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A Geographic Approach to Sectoral Carbon Inventory: Examining the Balance Between Consumption-Based Emissions and Land-Use Carbon Sequestration in Florida

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Carbon accounting is an important analytical task that provides baseline information to assist in establishing emissions targets, developing market-based carbon trading programs, and facilitating sustainable carbon management at the regional to international scales. Although a substantial amount of research has focused on carbon emissions inventory, limited studies have been conducted to estimate consumption-based emissions and their spatial distribution in relation to vegetation carbon sinks. In this article, we develop a new approach to model the spatially detailed consumption-based carbon emissions from the household energy and transportation sectors. Emissions were in turn integrated with vegetation carbon sequestration rates that were modeled through biophysical remote sensing techniques. This enables carbon balance analysis at detailed geographic locations.

To illustrate our approach for carbon balance analysis, we present a case study in Florida. Results indicate that, in 2001, Florida was able to self-assimilate residential carbon emissions from energy and transportation fuel consumption. Estimates indicate that net carbon sources (i.e., household emissions exceeding vegetation carbon assimilation) are associated with urban and suburban densities and net sinks with exurban and rural densities.

In sum, the research approach can be extended to household energy consumption and carbon assessment for other geographies at alternative scales. Key Words: carbon emissions inventory, GIS, household energy consumption, household transportation fuel consumption, vegetation carbon sinks.
Anthropogenic climate change challenges societies throughout the world. To slow the increase in global temperature, curbing emissions of carbon dioxide (CO₂), which account for nearly 75 percent of global annual greenhouse gas emissions, will be required worldwide (Intergovernmental Panel on Climate Change [IPCC] 2007). The global reduction of CO₂ emissions relies heavily on localized mitigation efforts (Knight et al. 2003) for which future targets are determined mainly by a country or region’s emissions history. For example, the Kyoto Protocol established different rates of emissions reduction among industrialized countries based on their development activities since the industrial revolution. The Protocol also required that each participating country provides data to estimate its respective 1990 emission levels to designate their future emission targets (United Nations 1998).

A carbon emissions inventory, or the estimation of a country or region’s historical emissions, quantifies sources and sinks of anthropogenic CO₂ over a certain geographic area and time period (U.S. Environmental Protection Agency [EPA] 2009a). It requires approaches that capture the spatial distribution of CO₂ sources associated with human activities as well as vegetation carbon sinks, which can be either anthropogenic (e.g., planted trees) or natural (e.g., undisturbed rainforests). An assessment of the literature suggests limitations with regard to several critical issues involved in the integrated assessment of historical emissions.

First, the calculation of carbon emissions is often based on production instead of consumption (Blasing, Broniak, and Marland 2005; Pétron et al. 2008). In this study we refer to consumption as consumer-based energy and material use. Traditional carbon emissions inventories have been performed based on combustion (e.g., electricity generation) or end use (e.g., iron and steel production) of fossil fuels, which are both on the side of industrial production. The setting of future emission targets according to production-based inventories has its pitfalls, because the consumption and production of fossil fuel–related energy and manufacturing products are often spatially disparate (Rose et al. 2005; Weber and Matthews 2008). This spatial mismatch between emissions producers and end users might have impaired international agreements on carbon emissions allowances (Helm 2008).

Second, emissions estimates are usually performed at coarse geographic scales such as by city, state, or country boundaries, with no disclosure of the spatial variation within those units (Gregg et al. 2009; Soav-cool and Brown 2010). The development of continuous data sets that describe intraunit geographic and temporal patterns of carbon emissions is still in an exploratory stage. This has been performed for the globe at 1° × 1° spatial resolution by allocating a country’s total CO₂ emissions based on distribution of that country’s population (Andres et al. 1996). More recently, emissions from fossil fuel–based combustion, known as the Vulcan inventory, were generated for the United States at a 10-km spatial resolution by incorporating emissions data available at electrical generating units and from vehicle miles traveled (Gurney et al. 2009). No spatially explicit accounts of consumption-based emissions have yet been reported.

Third, the integrated assessment of balance between anthropogenic emissions and natural carbon sinks is still limited to a few urban areas (Wentz et al. 2002; Pataki et al. 2009) as opposed to an inventory that captures carbon balance differentiation along a gradient of settlement densities. For the accounting of vegetation carbon sinks, a recent trend is to produce spatially detailed estimates from syntheses of ground surveys and ecological models with the addition of remote sensing observations (Cramer et al. 1999). These inventories, however, exist predominantly for spatially continuous vegetation communities (Imhoff et al. 2004). The accounting of carbon balance in human-dominated environments (i.e., cities, suburbs, and exurbs) requires interdisciplinary approaches that combine traditional socioeconomic and ecological studies (Grimm et al. 2008; Churkina, Brown, and Keoleian 2009; Wise et al. 2009).

