates from the IPCC's Emission Factor Database (*19*, 2006; www.ipcc-nggip.iges.or.jp/EFDB/main.php) and other literature were used to estimate biomass and soil C sequestration rates (Table 2). The IPCC created a series of C accounting methodology reports as well as the EFDB (*19*) for comparison and standardization between geographic/climatic regions. Although the soil and biomass sequestration rates in Table 2 were specifically assembled for Chittenden County, Vermont, the values may also be more generally applicable to similar climates and regions (note the reference and region of study from which the values were taken).

TABLE 2 Relative and percentage land cover (*15*), soil and biomass carbon sequestration rates by land cover type used for this study for calculation of carbon sequestration in

Chittenden County, Vermont. See notes for the reference where the value was obtained as well as the location of the original study

Land Type	Area (ha)	% Area	Soil Sequestration (Mg C ha^{-1} yr^{-1})	Biomass Sequestration (Mg C ha^{-1} yr^{-1})
Settlements - impervious surface	5,114.0	3.7	0.0[a]	0.0[a]
Settlements - pervious surface	10,771.5	7.7	1.9[b]	4.3[b]
Other Land	205.7	0.2	0.0[c]	0.0[c]
Forestland	85,001.9	61.0	0.0[d]	1.0[d]
Grassland	2,564.2	1.8	0.2[e]	2.0[f]
Cropland	30,780.3	22.1	0.0[g]	0.0[g]
Woody wetlands	4,087.5	2.9	0.5[h]	5.3[i]
Emergent herbaceous wetlands	869.9	0.6	0.5[h]	31.7[j]
Total	**139,395.0**	**100.0**	**23,460.9**	**184,004.4**

NOTES:
[a]It is assumed that paved surface has no biomass on it and that the soil it not sequestering any C
[b]Average of two plots; Chicago, IL (*20*)
[c]Other Land' category in Chittenden County was all barren land, which is defined as "Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life" (*15*)
[d]Weighted average by stand type and age (see Table 3); Chittenden County, Vermont
[e]Worldwide cool temperate moist forests (*3*)
[f]Values from abandoned croplands; Rhode Island (*21*)
[g]Croplands are assumed to have constant turnover and, therefore, no annual accumulation of biomass or uptake of C in the soils
[h]Northeast United States (*22*)
[i]Total Net Primary Productivity NPP); Flax Pond, Long Island, New York, United States (*23*)
[j]Average of above and belowground biomass; Sussex and New Castle Counties, Delaware, United States (*24*)

Supplementary forest level data that include forest-specific regional estimates of C stocks and sequestration rates were incorporated into the tool to account for the large variability in forest C fluxes. Forest C sequestration rates depend on geographic region, forest type, previous land use, management practices, and age (*25*). In order to capture the major sources of this variability, estimates from the USDA Forest Service's Carbon On Line Estimator COLE-EZ tool (*26*; http://ncasi.uml.edu/1605b/COLE-EZ.shtml) was integrated into the VILTCE to provide biomass and soil C sequestration rates by forest type and age. For the Chittenden County application, data were acquired from the most recent (2006) Forest Inventory and Analysis survey (FIA; *27*; http://www.ncrs2.fs.fed.us/4801/fiadb/fim30/wcfim30.asp) (Table 3). This database was chosen because it is a readily available source of data for forests in all of the United States.

TABLE 3 Biomass and soil sequestration rates of forest types in Chittenden County, Vermont, based on data from Carbon On Line Estimator (COLE-EZ; *26*) for reforested land; Forest Inventory and Analysis (*27*) data for forestland area, including average stand age, by forest type

Forest Type	Area (ha)	Average Stand Age	Biomass Sequestration (Mg C ha^{-1} yr^{-1})	Soil Sequestration (Mg C ha^{-1} yr^{-1})
Eastern white pine	2,627	78	0.6	0.0
White pine/hemlock	4,364	98	0.4	0.0
Sugarberry/hack-berry/elm/green ash	3,273	58	0.1	0.0
Red maple/lowland	1,862	98	0.0	0.0
Cottonwood/willow	4,068	46	0.3	0.0
Sugar maple/beech/yellow birch	54,067	46	1.3	0.0
Cherry/ash/yellow-poplar	3,161	33	1.9	0.0
Red maple/upland	12,001	74	0.4	0.0
Paper birch	1,841	33	0.5	0.0
Total/Average	**87,263**	**54**	**1.0**	**0.0**

