Integrated Land-Use, Transportation and Environmental Modeling

The Vermont Integrated Land-Use and Transportation Carbon Estimator

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Prepared by:
Jim Sullivan*
Anna Mika*
Joe Fraker*
David Hershey**
Kevin Hathaway**
Stephen Lawe**

*University of Vermont
**Resource Systems Group, Inc.

Transportation Research Center
Farrell Hall
210 Colchester Avenue
Burlington, VT 05405

Phone: (802) 656-1312
Website: www.uvm.edu/transportationcenter

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1 Introduction

The Vermont Integrated Land-Use and Transportation Carbon Estimator (VILTCE) project is part of a larger effort to develop environmental metrics related to travel, and to integrate these tools into a travel model under UVM TRC Signature Project No. 1B. The signature project teams intended to develop measures normally not considered in transportation models. By including these environmental metrics, travel models can be used for a wider range of applications and can consider important impacts resulting from a project or policy that might otherwise be overlooked. The signature project includes the following tasks:

1.) Development of new model-output environmental metrics to quantify net-carbon (C), storm water impacts, particulate impacts, robustness, and air pollution

2.) Integration of new output metrics into an advanced transportation model

3.) Evaluation of environmental metrics under alternative policy, planning, and investment scenarios

4.) Testing of the sensitivity of the model-output metrics to the level of model complexity

Work completed under Tasks 1 and 3 of the signature project is included in this report, specifically related to a tool for quantifying the net C resulting from transportation emissions and land-cover sequestration. Another overall long-term project goal has been to build a tool that uses publicly available data to calculate relative carbon sources/sinks for alternative transportation and land use scenarios for use in regions nation-wide. Additional steps taken toward that goal are also described in this report.

This work focuses on a method for quantifying some of the major effects of land-use change on C emissions from the integrated transportation and land-use system. By integrating land-cover data with traffic data, a tool was developed that estimates C sequestration and emissions associated with soil, biomass and transportation for a particular landscape configuration. This report describes the VILTCE method, the tool developed for applications in Vermont, and provides the results of an application to Chittenden County, Vermont, for the "baseline" case in 2005, for the baseline land-use and road network in 2030, for the land-use / road-network scenario developed through a stakeholder workshop for 2030, and for the scenario documented in the County's Metropolitan Transportation Plan (MTP) (CCMPO, 2005). It also describes the appropriate modifications that can be made to the VILTCE rate coefficients that will allow the method to be used for any region in the United States.

Section 2 of this report describes the sequestration rate coefficients for the Vermont application. Section 3 describes the calculation methods used by the VILTCE. Section 4 describes the development and use of the tool for applying the VILTCE in the ArcGIS platform. Section 5 contains the results of the application of the tool to the baseline scenario for 2005 for Chittenden County, along with the results of the application of the VILTCE method to current and future scenarios for Chittenden

County. Section 6 describes the modifications that can be made to the method to make it applicable nation-wide.

2 Rate Coefficients for the VILTCE

The first step in the development of the VILTCE was the investigation and documentation of sequestration-rate coefficients, in megagrams of carbon per hectare per year (Mg C/ha/yr) for the land-use types encountered in Vermont. Two land-use categorizations were used:

- National Land-Cover Database (Homer et. al., 2007)

- Inter-governmental Panel on Climate Change (IPCC, 2006)

The NLCD was used because it is readily available for the entire United States, and can be easily accessed and downloaded for any region at mrlc.gov. Cross-classification with the IPCC land uses was necessary because most of the resources for C stocks and C sequestration values use this classification. Carbon stocks are the quantity of carbon contained in any system which has the capacity to accumulate or release carbon, primarily in soil and biomass. Carbon sequestration rates are the rates at which carbon "sinks" remove carbon dioxide from the atmosphere. The C stocks and rate coefficients developed for Vermont are documented by Mika et. al. (2010) and are summarized here in Table 1.

Table 1 Carbon Stocks and Sequestration Rates in the VILTCE

	2001 NLCD Land-Cover Type	Assigned 2006 IPCC Category	% Pervious Surface	Stocks (Mg C / ha)		Sequestration Rates (Mg C/ha/yr)	
				Soil	Bio mass	Soil	Biomass
21	Developed, open space	Settlement - Pervious	90	33	0	1.9	4.3
22	Developed, low intensity		65				
23	Developed, medium intensity		35				
24	Developed, high intensity		10				
41	Deciduous forest	Forestland	100	75.1	136.6	0.0[1]	1.0[1]
42	Evergreen forest		100				
43	Mixed forest		100				
52	Scrub/shrub	Grassland	100	81.5	4.4	0.2	1.9
71	Grassland/herbaceous		100				
81	Pasture/hay	Cropland	100	70	0	0	0
82	Cultivated crops		100				
90	Woody wetlands	Wetlands	100	87	99	0.5	5.3
95	Emergent herbaceous wetlands		100		13.8		31.7
11	Open water	Other	100			0	0
12	Perennial Ice/Snow		100				
31	Barren Land		100				

Notes:
1. Weighted average by area and age for all forest types in Chittenden County.

Some of these values, like those for forestland, are specific to Chittenden County. Others would be suitable for any region in Vermont or the northeast United States. The fraction of pervious surface corresponding to each of the four "Developed" NLCD land-cover types are the mid-points of the ranges provided by the NLCD (Homer et. al., 2007).

3 Calculation Methods for the VILTCE

Separate calculation methods were developed for the VILTCE for land-cover carbon sequestration, land-cover carbon offset emissions, and transportation-related carbon emissions.

3.1 Land-Cover Sequestration Method

Carbon sequestration calculations are distinct for baseline-scenario and future-scenario calculations. The calculation method for carbon sequestration for a scenario is simply the product of sequestration rates to known, existing land-cover areas from the National Land Cover Database (Homer et. al., 2007) for the year of analysis. The "Raster to Polygon" tool in the "From Raster" set of tools in the "Conversion Tools" toolbox in ArcToolbox can be used to convert the raster NLCD GIS to vector format. The16 NLCD classes can then be assigned to IPCC cover types, as shown in Table 1. To align the results of the carbon sequestration calculation with the transportation emissions calculation, a user-input GIS layer of traffic-analysis zones (TAZs) as polygons is used to clip the vector-format NLCD and calculate the area of each land-cover type in Table 1 for each TAZ. These areas are mapped from NLCD land-cover types to categories from the IPCC. For "developed" land, only the fraction of pervious area noted in Table 1 is included in the calculation, since the impervious portion is not assumed to sequester any carbon. The result of this calculation is an overall sequestration total for the baseline-year, which is can be converted to a carbon-dioxide equivalent (CDE) using a factor of 3.66 Mg of CO_2 per Mg of C.

The forecast-scenario method must first predict land-cover change based upon changes in modeled demographics (housing and employment) by TAZ before calculating the sequestration for the forecast-year of the analysis. To accomplish this prediction, the projected growth in housing and employment by TAZ is used to generate a forecast-year land-cover. Additional households or jobs in the forecast year within a TAZ are assumed to add developed area to the baseline level, and create a corresponding reduction of the natural land-cover types or the pervious fraction of the existing developed area. The extent to which new jobs and households add developed area to the baseline level is moderated by assumed residential and employment densities. If the maximum density of an existing developed land-cover has not been reached, new jobs and households are added to it without the addition of newly developed land. The framework for how these land-cover transitions were calculated for each TAZ are illustrated in Figure 1.