In this article, we present an integrated research approach to model the CO₂ balance between consumption-based emissions and vegetation carbon sinks. Our study targets current research needs in emissions inventories with respect to the three points previously discussed. Consumption in this analysis...
includes the household usage of energy and transportation fuels, which account for approximately 40 percent of the carbon emissions in the United States (Brown, Southworth, and Sarzynski 2008). This inventory excludes energy and fuel consumption and associated carbon emissions from the commercial sector. The research approach presented in this article captures the spatial heterogeneity of energy and fuel consumption, consumption-based CO$_2$ emissions, and vegetation carbon sinks at the U.S. Census tract scale. The spatially explicit accounting of household consumption and carbon emissions or sinks were further examined among different settlement types characterized by their residential densities. Our approach integrates carbon emissions estimates based on socioeconomic data with ecological modeling of vegetation carbon sequestration potentials based on biophysical remote sensing methods. All data used in this study are publicly available in the United States and the research methods can be extended to other geographies, including the possibility of nationwide analysis at the Census tract and comparable scale.

**Integrated Spatially Explicit Carbon Balance Analysis**

This article develops a carbon accounting approach that (1) investigates sources of carbon emissions at the consumer end, (2) captures the spatial heterogeneity of energy and fuel consumption and related carbon emissions, and (3) provides a profile of carbon balance between emissions from consumption activities and sequestration by natural or managed vegetation. To illustrate our methods, we demonstrate an application involving the state of Florida, which is one of the largest states (by size) in the United States. In 2007, an executive order was issued on carbon emissions reduction targets for this state (State of Florida 2007).

In the United States, consumption-based emissions inventories are challenging to conduct at the substate scale. Although the U.S. Energy Information Administration (EIA) has collected point-location data about residential energy consumption since 1978, these data are distributed in aggregated form at the scale of Census regions, Census divisions, and states (EIA 2009). It is necessary to consider consumption patterns associated with households and their characteristics to estimate energy-related residential consumption at finer scales. Our methods make use of average consumption levels that vary by household size, as households form the basic measuring unit of home energy use. When this is combined with Census counts of households by household size, we are able to produce spatial estimates of residential energy consumption at the Census tract scale.

The different orientations of the social and natural sciences might explain the limited number of spatially oriented carbon balance analyses that account for both anthropogenic emissions and vegetation sequestration (Pickett et al. 2001). In fact, there are relatively few such endeavors. Among the limited efforts focusing on modeling carbon balance across heterogeneous landscapes, some scholars simulate the spatial distribution of the net carbon flow based on actual measures of CO$_2$ concentration in the atmosphere without partitioning the respective contribution of carbon sources and sinks. For example, in one study the spatial and temporal patterns of the atmospheric CO$_2$ were derived based on statistical regression of measured CO$_2$ concentration and variables such as traffic flow, population density, employment density, and vegetation density (Wentz et al. 2002). Other efforts tend to model carbon emissions and sinks separately and then derive the balance between those two. A recent study conducted in Salt Lake City, Utah, demonstrated an integrated approach that inventoried CO$_2$ emissions based on consumption records from local utility companies and estimated CO$_2$ sequestration rates based on a model of urban forest growth (Pataki et al. 2009). In this article, we aim to inventory emissions and sequestration separately to identify spatial locations associated with carbon sources and sinks. The vegetation carbon sinks are estimated based on photosynthesis activities of all green vegetation (including forests, shrub, grass, agriculture, and wetlands) using a modeling technique of biophysical remote sensing. This approach provides a continuous surface of vegetation carbon sink estimates at the spatial resolution of one kilometer.

**Study Area**

Florida is located in the southeast of the United States (Figure 1). It ranks as the fourth most populous state in this country (U.S. Census Bureau 2009). The climate of Florida ranges from subtropical in the north and central parts of the state to tropical in the southern part of the Keys (Box, Crumpacker, and Hardin 1993). Although the per capita total energy consumption of Florida ranked low (forty-fourth in the country), Florida’s per capita residential electricity demand is relatively high. This could be attributed to the high cooling demand during the hot summer
months and the extensive use of electricity (87 percent of share in 2000) for home heating during the winter months (EIA 2010). Florida’s per capita carbon emissions, calculated based on fossil fuels used for energy production and manufacturing products, were below the national average during the time period between 1960 and 2000 (Blasing, Broniak, and Marland 2005). This might be due partly to Florida’s focus on tourism and agriculture instead of energy-intensive manufacturing.

Data and Methods

The research approach on carbon accounting for Florida consists of two parts. First, we investigated CO2 emissions released from residential household energy and transportation fuel consumption at the U.S. Census tract scale. Second, we estimated vegetation carbon sinks measured by plant net photosynthesis at 1-km resolution using remote sensing and ecological approaches, the results of which were aggregated to Census tracts. The household energy and transportation fuel consumption, consumption-based carbon emissions, vegetation carbon sinks, and carbon balance were then connected to four settlement categories as measured by Census housing unit densities.