COLE-EZ (*26*) provided C sequestration data by stand age for either newly-established forests (afforestation) or for forests undergoing reforestation. Because forests in Vermont are, on the whole, in the recovery phase following the turn-of-the-century deforestation event, the "reforestation" values were used. The C sequestration rates were calculated for the current average stand age (overall weighted average = 54) in Chittenden County (Table 3). For reforested land, COLE-EZ (*26*) reports that soil C sequestration rates are 0 Mg C ha^{-1} yr^{-1}; for afforested land (i.e. for land where forests have not previously been present), soil C sequestration rates from COLE-EZ are greater than zero.

The resolution available for FIA (*27*) forest types is finer and more detailed than the resolution available for the forest cover types available from NLCD. Because the land-use datasets implemented in the VILTCE were designed for the broadest possible application rather than for detailed information on specific forest types, forests in the VILTCE are categorized following the NLCD scheme as "deciduous", "evergreen", or "mixed". In order to represent the forest land base as accurately as possible, we calculated a weighted county-level average, accounting for the area in each of the FIA (*27*) forest types for the biomass C sequestration rate (1.0 Mg C ha^{-1}, yr^{-1} for the current average stand age).

Part II: Transportation Emissions: The Four Step Model and Traffic Analysis Zones

The VILTCE aims to utilize data and models that the target user, Metropolitan Planning Organizations (MPOs), would have readily available. It was assumed that MPOs in the United States will have access to a four-step transportation demand model, which typically estimates the number of trips by model period (day, peak/offpeak, hour, etc.), VMT, average length of trips, the destinations of these trips, mode of transportation, and which highway or transit network is likely to be used (*28*). In the mode choice step, calculations are used to compare the attractiveness of each mode of travel (such as automobile, public transit, etc.) to determine how likely each mode is to be used for a particular trip (*29*). The modeling typically occurs at the Traffic Analysis Zone (TAZ), an area defined by socio-economic, demographic, and land-use characteristics (*30*). In the VILTCE, the emissions from the transportation sector are calculated both network-wide and per link in order not only to give overall emissions for the region of interest, but also to indicate which links may be contributing the most emissions (due to high volumes or congestion issues).

The travel demand model outputs, such as total VMT, can be used to calculate the corresponding emissions from each modeled vehicle class type. Several vehicle emissions models have already been created including: the commonly used Environmental Protection Agency (EPA)'s MOBILE6 Vehicle Emission Modeling Software (www.epa.gov/oms/m6.htm); a replacement for MOBILE6, the MOtor Vehicle Emission Simulator (MOVES; www.epa.gov/oms/ngm.htm); and California Environmental Protection Agency's EMission FACtors (EMFAC; www.arb.ca.gov/msei/onroad/latest_version.htm) model. A simplified version of those models was used in this work which leverages speed-based emission rates for three vehicle classes.

The VILTCE considers auto, medium and heavy truck volumes on each road link for each hour of the day, although an hourly average is calculated if the user only has daily data. Since fuel economy is dependent on vehicle speed, emission rates (in grams/mile) were applied for each operating speed (integers from 1 to 80 mph) to estimate total CO_2 emissions in the VILTCE. The transportation emissions are presented as Mg CO_2 per road link in the network.

The total C sequestration by biomass and soil is also presented as overall CO_2 in the final output in order to have a final value for the total CO_2 flux in the region of interest. A summary of the inputs and outputs for the VILTCE are illustrated in Figure 1.

These rates by operating speeds are obviously most useful where four-step models estimate congested and uncongested conditions such as a four-period model. The total C sequestration by biomass and soil is also presented as overall CO_2 in the final output in order to have a final value for the total CO_2 flux in the region of interest. A summary of the inputs and outputs for the VILTCE are illustrated in Figure 1.