Original   Scenario
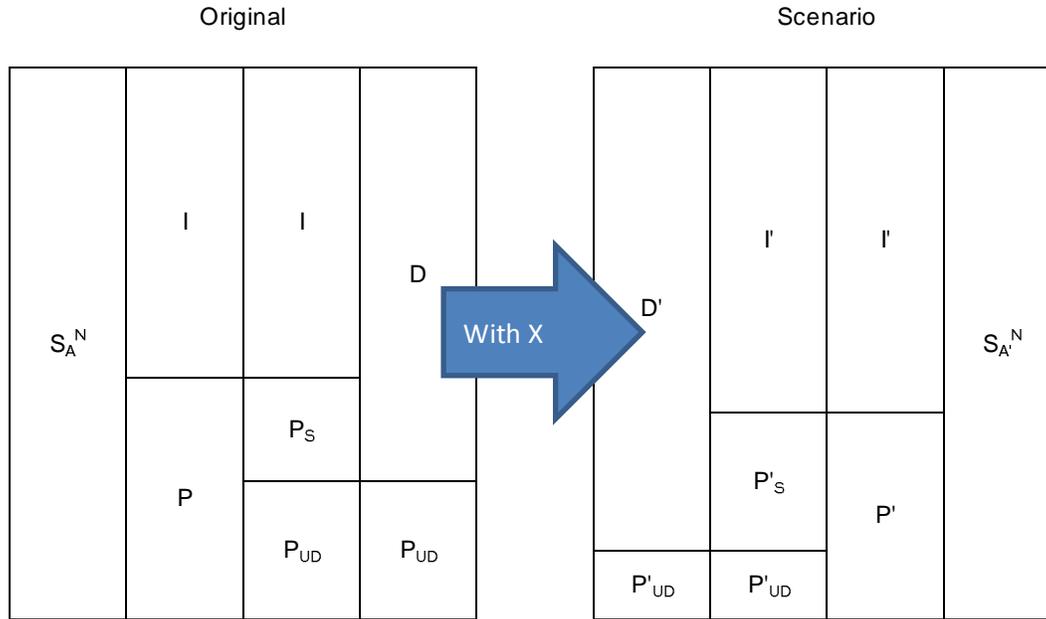
Figure 1 Land Cover Transition Framework

In the figure, the original development intensity (10%, 35%, 65%, or 90% pervious), A, for the area settled at this intensity in TAZ N (S_A^N) is assumed to be the proportion of pervious land, P, to total settled land:

A = P / (I+P)

Where I is the existing area of impervious land.

It is also assumed that the existing developed land, D, consists of impervious land, I, and pervious settlement P_S. However, the settlement also consists of pervious land which is undeveloped, and will remain so as a "reserve" of pervious undeveloped land (P_{UD}) land which cannot be reduced beyond the maximum development intensity for that TAZ, A^N_{max}. The maximum development intensity for each TAZ is assumed to be its current maximum developed intensity.

As land cover changes during a transition period to the scenario-year, the following governing equations were used to calculate the newly developed land, D', and the new pervious land area, P':

D' = X + D

P' = P – X*(I / (I+P))

Under the constraint that

D' / (D' + P'_{UD}) <= A^N_{max}

Two assumptions about new development on existing developed land are critical:

1. Maximum densities for each TAZ are determined by the maximum density currently present. Therefore, if an existing TAZ only has developed land that

is 35% pervious but no developed land that is less than 35% pervious, then higher densities are not permitted.

2. The intensity of new settlement on previously developed land occurs in proportion to the existing development intensity on that land.

The first assumption could be relaxed to consider a development scenario which encourages denser growth, allowing all of the TAZs to be developable to the "high-intensity" land cover.

Once all of the maximum densities have been reached, it is assumed that remaining new jobs and households require the clearing and development of natural land – either forestland, grassland, or cropland. The new development is spread proportionally across the baseline land-cover types. For instance, if cropland is 20% of the developable land in a TAZ, and grassland is 80%, cropland receives 20% of the total land lost to development and grassland receives 80%. It is assumed that wetland area does not change, since development is generally prohibited or offset by requirements to replace or protect wetlands. Once the new developments have been allocated to the appropriate land-cover, pervious area is re-calculated for all developed areas. The resulting forecasted land-cover is then used to calculate the carbon sequestration for the forecast-year.

3.2 Land Cover Carbon Offset Emissions Method

Depending on the amount of time which passes between the baseline-year and the forecast-year, land cover changes will cause carbon stocks to "transition", resulting in a net change in soil and biomass stocks. Actual sequestered carbon *during* the transition years is not included in the calculation, but to account for the release of carbon from the stock when land-cover changes, a carbon offset emission is calculated. In the VILTCE, this transition calculation is based on the fraction of the soil and biomass stock assumed to be lost (or gained) for every possible transition, as shown in Table 2.

Table 2 Change in Stocks for Land-Cover Transitions

	Forecast Land Cover is…											
	Biomass Stock Change (%)						Soil Stock Change (%)					
Baseline Land	Settlement						Settlement					
Cover is…	Imp.	Per.	F	G	C	W	Imp	Per.	F	G	C	W
Settlement – Pervious (Per.)	-100		See Note 1.				-10		See Note 1.			
Forestland (F)	-100	-98		-100	-100	-100	-10	0		8	-42	-2
Grassland (G)	-100	-30	0		-100	-100	-10	0	53		-59	-2
Cropland (C)	0	0	0	0		0	-10	0	53	19		-2
Wetland (W)	-100	-100	-100	-100	-100		-11	-11	-11	-11	-11	

Notes:
1. The VILTCE assumes that no land is transitioned from Settlement back to a natural land cover.

These fractions are applied to each land-cover type conversion, generating a "transition" value, which represents soil and biomass stock released in the conversion of land cover from the baseline year to the forecast year. This transition

value is also converted to CDE and is included in the calculation of net carbon for the forecast-year. The transition values are subtracted from the sequestration values to get the final net sequestration values after factoring offset emissions from loss of soil and biomass stocks.

3.3 Transportation Emissions Method

The VILTCE aims to utilize data and models that most planning agencies would have readily available. It is targeted toward MPOs which have access to a four-step travel-demand model capable of estimating travel demand and assigning that demand to the roadway network. Using the estimated vehicle speeds and either an assumed or known distribution of flows for three vehicle-types (privately-owned vehicles, or POVs, medium trucks, and heavy trucks), emissions from the transportation sector are calculated for each link. The distribution of vehicle types can be part of the output of a travel demand model (if available) or it can be assumed as a fleet mix.

Since fuel economy is dependent on vehicle speed, emission rates (in grams/mile) were developed for the VILTCE for each operating speed (integers from 0.1 to 75 mph) to estimate carbon dioxide emissions for each of the three vehicle classes. These emission rates are based on data from the following sources:

- Environmental Protection Agency (EPA)'s MOBILE6 Vehicle Emission Modeling Software (www.epa.gov/oms/m6.htm)
- The MOtor Vehicle Emission Simulator (MOVES; www.epa.gov/oms/ngm.htm)
- California Environmental Protection Agency's EMission FACtors (EMFAC; www.arb.ca.gov/msei/onroad/latest_version.htm) model

Emission rates, in grams of CO_2 emitted per mile, used in the VILTCE are provided in Table 3.