Estimating Household Energy and Fuel Consumption and Carbon Emissions

In this study, household carbon emissions were measured as CO2 emitted through household energy use and transportation fuel. The total annual CO2 emissions from household energy consumption in 2001 ($E_e$; kg) were estimated for each Census tract in Florida using the following equation:

$$E_e = \left( \sum_{i=1}^{6} HH_i \times Btu_i \right) \times 74.046 \times 0.697$$

where $\sum_{i=1}^{6} HH_i \times Btu_i$ (million Btu) is the annual total household energy consumption for a given Census tract. $HH_i$ is the Census 2000 total number of households by household size (e.g., one-person household vs. two-person household) within that Census tract, $i$ ranges from one to six (with six representing households of six or more residents). $Btu_i$ (million Btu) is the average per household energy consumption by household size in 2001 (EIA 2001a). In Florida, approximately 97 percent of the total household energy consumption came from electricity; consumption of 1 million Btu was equivalent to 74.046 kWh generated through electricity (EIA 2001b). The CO2 emission coefficient was
0.697 kg/kWh for electricity generation in Florida (EIA 2002). Therefore, the total annual CO₂ emissions (kg) from household energy use were approximated based on energy consumption multiplied by the two scalars in Equation 1.

We used a standard method published by the U.S. EPA to estimate CO₂ emissions from household transportation (U.S. EPA 2005). According to this method, a typical passenger vehicle was modeled as emitting 8.877 kg of CO₂ per gallon of gas used. The total annual CO₂ emissions from household transportation in 2001 (Eₜ; kg) were obtained for each Census tract in Florida using Equation 2:

\[ Eₜ = \frac{VMT}{MPG} \times 8.877 \times 365 \]  

where VMT is the daily vehicle miles of travel (VMT) per Census tract calculated based on the National Household Travel Survey (NHTS) transferability data set (Oak Ridge National Laboratory 2007). The NHTS collected daily commuting and noncommuting trips of all members in the sampled households. Those nationwide point samples were transferred to the aggregated travel behavior by Census tract through integrating settlement patterns and other socioeconomic data (Hu et al. 2007). Households were categorized into clusters based on settlement patterns, economic characteristics, and demographic characteristics of the Census tracts where they were located. The sample-based VMT values were assigned to all households within the same clusters and then summed up by Census tracts (Andrews 2008). MPG is the average miles per gallon (MPG) estimated based on the national average fuel economy for passenger vehicles (20.3 mpg) used in the EPA Mobile6.2 emissions modeling program (U.S. EPA 2005, 2009b).

Calculating Vegetation Carbon Assimilation Capacity

The potential vegetation carbon sinks were measured as gross primary production (GPP) of land multiplied by a scalar 0.5. GPP refers to the total amount of CO₂ entering an ecosystem through photosynthesis during a year (Chapin, Matson, and Mooney 2002). Approximately half of the total GPP is used for plant respiration (DeLucia et al. 2007). GPP minus plant respiration (i.e., net photosynthesis) indicates the maximum potential vegetation assimilation of CO₂ from the atmosphere. Estimates of GPP were obtained using the light-use efficiency approach (Running et al. 2004; Zhao, Brown, and Bergen 2007). Our analysis includes deriving the actual light-use efficiency (ε) parameters and estimating the absorbed photosynthetically active radiation (APAR) for different types of vegetation and land cover (Zhao 2011). The 2001 National Land Cover Database (Homer et al. 2007) was used to generate ten vegetation and land-cover type based on documented empirical measures (Yang et al. 2007) multiplied by temperature and vapor pressure deficit (VPD) scalars (unpublished data). APAR was modeled based on the 2001 biweekly Advanced Very High Resolution Radiometer (AVHRR) normalized difference vegetation index (NDVI; U.S. Geological Survey EROS Data Center 2006) and solar radiation (Mitchell et al. 2004). The estimates of GPP, calculated at 1-km resolution throughout Florida, were aggregated to Census tracts for further analyses.

Linking Energy and Fuel Consumption and Carbon Balance to Settlement Patterns

The tract-level household energy and fuel consumption and carbon emissions and sinks were compared across four settlement categories including urban, suburban, exurban, and rural densities. Following the definition of Theobald (2001), urban densities are defined as settlement at 1 or more housing units per acre, suburban densities at 0.1 to 1 units per acre, exurban densities at 0.025 to 0.1 units per acre, and rural densities at less than 0.025 units per acre. Univariate analysis of variance (ANOVA) was constructed to detect effects of settlement category on household energy and fuel consumption, consumption-based carbon emissions, vegetation carbon sequestration, and carbon balance, respectively. The dependent variable was the tract-level per unit area or per capita measure of consumption or CO₂, and the factor variable was settlement category. Mean values for energy and fuel consumption and CO₂ estimates were derived and reported by settlement categories.