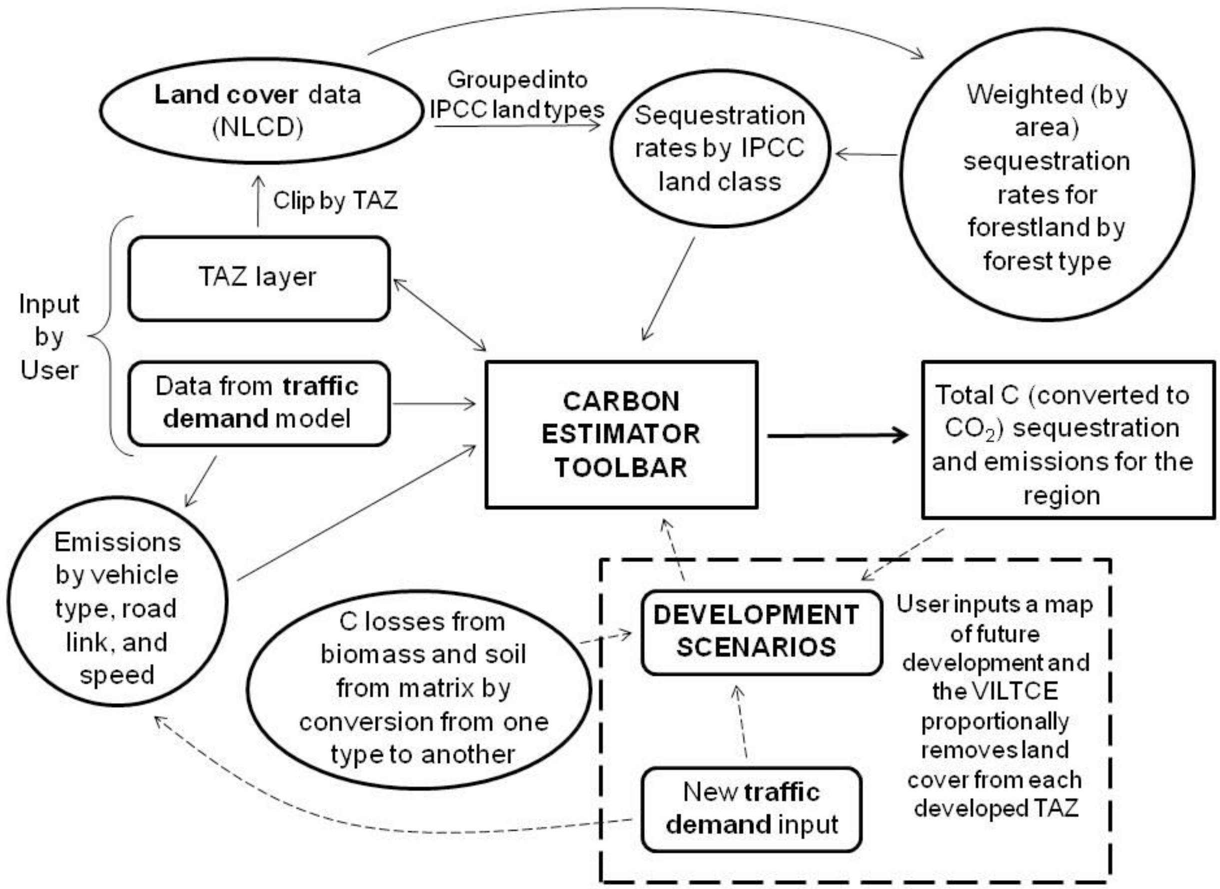

FIGURE 1 Summary of Vermont Integrated Land-use and Transportation Carbon Estimator (VILTCE) outputs and inputs. The circles represent data that will be integrated into the VILTCE, the rounded rectangles represent input required from the user, the center rectangle is the VILTCE itself, and the rectangle to the right of it is the output from the VILTCE. Solid arrows correspond to flows of information to/from the VILTCE while the dashed arrows signify flow of information for potential development scenarios (see Future Work section in Conclusions).

RESULTS

Carbon Sequestration

Under current conditions, Chittenden County's soils sequester approximately 23,500 Mg C yr^{-1} while its biomass takes up 184,000 Mg C yr^{-1}. This amounts to a total annual sequestration of 207,500 Mg C yr^{-1} or 760,200 Mg CO_2 yr^{-1}.