Table 3 Emissions Rates in the VILTCE

Speed (mph)	Emission Rates (grams/mile)			Speed (mph)	Emission Rates (grams/mile)		
	POV	Medium Truck	Heavy Truck		POV	Medium Truck	Heavy Truck
0.1	1738	2527	3315	38	385	1125	1865
1	1568	2416	3264	39	381	1109	1837
2	1398	2305	3213	40	378	1093	1808
3	1227	2195	3162	41	377	1083	1790
4	1057	2084	3111	42	377	1074	1771
5	887	1974	3060	43	376	1064	1752
6	849	1933	3016	44	375	1054	1733
7	810	1891	2973	45	375	1045	1715
8	772	1850	2929	46	374	1033	1693
9	734	1809	2885	47	374	1022	1671
10	695	1768	2842	48	374	1011	1648
11	672	1738	2804	49	373	1000	1626
12	649	1707	2766	50	373	989	1604
13	626	1677	2728	51	374	981	1589
14	603	1646	2690	52	374	974	1575

Speed (mph)	Emission Rates (grams/mile)			Speed (mph)	Emission Rates (grams/mile)		
	POV	Medium Truck	Heavy Truck		POV	Medium Truck	Heavy Truck
15	579	1616	2652	53	375	967	1560
16	562	1591	2619	54	376	960	1545
17	545	1566	2586	55	376	953	1530
18	528	1540	2553	56	380	946	1512
19	511	1515	2520	57	384	939	1495
20	494	1490	2486	58	388	932	1477
21	482	1467	2452	59	391	925	1459
22	470	1444	2417	60	395	918	1441
23	458	1420	2382	61	399	918	1437
24	446	1397	2348	62	403	918	1433
25	435	1374	2313	63	406	918	1429
26	430	1352	2274	64	410	918	1425
27	426	1330	2234	65	414	917	1421
28	422	1308	2195	66	418	924	1429
29	418	1287	2155	67	422	930	1438
30	414	1265	2116	68	426	936	1446
31	410	1246	2083	69	430	942	1454
32	406	1228	2050	70	435	949	1463
33	403	1210	2017	71	439	970	1502
34	399	1191	1983	72	444	992	1541
35	395	1173	1950	73	448	1014	1580
36	392	1157	1922	74	453	1036	1619
37	388	1141	1893	75	457	1058	1658

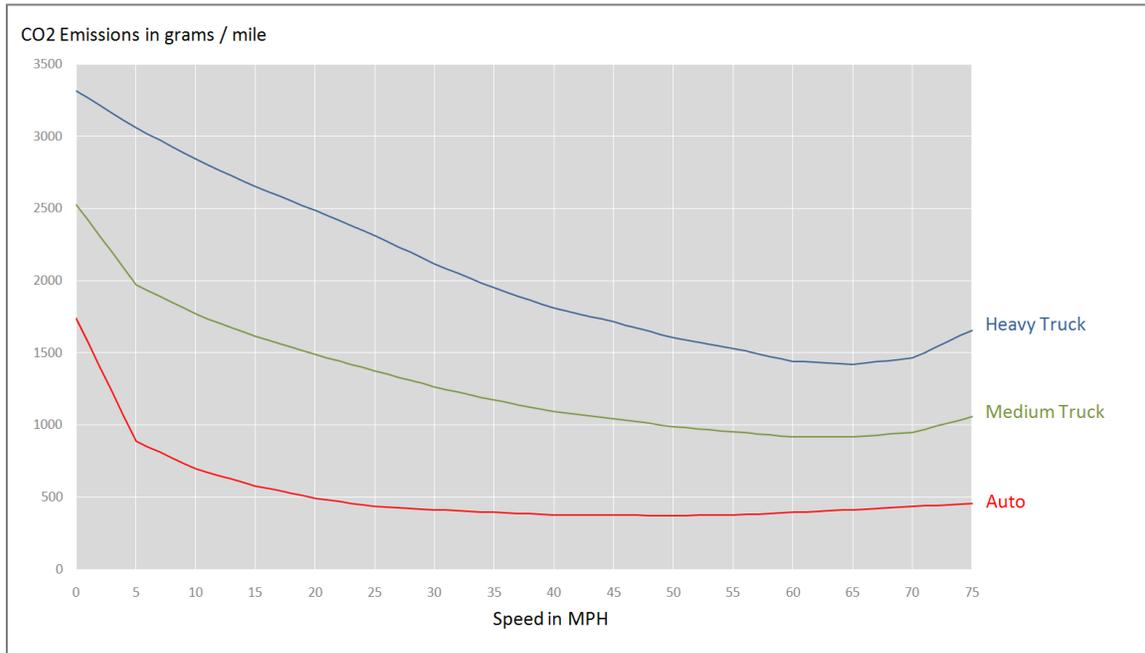These emission rates are plotted in Figure 2.

Figure 2 Emissions Rates in the VILTCE

The primary assumption here is that, although individual vehicle speeds vary along a given link in the road network, the average speed calculated by a travel-demand model does a satisfactory job of representing that variation.

4   Development and Use of the VILTCE Tool

The VILTCE tool was implemented as a custom application within the ArcGIS 9.3 desktop software.The application was developed in VB.Net, using the ESRI's ArcObjects, to create the specific functionality required for the tool. ESRI's ArcObjects are software components released as an Application Programming Interface (API) for developers to customize the ArcGIS software suite.   Development of the VILTCE tool was done within Microsoft Visual Studio. Custom VB.Net code was written in class modules as wrapper code to the COM-based ArcObjects libraries. An installation program was written to install the compiled source code. The only additional required software is ESRI's ArcGIS 9.3 desktop software at the ArcView level.

The interface is accessed as a toolbar within the ArcGIS desktop software. Once the VILTCE toolbar is installed, it can be activated by checking "Carbon Calculator Toolbar" under View/Toolbars. As shown in Figure 3, the VILTCE toolbar contains two items, a "Carbon Processing Menu" dropdown and a "Scenario Evaluation" button. The "Carbon Processing Menu" contains links to two forms, one for generating the transportation emissions (Transportation Carbon Calculation) and one for generating the land-cover sequestration (Landcover Carbon Calculation).
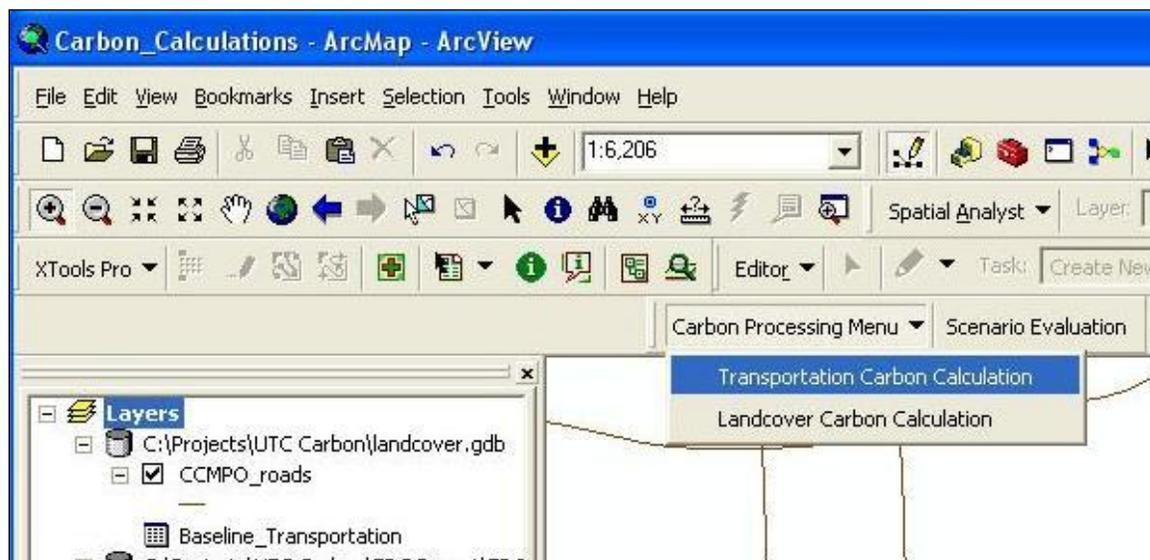
Figure 3 Carbon Calculator Toolbar for the VILTCE Tool

The "Scenario Evaluation" button uses transportation and land-cover data created in the "Carbon Processing Menu", so the "Carbon Processing Menu" steps must be completed first.

Input data for the Carbon Processing steps must be stored in an ESRI file geodatabase, and added to the map for use with the tool. Output data will be created in the same file geodatabase. Several feature classes are required in the file geodatabase to run the calculator in its entirety. Required feature classes for Transportation Carbon Calculation is a line-based transportation roadway network that has travel volume, speed, and length attributes for every link in the network. The required feature classes for the Landcover Carbon Calculation are:

- NLCD land-cover layer (in vector format)

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- TAZ polygon layer with demographics (employment and population)

It is possible to run just the "Transportation Carbon Calculation" or just the "Landcover Carbon Calculation" individually.

4.1 Transportation Analysis

The "Transportation Carbon Calculation" selection opens the transportation processing form shown in Figure 4.

Figure 4 Transportation Carbon Calculation for the VILTCE Tool

The transportation network layer must be open in the ArcMap document (*.mxd). The form allows users to select their transportation network for the baseline scenario (under the "Period 1" dropdown), and the fields to be used in that layer for link volume, link travel time, and link length. Directional input for link volumes and travel times are permissible. The user may also alter the default Fleet Distribution values in the bottom left corner. The "Multiplier for Annual Value" text box contains the value that will be used to multiply the daily values to obtain the annual carbon emissions. The default value of 365 may be changed if necessary. The default value of the "Length Units" drop-down box is "Miles", but this may be changed to "Miles x 100" or "Meters" depending on the units of the input data. Once these fields in the form have been addressed, clicking the "Calculate" button will create a table called "baseline_transportation" in the file geodatabase which contains the link-specific carbon dioxide emissions for the baseline-year.

To calculate the transportation emissions for a forecast-year, the appropriate ArcMap document and/or fields for volume, travel time, and length from the current ArcMap document must be selected which represent travel in the forecast-year. The user should select the "Future Scenario" checkbox and enter the number of years

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between the baseline-year and the forecast-year. This time, clicking the "Calculate" button will generate a table called "scenario_transportation" in the file geodatabase which contains the link-specific carbon dioxide emissions for the forecast-year. The 'Transportation Processing" window is closed by clicking the "X" in the top right corner.

4.2 Landcover Analysis

To run the land-cover analysis, a polygon-based TAZ layer and a NLCD vector land-cover layer must be open in the ArcMap document. The TAZ layer must contain fields for employment and households for the baseline-year and the forecast-year if a forecast is being modeled. To run the analysis, select the link for the Landcover Carbon Calculation from the "Carbon Processing Menu" dropdown, which will reveal the Landcover Processing form shown in Figure 5.

Figure 5 Landcover Processing Window for the VILTCE Tool

On the top section of the form, make selections under "Baseline Landcover" by selecting the TAZ layer for the baseline-year and the TAZ ID field from the selected TAZ layer. Then select the Landcover Layer from the dropdown box – this should be the NLCD layer. Click the "Process Baseline" button to create the output table "baseline_landcover" in the file geodatabase.

Run a future scenario by checking the "Future Scenario" checkbox to activate this section of the form. Select the same TAZ layer as was used in the baseline process under "Baseline TAZ Layer". You must also select the TAZ ID, Employment and Population fields for this layer.

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Select the Scenario TAZ layer under "Scenario TAZ Layer" and the TAZ ID, Employment and Population fields for this layer. Select the same NLCD landcover layer that was used for the baseline calculation. If desired, change the default values in the "Specify Housing Density" text-input boxes. You may enter a different value to be used as the average acres per development unit to encourage higher density development in the forecast-year scenario. Then enter the "Years after baseline", which is the difference between the baseline-year and the forecast-year, and will be used to name the output table. For example, a baseline year of 2010 and a scenario year of 2020 should have the value 10. Finally, click the "Process Scenario" button to create the output table "scenario_xx_landcover" in the file geodatabase, where "xx" is the "Years after baseline" value. Close the 'Landcover Processing" window by clicking the "X" in the top right corner.

4.3 Scenario Comparison for Transportation and Land-Cover

The Scenario Comparison form allows the baseline and forecast results to be summed and compared. The user can click the "Scenario Evaluation" button (see Figure 3) to open the "Scenario Comparison" form shown in Figure 6.

Figure 6 Scenario Evaluation Window in the VILTCE Tool

Choose the baseline and scenario output tables which were created from the Transportation and Landcover Carbon Calculations in the previous steps. Then, for each of the Landcover tables (baseline_landcover and scenario_xx_landcover), select the TAZ identifier field. The "Run Comparison" button will create a table named "Final_Results", which is added to the map. In the "Final_Results" table. the "diff_lc" field contains the difference in carbon sequestration in the land-cover for the baseline and scenario years. The "diff_transp" field contains the difference in carbon emissions from transportation for the baseline and scenario years. The "net_change_annual_MgCO2" field is the difference of the total sequestration and emissions between the baseline to the scenario year.

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5 Summary of VILTCE Applications

5.1 2005 Chittenden County Application

The VILTCE was applied to Chittenden County, Vermont as a case study, using the VILTCE tool. For the 2005 baseline-year, the County's soils and biomass in all land types were estimated to sequester approximately 86,000 and 673,500 Mg of carbon dioxide, respectively, for a total annual sequestration of 759,500 Mg of carbon dioxide. The transportation emissions resulted in approximately 797,200 Mg of carbon dioxide emitted. Therefore, Chittenden County was an overall C source (net release of C) in 2005, emitting 37,700 Mg of carbon dioxide, without taking electricity and heating emissions into account. For additional information on this analysis, refer to Mika et al. (2010).

A revised application of the VILTCE method was applied in 2012 without using the ArcGIS tool. This application was carried out using spatial analysis methods in TransCAD, a transportation GIS software by Caliper Corp., and database analysis tools in MS Excel. This application revealed similar results for total land cover sequestration (205,000 Mg of C or 751,650 Mg of CO_2) and transportation emissions (231,000 Mg C or 847,000 MG of CO_2) in 2005. Differences between these results and the results from Mika et. al. (2010) were caused by the use of the actual fleet mix from the CCMPO model (instead of estimates based on fleet mix, as the tool uses), and differences between the spatial-analysis algorithms used to estimate land cover areas by TAZ between ArcGIS and TransCAD. However, these differences are expected to be within the expected sensitivity of the input parameters.

5.2 2030 Chittenden County Scenarios Application

A stakeholder workshop was sponsored in 2009 for a separate USDOT-funded project to solicit input from the planning, business, and environmental communities about alternative future development scenarios for Chittenden County. The scenarios were intended to represent possible shifts in policy, investment, or external conditions in the County. Approximately 70 people, including most of the planners from CCRPC and the county's major towns and cities, attended the workshop. A total of five alternative scenarios were developed in the workshop – the one used in this study represents the scenario that was most expected by the workshop participants to represent actual conditions in 2030. The other scenario used in this study comes from the County's MTP (CCMPO, 2005). The scenario documented in the MTP was adopted in 2005 as the planned scenario for 2025.