The largest annual C sequestration rate in Chittenden County is in forestland (40% of total biomass and soil sequestration) simply because forestland is the majority (61%) of the land cover in the county (Table 2). COLE-EZ (*23*) estimates a sequestration rate of 0 Mg C ha^{-1} yr^{-1} for reforested land, so there is no annual uptake of C by forest soils in Chittenden County. The pervious surfaces in urban areas also sequester a large amount of C in biomass (22% of total sequestration) and had the highest soil sequestration (87% of total soil and 10% of total biomass and soil sequestration). Woody and emergent herbaceous wetlands account for 11% and 13%, respectively, of total annual sequestration in the county (Table 2).

The largest percentage of land cover in Chittenden County is forestland, but pervious surfaces in urban areas had the highest soil sequestration rate, 1.9 Mg C ha^{-1} yr^{-1}, while emergent herbaceous wetlands had the highest biomass sequestration rate, 31.7 Mg C ha^{-1} yr^{-1} (Table 2). Figure 2 illustrates the NLCD land cover types by TAZ (Figure 2A) and the total C by TAZ in Chittenden County (Figure 2B). Figure 2B illustrates that the highest occurring in the northern part of the county where wetlands exist and that freshwater does not sequester any C.

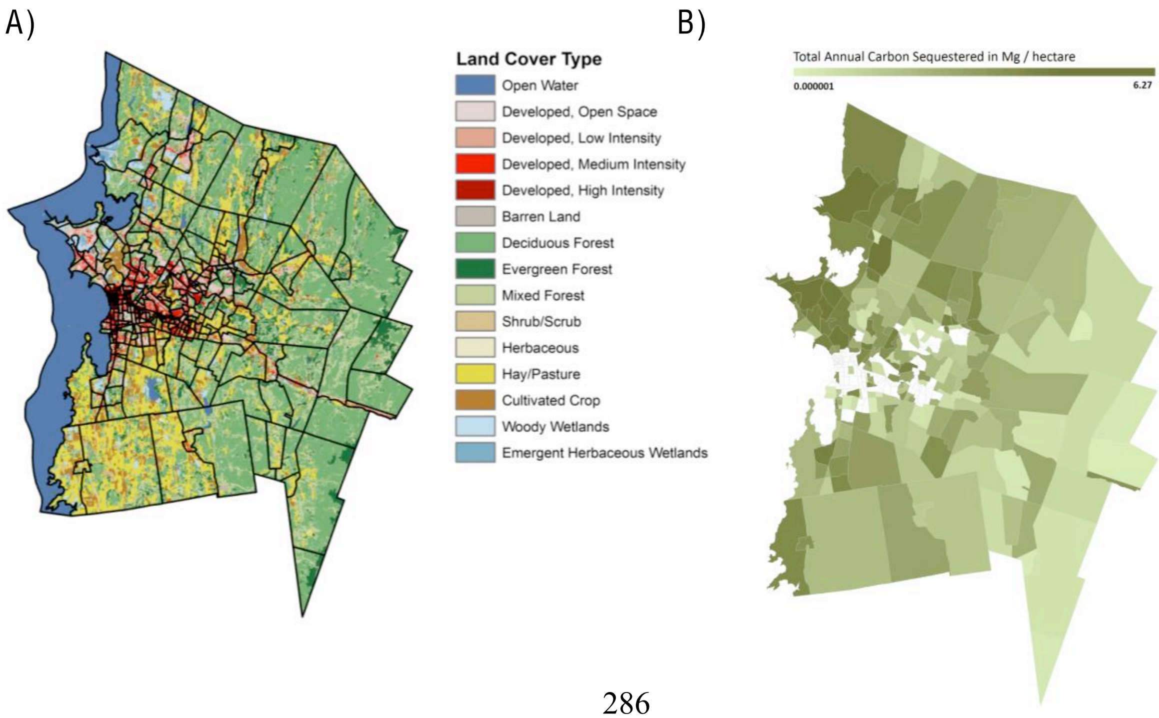

FIGURE 2 A) The NLCD land cover type by Traffic Analysis Zone (TAZ) and B) the total annual soil and biomass carbon by TAZ area (Mg C yr^{-1} ha^{-1}) for each TAZ in Chittenden County, Vermont. TAZs with 0 Mg C yr^{-1} ha^{-1} are shown in white

Emissions from Transportation

The total transportation emissions for Chittenden County, Vermont were estimated by the VILTCE to equal approximately 797,900 Mg CO_2 yr^{-1} (217,800 Mg C yr^{-1}). The road with the highest emissions in the county was the main interstate highway going through the county: I-89. Sections of I-89 had higher emissions than others. The road link with the highest emissions was the section of I-89 just past Williston, Vermont in both southbound and northbound directions (Figure 3), with over 26,000 Mg CO_2 being emitted per year for each direction.

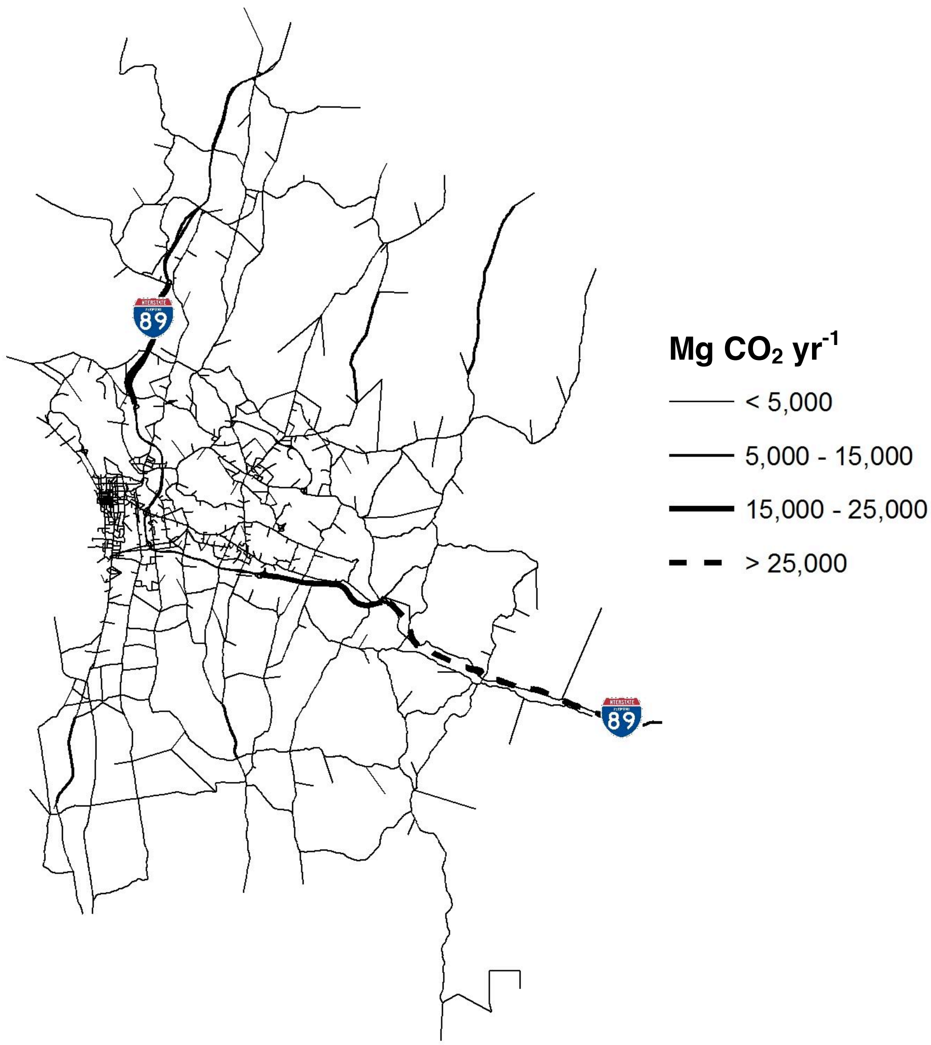

FIGURE 3 Transportation emissions in Mg CO_2 yr^{-1} for Chittenden County, Vermont by road link.

The four other links with the highest emission rates (above 14,000 Mg CO_2 yr^{-1}) included the section of I-89 near Colchester, Vermont just north of Burlington, Vermont in both northbound and southbound directions as well as the both directions of the section of I-89 leading up to the highest emitting section of I-89, which goes east through South Burlington, Vermont toward Williston, Vermont (Figure 3).

Finally, if the total transportation emissions in Chittenden County are approximately 797,900 Mg CO_2 yr^{-1} and the total sequestration in the county is 760,200 Mg CO_2 yr^{-1}, the overall C balance of the county is a net emission of 37,700 Mg CO_2 yr^{-1} (10,300 Mg C yr^{-1}).