The highway networks for these two scenarios are used to route traffic and calculate transportation emissions in this study, along with a highway network that is identical to the one present in 2005. The 2005 scenario represents the "baseline" case and assumes that no new roadways are constructed between 2005 and 2030. The additional roads assumed to be constructed for the MTP and stakeholder scenarios are shown in Figure 7.
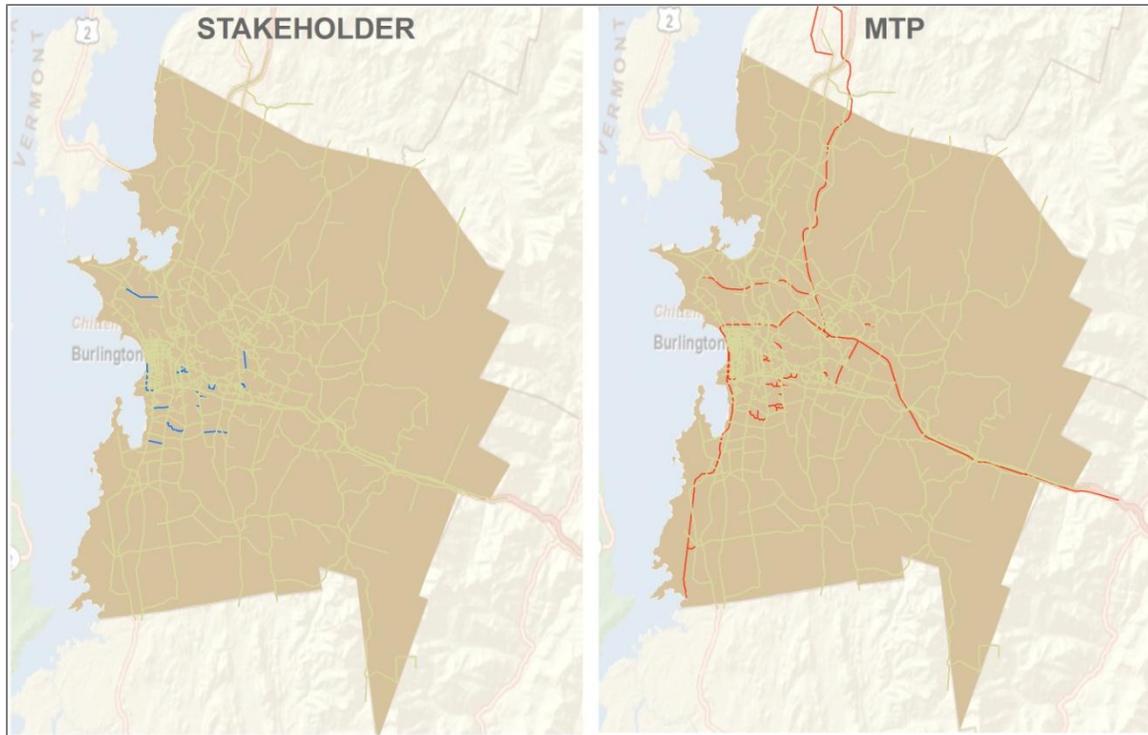
Figure 7 Road Networks for the Stakeholder (in Blue) and MTP (in Red) Scenarios (Baseline Road Network is Shown in Yellow)

Forecasted travel-demand and land-use for 2030 were developed separately for the stakeholder scenario and the MTP & baseline scenarios. Demographic data for the stakeholder scenario was estimated using an integrated transportation & land-use modeling package which features UrbanSim, an urban growth simulation land-use model. UrbanSim allocates development (population and employment) spatially by assigning values to TAZs. UrbanSim is a land-use model that simulates urban growth for a region based on externally derived estimates of population and employment growth (control totals). Using a series of complex algorithms, this expected growth is spatially allocated across the landscape to simulate the pattern of future development and land use. The existing employment density in Chittenden County, Vermont was used to develop the parameter that represents land lost to increased employment. The area of "high intensity" development in the NLCD layer for Chittenden County, Vermont, which includes industrial/commercial land, but also apartment buildings and the university, was divided by the average number of employees in all the sectors, resulting in a parameter value of 0.0015 hectares/employee. This parameter was used to calculate land "lost" to development when jobs are added to a TAZ. Forecasted travel demand for 2030 from the CCMPO Regional Transportation Model (CCMPO, 2008) was used for all 2030 scenarios.

Each of the scenarios was processed using the VILTCE without the ArcGIS tool, so the results are compared to the base-year results calculated without the tool. All results are illustrated graphically in Figure 8.
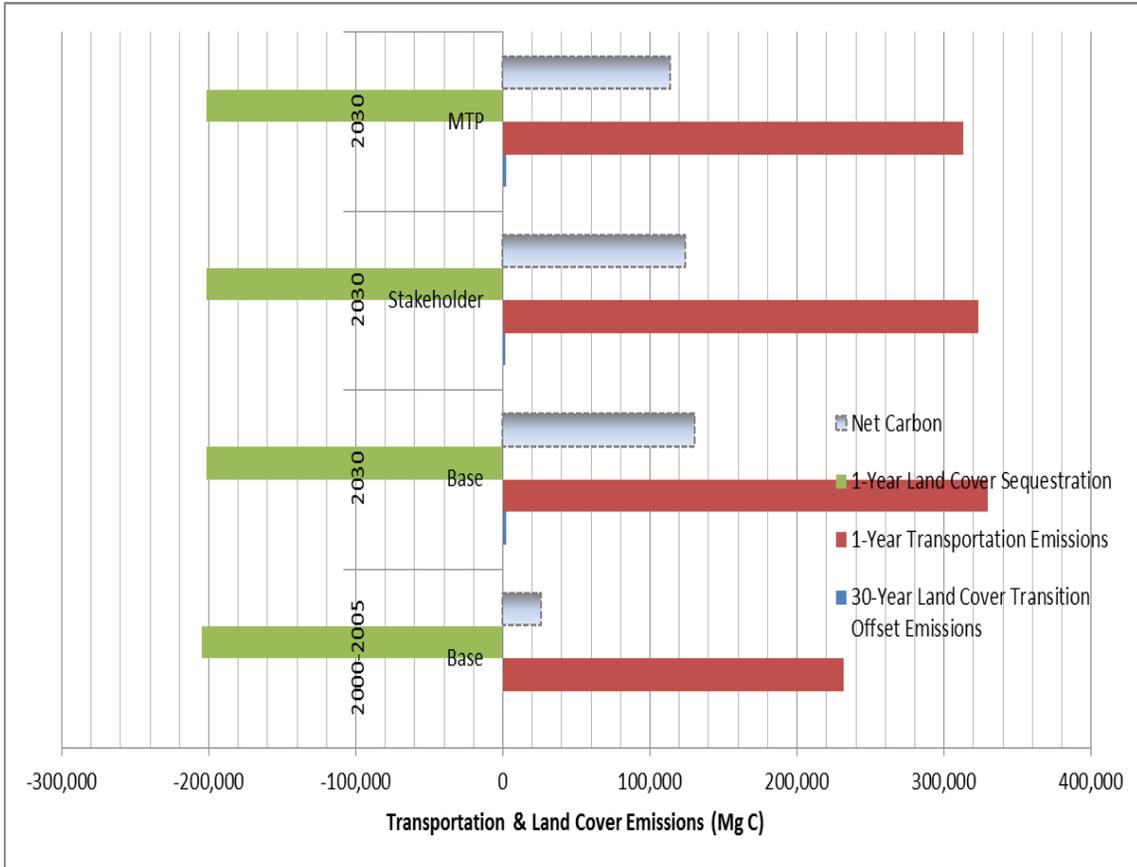
Figure 8 Results of the 2030 Scenario Applications with the Base-Year Application of the VILTCE

The change is sequestration potential and offset emissions between each of the three future scenarios are negligible when compared to the growth in transportation-related emissions. This result is likely due to the fact that none of the TAZs required non-developed land cover to be used to accommodate forecasted residential and employment growth.

For 37 of the 335 TAZs, primarily in the denser Burlington area, the forecasted growth could not be accommodated with the existing developed areas using the default employment and residential densities. However, none of these TAZs had any cropland, grassland, or forested area to accommodate the overflow, so it was assumed that increased densities will be used to force-fit the forecasted growth into the existing developed area.

6 Rate Coefficients and Parameters for an ILTCE

The focus of this section is on the development of new land cover C sequestration rate coefficients to accurately account for regional variability throughout the United States. Values were applied state by state in order to provide the most accurate C rates and stocks, which are dependent on geographic location, climate and other environmental factors. While state boundaries are not determinate of these environmental factors, they are close estimates as similar environmental conditions occur within most states.

Some of the research documented in this section updates the rates used in the VILTCE. This field of research is rapidly evolving, so new studies with improved rate coefficients are appearing more often. The recommended rates for Vermont are documented below, along with those for the rest of the nation.

6.1 Data Collection

Staying consistent with previous research by Mika et al., land-cover types from the NLCD were used to categorize rate coefficients for other regions in the United States. The following is a description of the rate coefficients by NLCD class and the sources they were obtained from. A summary of the average rate coefficients for the entire nation is provided in Table 4.