DISCUSSION

With rising atmospheric CO_2 concentrations and warming occurring much faster than previously anticipated (*31*), there is increasing pressure on governments, companies, and individuals to calculate and regulate their emissions. Carbon 'budgets' have already been completed on global (*4*, *32*), national (*33*), and regional (*34*) scales. Those studies differ not only in their spatial scale, but also in their temporal scale, level of detail, and methods (see Houghton (*35*) for discussion). The robustness of any C budget depends strongly on the accounting methods used as well as the quality of the input data. The same is true for a carbon calculator such as the one presented here; therefore, it can be assumed that the largest uncertainties in the results from the model are due to the quality of the data.

Model Assumptions

In order to have widely applicable tool that can be expanded to other regions in the United States, databases such as the NLCD were used instead of more regional fine-scale data. In order to try to account for some of the short-comings of the data, supplementary forest level data were incorporated as well as more regionally-based C stocks and sequestration rates. Although those are currently only applicable to the Vermont area, look-up tables may easily be created following the templates given here in Tables 2 and 3 for additional regions. Also, in order to have broad applicability, so that the VILTCE can be expanded to other regions of the United States in the future, the NLCD was chosen because it has full coverage of the country.

The NLCD data may be a source of uncertainty because the land cover is from 2001 and is likely to have changed since. Although the creators of the NLCD, the MRLC, are working on a 2006 version, that is already 3 years out of date at the time of this publication. The rate of land-use change varies by region; Houghton identified the rate of land-use change and the effects of human activity on C stocks in ecosystems as the two main sources of uncertainty in C flux estimates (*35*).

In addition, because the NLCD does not classify forestland by species group as FIA (*24*) does, the FIA (*24*) data were used to supplement forest stand age and forest type in Chittenden County. The biomass in forestland in Chittenden County had the highest uptake of C with a weighted average of 136.6 Mg C ha^{-1}, but this ranges from 55.9 Mg C ha^{-1} for paper birch to 177.5 Mg C ha^{-1} for white pine/hemlock (Table 3). Therefore, the pre-existing forest type prior to land clearing for development will have considerably different impacts on the overall C budget in studies that involve comparing the C footprint of various development scenarios.

It can be presumed that the VILTCE described in this study does not include all of the possible sources and sinks of C and is not a full C accounting tool. It does not include emissions from electricity and heating, for instance, which are likely to be a large component of the emissions in Chittenden County. In 2005, transportation accounted for 44% of the state's greenhouse gas emissions while fuel use by the residential, commercial, and industrial sectors accounted for about 30% of the total greenhouse gas emissions in Vermont (*17*). Chittenden County possesses 25% of the state's population and is therefore likely to be a large source of those emissions. Based on the estimate of greenhouse gas emissions calculations from fuel use in Vermont and Quigley's (*18*) estimate of 53% in Chittenden county, it can be assumed that the total emissions from Chittenden County estimated in this study (from transportation alone) are less than half of the actual anthropogenic emissions. Incorporating methods that estimate greenhouse gas emissions from energy use is the next logical step in expanding the employability and value of the VILTCE. In the meantime, the goal of this research was to integrate transportation and land-use change into a tool that would calculate the change in C from various development scenarios.

Finally, the traffic demand model is another source of uncertainty. As with the C stock and sequestration rates, the level of detail and the quality of the input data impact the overall results from the VILTCE. For example, the four-step transportation demand model has been widely criticized for not having robust assumptions and for being too simplistic (*29*, *28*). The largest criticism is that the four-step process does not take human behavior into account and only models single trips; however, people often try to minimize their travel time and distance by running multiple errands on one outing (*29*). The current approach simplifies this kind of "trip chaining" (*29*) and is likely to result in imprecise data on travel demand. The reasons for mode choice and other travel behavior decisions cannot be taken into account in the four-step process because they are too complex to model (*28*). Travel demand models often use cars to represent distance, but the time and distance between destinations is different depending on the mode (*29*). Furthermore, the response of individuals to incentives and other policy changes are difficult to represent in a simple four-step model (*28*). However, CO_2 emissions from transportation are very robust to the methodology chosen and our results are unlikely to be attributable to the methods used.