Table 4 National Average Carbon Stocks and Sequestration Rates

	2001 NLCD Land-Cover Type	Assigned 2006 IPCC Category	% Pervious Surface	Stocks (Mg C / ha)		Sequestration Rates (Mg C/ha/yr)	
				Soil	Bio mass	Soil	Biomass
21	Developed, open space	Settlement - Pervious	90	77.9	26.7	0.5	0.9
22	Developed, low intensity		65				
23	Developed, medium intensity		35				
24	Developed, high intensity		10				
41	Deciduous forest	Forestland	100	140.3	158.5	0.7	1.0
42	Evergreen forest		100	135.3	148.6	0.5	0.7
43	Mixed forest		100	137.7	153.3	0.7	0.9
52	Scrub/shrub	Grassland	100				
71	Grassland/herbaceous		100	53.0	0.0	0.5	0.0
81	Pasture/hay	Cropland	100			0.3	0
82	Cultivated crops		100	42	0		
90	Woody wetlands	Wetlands	100	87	99	0.5	5.3
95	Emergent herbaceous wetlands		100		13.8		31.7
11	Open water	Other	100	0	0	0	0
12	Perennial Ice/Snow		100	0	0	0	0
31	Barren Land		100	0	0	0	0

6.1.1 Settlements- Pervious Surface

The national averages for this class are shown in Table 4. Due to high regional variability for pervious settlements, Table 5 was created to show the breakdown of rates for each state.

Table 5 Stocks and Sequestration Rates by State

State	Stocks (Mg C / ha)		Sequestration Rates (Mg C/ha/yr)	
	Soil	Biomass	Soil	Biomass
Alabama	72.0	44.6	0.8	1.4
Arkansas	65.0	23.1	0.4	0.8
Florida	98.0	17.0	0.3	0.6
Georgia	81.0	51.2	0.9	1.7
Kentucky	82.0	30.9	0.6	1
Louisiana	90.0	23.4	0.4	0.8
Mississippi	84.0	35.7	0.7	1.2
North Carolina	79.0	39.7	0.7	1.3
Oklahoma	50.0	13.4	0.2	0.4
South Carolina	83.0	36.8	0.7	1.2
Tennessee	67.0	40.6	0.7	1.3
Texas	62.0	9.7	0.2	0.3
Virginia	77.0	32.7	0.6	1.1
South Regional Average	**76.2**	**30.7**	**0.6**	**1.0**
Connecticut	113.0	20.2	0.4	0.7
Deleware	86.0	42.8	0.8	1.4
Maine	122.0	44.1	0.8	1.4
Maryland	85.0	37.1	0.7	1.2
Massachusetts	118.0	23.4	0.4	0.8
New Hampshire	127.0	45.4	0.8	1.5
New Jersey	101.0	38.3	0.7	1.2
New York	97.0	24.3	0.4	0.8
Ohio	81.0	35.4	0.6	1.1
Pennsylvania	86.0	31.8	0.6	1
Rhode Island	113.0	8.2	0.2	0.3
Vermont	104.0	33.3	0.6	1.1
West Virginia	86.0	39.0	0.7	1.3
Northeast Regional Average	**101.5**	**32.6**	**0.6**	**1.1**
Illinois	71.0	31.2	0.6	1
Indiana	65.0	28.9	0.5	0.9
Iowa	65.0	30.6	0.6	1
Kansas	67.0	19.0	0.3	0.6
Michigan	88.0	27.5	0.5	0.9
Minnesota	104.0	34.6	0.6	1.1

State	Stocks (Mg C / ha)		Sequestration Rates (Mg C/ha/yr)	
	Soil	Biomass	Soil	Biomass
Missouri	68.0	28.3	0.5	0.9
Nebraska	61.0	19.5	0.3	0.6
North Dakota	69.0	7.2	0.1	0.2
South Dakota	63.0	17.8	0.3	0.6
Wisconsin	81.0	23.9	0.4	0.8
North-Central Regional Average	**72.9**	**24.4**	**0.4**	**0.8**
Arizona	47.0	10.5	0.2	0.3
California	67.0	10.1	0.2	0.3
Colorado	58.0	12.0	0.2	0.4
Idaho	50.0	23.7	0.4	0.8
Montana	58.0	45.7	0.8	1.5
Nevada	46.0	9.2	0.2	0.3
New Mexico	48.0	4.4	0.1	0.1
Oregon	70.0	28.1	0.5	0.9
Utah	54.0	13.0	0.2	0.4
Washington	71.0	31.1	0.6	1
Wyoming	58.0	3.3	0.1	0.1
West Regional Average	**57.0**	**17.4**	**0.3**	**0.6**

The data for Table 5 were obtained from three sources. Soil stocks were obtained from Pouyat et. al. (2006) which gives state-by-state values. For biomass stocks, data from Nowak et. al. (2001) was used which also provided state-by-state values. A combination of sources was used for soil sequestration rates. Qian et. al. (2010) provided a general sequestration value for urban soils of 0.55 Mg C ha^{-1} yr^{-1}. This value was multiplied by state-by-state biomass sequestration values from Nowak et. al. (2001) in order to represent state differences in soil sequestration rates. No data was available on soil sequestration by urban area by state so this calculation is based on the assumption that soil and biomass sequestration are both influenced by the same regional factors. Nowak et. al. (2001) was used for biomass sequestration rates by state.

The source Jo et. al. (1995) was consulted but not used. This source calculated urban biomass sequestration rates for urban areas but is believed to have over-estimated rates, based on Nowak et. al. (2001) and Pouyat et. al. (2006). This source may have created over-estimations in its use in the VILTCE.

6.1.2 Forestland

Table 6 provides state and regional values for mixed, coniferous, and deciduous forests, respectively. Due to a high level of regional variability, the state-by-state values are necessary to provide accurate rates.