The final uncertainties in the output from the model is due to the freedom given to the user to adjust the number of hectares per housing unit and input scenarios of future growth. MPOs model 30 years into the future, which results in many assumptions about the growth in population, housing units, and the number of jobs in the region. Although those options result in even more assumptions, they also give the user more freedom to compare the C footprint of various scenarios of development and may be a major reason why the VILTCE is attractive to MPOs.

CONCLUSIONS

This paper presented the methods and data used in the creation of the Vermont Integrated Land-use and Transportation Carbon Estimator (VILTCE); an ArcGIS toolbar that calculates the overall spatial C balance from land-use and transportation for a particular region. Chittenden County, Vermont, was used as a case study to present values and the methods used for the calculations. National databases were used for land cover in order for the possibility of expansion to other regions in the country outside of the Northeast. Supplemental forest stand and stand age data were used in order to get more accurate assessment of the C in forestland. Regional values were used where possible for the C stock and sequestration rates. Those were taken from existing databases and published literature and may be replicated for other regions with corresponding values for those climates. For transportation emissions, the user will input traffic demand data from a simple four-step transportation model that all Metropolitan Planning Organizations (MPOs) would have available.

The purpose of this work was not to create a comprehensive C accounting tool, but to construct a functional tool that regional planners could use to assess the greenhouse gas implications of changing the transportation and/or land-use change patterns. The VILTCE does not attempt to include all the possible emissions from all the land-use types and does not include emissions from energy use or industrial processes. Despite that limitation, the VILTCE will be able to inform the user of potential effects of alternative development scenario by comparing their corresponding C footprint.

Future Work: Development Scenarios

Future work should focus on incorporating other significant emissions such as those mentioned here (i.e. electricity and heating) as well as expanding the C sequestration rates values to other regions of the United States. A look-up table such as Table 2 can be created for other regions using literature and database values such as those used here. A major focus of our future work will include comparing the C footprint of various development scenarios for Chittenden County, Vermont, and expanding the development scenarios functions in the VILTCE.

Future scenarios may be modeled once the current C stocks and sequestration rates of each land-use type, as well as the CO_2 emissions from transportation, have been computed. The C biomass and soil stocks for Chittenden County have already been calculated based on C densities for each IPCC land cover type from literature and IPCC EFDB (*16*) values and will be integrated into the VILTCE. Similar look-up tables can be created for other regions in the same way that sequestration look-up tables are created for other regions. The user will be able to specify future land-use change by inputting a TAZ GIS layer, which would contain the number of future housing units and total jobs. The VILTCE will then allow the user to specify the amount of land that is consumed per new housing unit/employment in order to investigate the effects on C emissions and sequestration from potential development. The user will also be required to input a new traffic demand layer, which they should have already run using their four-step traffic demand model.

However, MPOs may not know exactly where in a specific TAZ those housing units or jobs may be located; therefore, the VILTCE will remove a proportional amount of each land cover type in that TAZ depending on the area of each land cover per TAZ. For example, if a TAZ is 80% forest, 10% cropland, and 10% grassland, then a 1.0 hectare development will consume 0.8 ha of forest, 0.1 ha of cropland, and 0.1 ha of grassland. The VILTCE will then determine the depletion in C stocks from the removal of biomass, the change in soil C, as well as the amount of C emitted/stored resulting from the transition itself. This “instantaneous” change in C from the transition itself is in the form of a matrix that has already been created for Chittenden County, Vermont, and may be created for other regions as well. The development of the development scenario functions in the VILTCE will be discussed in a future publication. The same biomass and soil C sequestration rates will be used for post-transition as the ones used to calculate the current conditions (i.e. Table 2).

Forest biomass and soil C stocks will be calculated in the same way that C sequestration rates for forests were calculated based on area of stand age and forest type, using USDA’s COLE

(*36*; http://ncasi.uml.edu/COLE/cole.html). In order to represent the forest land base as accurately as possible, we calculated a weighted county-level average, accounting for the area in each of the FIA (*24*) forest types for the biomass and soil C stocks (136.6 and 75.1 Mg C ha^{-1}, respectively, for the current average stand age). In the future, the vector format of downloaded NLCD files will be made available for all MPOs in the Northeast, since the C sequestration rates provided here can be used for this entire region.

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