Table 6 Stocks and Sequestration Rates for Forests by State

| State | Stocks (Mg C / ha) | | | | | | Sequestration Rates (Mg C/ha/yr) | | | | | |
| | Soil | | | Biomass | | | Soil | | | Biomass | | |
	M	C	D	M	C	D	M	C	D	M	C	D
Alabama	129.2	131.9	126.4	136.5	141.8	130.8	0.4	0.3	0.7	0.6	0.4	1.1
Arkansas	123.9	129.9	119.7	125.7	137.8	117.5	0.6	0.5	0.9	0.8	0.7	1.3
Florida	153.1	152.4	145.9	184.2	182.7	169.9	0.7	0.2	1.2	0.9	0.3	1.7
Georgia	152.1	155.8	149.4	182.2	189.5	176.7	0.6	0.5	1.1	0.9	0.7	1.5
Kentucky	129.7	141.1	129.6	137.4	160.2	137.3	1.1	1.3	1.1	1.6	1.8	1.6
Louisiana	132.1	135.4	126.8	142.2	148.8	131.6	0.6	0.5	1.0	0.8	0.7	1.5
Mississippi	133.0	135.6	129.1	143.9	149.1	136.1	0.5	0.4	1.0	0.8	0.5	1.4
North Carolina	149.3	154.4	145.6	176.6	186.7	169.2	1.0	0.7	1.2	1.4	1.0	1.7
Oklahoma	113.9	120.8	111.4	105.9	119.5	100.8	0.4	0.3	0.6	0.6	0.4	0.9
South Carolina	155.0	153.4	153.4	188.1	184.8	184.8	0.5	0.3	1.1	0.8	0.5	1.6
Tennessee	128.6	141.0	127.6	135.1	160.0	133.2	1.1	0.8	1.1	1.6	1.2	1.6
Texas	111.5	116.2	114.0	101.0	110.5	105.9	0.5	0.2	0.5	0.7	0.3	0.7
Virginia	145.5	156.6	141.5	169.1	191.2	160.9	0.6	0.5	0.8	0.9	0.6	1.1
South Regional Average	**135.1**	**140.3**	**132.3**	**148.3**	**158.7**	**142.7**	**0.7**	**0.5**	**1.0**	**0.9**	**0.7**	**1.4**
Connecticut	0.6	97.0	150.4	179.1	71.9	178.8	0.5	0.2	0.5	0.8	0.3	0.8
Deleware	0.8	168.1	157.1	200.7	214.2	192.2	0.4	0.1	0.9	0.6	0.1	1.3
Maine	0.9	155.6	145.5	176.2	189.2	169.1	0.5	0.7	0.7	0.8	1.0	1.0
Maryland	0.9	159.4	162.8	203.5	196.9	203.6	0.4	0.1	0.4	0.5	0.2	0.6
Massachusetts	1.6	159.8	152.1	183.2	197.6	182.2	1.1	1.1	1.1	1.6	1.6	1.5
New Hampshire	0.8	164.2	156.4	193.1	206.5	190.9	0.5	0.3	0.6	0.7	0.5	0.9
New Jersey	0.8	136.9	101.2	172.4	151.7	80.4	0.6	0.0	0.6	0.9	0.0	0.9
New York	1.4	158.9	154.8	187.4	195.8	187.5	0.7	0.6	0.7	1.0	0.9	1.0
Ohio	0.6	159.2	153.5	185.0	196.5	185.0	0.8	0.8	0.8	1.1	1.2	1.1
Pennsylvania	0.8	151.9	148.1	174.6	181.8	174.3	0.8	0.7	0.8	1.1	1.0	1.1
Rhode Island	1.6	104.0	146.0	173.9	85.9	170.1	0.7	0.4	0.7	0.9	0.6	0.9
Vermont	0.7	161.4	156.1	191.8	200.7	190.2	0.9	0.9	0.9	1.3	1.2	1.3
West Virginia	0.9	148.8	149.5	176.4	175.6	177.0	0.6	0.1	0.6	0.8	0.2	0.8
Northeast Regional Average	**0.9**	**148.1**	**148.7**	**184.4**	**174.2**	**175.5**	**0.7**	**0.5**	**0.7**	**0.9**	**0.7**	**1.0**
Illinois	138.3	138.0	138.2	154.6	154.0	154.5	0.4	0.3	0.4	0.5	0.4	0.5
Indiana	150.8	144.3	150.8	179.5	166.6	179.6	0.2	0.3	0.2	0.3	0.5	0.3
Iowa	132.7	104.0	132.1	143.3	85.9	142.2	0.6	0.4	0.6	0.8	0.6	0.8
Kansas	147.3	104.0	148.7	172.5	85.9	175.4	0.4	0.4	0.4	0.5	0.6	0.5
Michigan	182.8	205.3	176.3	243.5	288.6	230.7	0.6	0.4	0.7	0.9	0.6	1.0
Minnesota	180.7	197.7	170.0	239.4	273.4	218.0	0.1	1.0	0.4	0.2	1.4	0.5
Missouri	126.1	129.2	125.9	130.2	136.4	129.9	0.3	0.1	0.3	0.5	0.2	0.5

| | Stocks (Mg C / ha) | | | | | | Sequestration Rates (Mg C/ha/yr) | | | | | |
| | Soil | | | Biomass | | | Soil | | | Biomass | | |
State	M	C	D	M	C	D	M	C	D	M	C	D
Nebraska	136.3	109.4	146.8	150.6	96.9	171.5	0.8	0.4	1.7	1.1	0.5	2.4
North Dakota	130.0	104.0	134.4	138.0	85.9	146.8	0.5	0.4	0.5	0.7	0.6	0.6
South Dakota	118.8	112.5	132.9	115.6	103.1	143.9	0.3	0.4	0.3	0.5	0.6	0.4
Wisconsin	174.4	170.7	170.7	226.9	219.5	219.5	0.6	0.7	0.7	0.8	0.9	0.9
North-Central Regional Average	**147.1**	**138.1**	**147.9**	**172.2**	**154.2**	**173.8**	**0.4**	**0.4**	**0.5**	**0.6**	**0.6**	**0.8**
Arizona	95.0	92.9	123.8	68.0	63.8	125.7	0.3	0.3	0.7	0.4	0.4	1.0
California – N	125.8	142.6	115.5	129.7	163.1	108.9	1.5	1.8	1.1	2.2	2.5	1.6
California – S	106.1	95.5	110.3	90.1	69.0	98.6	0.4	0.3	0.7	0.5	0.5	0.9
Colorado	105.9	102.0	121.1	89.7	82.0	120.1	0.6	0.5	0.6	0.9	0.7	0.9
Idaho	123.7	125.2	122.1	125.5	128.5	122.2	0.8	0.9	0.6	1.2	1.2	0.8
Montana	110.3	110.1	128.1	98.5	98.1	134.2	0.6	0.5	0.1	0.8	0.7	0.2
Nevada	88.0	85.6	138.4	53.9	49.2	154.9	0.1	0.2	0.1	0.2	0.2	0.2
New Mexico	102.3	98.0	122.2	82.5	74.0	122.5	0.5	0.5	0.8	0.7	0.7	1.1
Oregon – W	185.3	195.2	173.6	248.7	268.4	225.3	2.9	3.1	0.4	4.1	4.4	0.6
Oregon – E	115.8	113.6	115.1	109.6	105.3	108.3	0.6	0.7	0.4	0.9	1.0	0.6
Utah	104.6	94.1	114.8	87.1	66.2	107.7	0.1	0.3	0.6	0.1	0.4	0.8
Washington – W	189.6	198.5	189.4	257.2	275.0	256.7	3.2	3.2	1.4	4.5	4.6	2.0
Washington – E	135.8	134.8	136.8	149.6	147.6	151.5	1.0	1.0	0.1	1.4	1.5	0.1
Wyoming	102.7	101.0	120.3	83.3	80.0	118.6	0.4	0.4	0.5	0.6	0.6	0.8
West Regional Average	**107.2**	**111.5**	**132.0**	**92.3**	**101.0**	**141.9**	**0.7**	**0.7**	**0.5**	**1.0**	**1.0**	**0.8**

Notes:
M- mixed forest
C – coniferous forest
D – deciduous forest

Two sources were used for the forestland rate coefficients. For soil stocks, Lal, R. (2005) determined an average value of 122 Mg C ha⁻¹. To apply this to all states, 122 Mg C ha⁻¹ was multiplied by state-by-state biomass stock rates from Van Deusen and Heath (2010; 2012), with the assumption that the biomass stocks are proportional to the soil stocks by state. For soil sequestration, an average value of 0.7 Mg C ha⁻¹ yr⁻¹ from Lal, R. (2005) was multiplied by state-by-state biomass sequestration values from Van Deusen and Heath (2010; 2012). Van Deusen and Heath (2010; 2012) was used directly for biomass stock and biomass sequestration rates.

The Carbon Online Estimator tool (Van Deusen and Heath, 2012) was used for the forest-specific rates by state. The rate coefficients are calculated based on forest type, location, age and whether the forest is afforested of reforested. Reforested values were chosen for all states because most forests are in a regrowth phase after large-scale logging stopped in the mid-20th century. An average forest age of 40 years was used for all states in the West, South and Northeast regions. An average forest age of 60 years was used for all states in the Northern region. Rates for

mixed (M), coniferous (C) and deciduous (D) forests were calculated separately for every state.

The Western states of Washington, Oregon and California were sub-divided to represent strong environmental boundaries within those states that affect forest dynamics. Washington and Oregon were divided into Eastern and Western sections while California were divided into northern and southern regions. These forestland values are significantly greater than the values used in the VILTCE. This variation is due to the fact that the VILTCE assigns a value of 0 Mg C for soils stocks.

Two important variables that affect C sequestration and stock rates were addressed by the coefficients for Pervious Surfaces. The first was density of urban canopy cover and the second was growth rates of urban canopy cover. Urban tree density is highly variable and is dependent on a number of factors ranging from environmental conditions to local governmental policies. These issues are addressed by Nowak et. al. (2001) who determined urban tree density for every state on these two criteria. Similarly, urban tree growth rates are often higher than forestland because of increased management and more direct sun. As a result, trees in the Pervious Surface NLCD category sequester more C on a per tree basis than trees in the NLCD forestland category. However, on a per hectare basis, urban trees sequester less due to the lack of tree density in the Pervious Surface cover type.

6.1.3 Grassland

Yang et. al. (2010) determined a rate of 53 Mg C ha^{-1} for soil stock. Conant et. al. (2001) determined a rate of 0.5 Mg C ha^{-1} yr^{-1} for soil sequestration. Since the primary sequestration and stock for grasslands occurs in soils and not in biomass, rates of 0 were assumed for to biomass stock and sequestration. These values are not as regionally dependent as the forest and soil values. Therefore, separate regional and state delineations are not necessary to capture the variations. Most extensive grasslands are mostly located in the central United States within the same climatic zone.

These values vary substantially from those used in the VILTCE, which included a soil sequestration rate of .2 Mg C ha^{-1} yr^{-1} and a biomass sequestration rate of 2.0 Mg C ha^{-1} yr^{-1}. The values in the VILTCE were determined from a Rhode Island study (Hooker and Compton, 2003) which now conflicts with more recent literature.

6.1.4 Cropland

Like grasslands, croplands were also determined to not be regionally dependent enough to warrant state and regional values. Anthropogenic crop maintenance practices generally act to make stock and sequestration rates more uniform across regions. A rate of 42 Mg C ha^{-1} for soil stock was obtained from Chan, Y. (2008). A rate of 0.3 Mg C ha^{-1} yr^{-1} for soil sequestration was obtained from Weiske (2007). Janzen (2006) and Derner (2007) were also consulted for verification of this rate. Small changes in agricultural practices can have significant impacts on overall stock and sequestration rates of cropland soil. Organic, no-till practices increase stock and sequestration rates. The 0.3 Mg C ha^{-1} yr^{-1} sequestration value used does not account for these practices so there may be a high level of farm-to-farm variation. Rates of 0 are assumed for biomass since there is often no net accumulation of vegetation on a farm.

In the VILTCE, rates of 0 Mg C were used for biomass and soil sequestration. While this is correct for biomass, it can be updated for soils, as crop debris and root systems continue to sequester C in soil.

6.1.5 Wetlands

Wetland values from the VILTCE were kept as is, since no updated rates could be found in the literature.

7 Conclusions and Recommendations

7.1 Conclusions

This report documented the development of methods and rate coefficients for the VILTCE, and the research documented toward the development of a nation-wide ILTCE. The VILTCE is a new output metric for advanced transportation models. The development and use of an ArcGIS tool for the application of the VILTCE to forecasting net carbon change is also documented. By including these environmental metrics, travel models can be used for a wider range of applications and can consider important impacts resulting from a project or policy that might otherwise be overlooked. The use of the VILTCE is also demonstrated in a base-year application to the Chittenden County Travel Model, along with three 2030 scenarios for Chittenden County.

This work focuses on a method for quantifying the major effects of land-use change on net carbon from the integrated transportation and land-use system. By integrating land-cover data with traffic data, a method was developed that estimates C sequestration and emissions associated with soil, biomass and transportation for a particular landscape configuration.

The results of the base-year application suggest that carbon sequestration and carbon emissions from transportation roughly balance one another in Chittenden County. Clearly the presence of biomass in the County's wetlands, settlements, and grasslands, and forestlands are an important component of its net carbon balance. It may be advisable for planners in Chittenden County to consider the protection of these biomass resources for their contribution to this carbon balance.

The results of the 2030 scenario applications suggest that land-cover changes due to likely additions of housing and employment will not significantly affect net carbon. However, corresponding changes in travel trends with the same housing and employment demonstrate a marked increase in carbon emissions. This finding suggests that, although increased urban densities are favorable for a carbon future, the primary reason for this is not that open space will be conserved, the primary reason is that these increased densities will cut down on travel, which has a much greater impact.

7.2 Limitations and Recommendations

Developing forecasting tools presents an inherent challenge to scientists and planners since they necessitate specifying future values of independent variables, the variables' future effects, and complex system interactions under changing conditions. Emissions from transportation, land-use change and subsequent land-cover fluctuations are difficult to predict since the interaction of these systems is still only loosely understood. Because of this, any planning decisions should require a full land-use and transportation forecasting effort to commence. Limitations to this study include those associated with the process of forecasting land-use and transportation changes, those associated with modeling land-cover change from land-use change, and those associated with modeling the estimation of net carbon.

The understanding of how land-cover changes will result from land-use (numbers of households and jobs) changes is still not well understood in the research community. For the VILTCE model an assumption was made that a proportional amount of development would occur for all developable NLCD types. For example, if a TAZ is 70% forestland and 30% cropland, the same ratio of land cover (70%/30%) would be taken away in the calculations after the maximum densities had been reached in the developed areas. More recent research has suggested that cropland and grassland are preferentially taken away during development disproportionately when it is available, presumably due to the lower cost of clearing and permitting new construction. This preference will result in less stock loss from conversion from forestland to developed land. In addition, the VILTCE method used to allocate new development should not unilaterally fill existing low- and medium-intensity development. Particularly in exurban areas, it would not seem likely that existing developed areas would be completely filled before cropland and grassland were developed. This tendency would be particularly true where minimum lot sizes exist. Additional research should be conducted to improve the process for adding developed intensity to existing low- and medium-intensity developed area, or to developing cropland and grassland.

Although we estimate the MTP scenario to produce the lowest transportation-based emissions, we have ignored that this scenario (along with the Stakeholder scenario) include the construction of new road miles, which itself will be an emitter of carbon due to the operation of construction vehicles and the land occupied by the new roads themselves. These elements of the developed road network are an environmental externality critical to completely comparing carbon emissions from the new transportation infrastructure. New road projects will need to convert land cover to the developed-high intensity NLCD class. This can be demonstrated methodologically by buffering the roads layer in GIS and intersecting it with the NLCD vector layer and measuring the actual undeveloped land-cover lost to the new road. Ideally, the buffer could be user-specified as road widths are not uniform. If not, an estimated buffer of 50 feet could be used. This would account for the road itself which can range from 24 feet for residential streets to 42 feet for multi-lane roads as well as adjacent land that will be converted during the construction process.

Future vehicle emission rates are assumed to follow similar curves under the scenario modeling assumptions. However, it is difficult to predict how fuel economy improvements could change - both the averages and speed-adjusted distributions are likely to shift. Further, baseline emission rates for cars and trucks remain poorly applied in most tools like this. Although ongoing research into tailpipe emissions for gasoline, biofuel, and diesel-powered vehicles is underway, applying this work in an accurate manner remains a challenge. Future iterations of this method should link to the data used to populate the MOVES platform for vehicle emissions, so that updates to MOVES can be utilized. In addition, a better understanding of the role of electric power as a fuel for the vehicle fleet is necessary. To understand current options for travelers using plug-in electric cars and electric-powered transit, we must account for regional grid-system emission rates. Incorporating a region-specific grid emissions rate table would be a simple first step.

Modeling the estimation of net carbon from a land-cover scenario also has limitations in the research community. Research into the rate coefficients of carbon sequestration and stock storage of various types of biomass and soil in the United States has resulted in significant conflict and variation. As this research area matures, it is expected that the rates will become more firm. As noted, though,

between the time when this work began (2009) and ended (2012), many of the rates were revisited and updated. So the application of ILTCE method nation-wide would have to utilize the updated coefficients and be predicated on additional research to see if newer rates are available at the time.

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