Results and Discussion

The State-Level Estimates

Florida, as a whole, appears to contain sufficient carbon sinks to offset all CO₂ emitted through household energy and fuel consumption in 2001. The estimated total annual household energy consumption was 0.58
quadrillion Btu for the entire state, which would produce approximately 30 million tons of CO₂ emissions. The total annual household vehicle travel was estimated to be approximately 74 billion miles for the entire state, which was responsible for approximately 32 million tons of CO₂ emissions. Therefore, the total annual CO₂ emitted through household energy and transportation fuel consumption in 2001 was approximately 62 million tons, which is less than the vegetation carbon assimilation capacity (88 million tons) as measured by plant net photosynthesis during the same year.

According to the last decennial Census, Florida was home to approximately 16 million residents and 6.3 million households in 2000. The per capita annual household energy and transportation fuel emissions were estimated to be 3.9 tons of CO₂ in 2001, whereas each Florida household accounted for 9.8 tons of CO₂ emissions annually on average. According to our estimates, the potential vegetation carbon sinks in Florida were 5.5 tons per person and approximately 14 tons per household.

Energy and Fuel Consumption and Carbon Balance by Census Tract

The spatial variation in household energy and transportation fuel consumption was high at the Census tract scale (Figure 2). Tracts with high energy consumption ranks might not be associated with high levels of transportation fuel usage considering that Pearson’s correlation is 0.3 (significance = 0.01) between the tract-level total household energy consumption and VMT. The consumption-based CO₂ emissions normalized by Census tract area (i.e., density of emissions) followed roughly the distribution of population centers. The correlation between emissions from energy use and emissions from transportation fuel is relatively high (Pearson’s correlation = 0.774, significance = 0.01) according to the tract-level density-based emissions measures.

The density-based carbon sinks estimate, or plant net photosynthesis per unit area, also varied significantly throughout Florida (Figure 3). At the Census tract scale, plant net photosynthesis correlated negatively (Pearson’s correlation = −0.506, significance = 0.01) with the energy-based emissions measured by density. This indicates that tracts with higher levels of CO₂ emissions are less likely to be home to vegetation carbon sinks, which is due possibly to the reduction in greenspace associated with residential and commercial development.

Carbon balance, calculated as the total emissions from energy and transportation fuel consumption subtracting plant net photosynthesis, was generated statewide by Census tract. The spatial pattern of the estimated carbon balance varies significantly when measured by the total, per unit area, and per capita estimates (Figure 4). When measured by per unit area CO₂ balance (Figure 4B), densely populated cities such as Miami, Fort Lauderdale, Tampa, St. Petersburg, Orlando, and Jacksonville were found to be associated with net CO₂ sources (i.e., emissions exceeding vegetation carbon assimilation). Measured by per capita CO₂ balance (Figure 4C), the net carbon sources tend to extend away from the densest settlement areas.

Energy and Fuel Consumption and Carbon Balance by Settlement Densities

Four settlement categories were generated for Florida based on Census 2000 housing-unit densities (Figure 5).
Figure 3. Vegetation carbon assimilation potential measured as gross primary production (GPP) at 1-km resolution (A) and as plant net photosynthesis aggregated by Census tract (B).

Accordingly half of the state’s total population and households resided in urban areas, which accounted for less than 4 percent of the total area of Florida. The urban and suburban areas together were home to nearly 90 percent of the total state population and households. Exurban densities accounted for approximately 30 percent of the state’s total land and 8 percent of the state’s total population and households. Rural densities occupied the largest proportion (45 percent) of the state’s total land, with less than 4 percent of the total population and households distributed within those areas.

According to an ANOVA (Table 1), effect of settlement category on consumption and CO2 levels is greater when measured by per unit area estimates than by per capita measures. The household energy consumption over per unit area was significantly higher at urban and suburban densities than the same measure at exurban and rural densities (Table 2), whereas the per capita energy consumption was less distinctive among the four settlement categories (Table 3). No variation in household transportation measured by per capita VMT can be attributed to settlement category (Table 1). Exurban densities, however, were found to be associated with the highest per capita VMT at a rate significantly
higher than the same estimate at urban densities (Table 3). This result corroborates earlier research findings about the increasing transportation needs within the periurban zones (Ewing and Rong 2008; Brownstone and Golob 2009).

With regard to vegetation carbon sinks, both exurban and rural densities were associated with the increased amount of plant net photosynthesis, compared to the urban and suburban densities (Table 2 and Table 3). The carbon assimilation potential of exurban and rural densities appears to be similar when measured by carbon flux density (Table 2), whereas rural densities are superior for vegetation carbon assimilation than exurban densities when measured by per capita estimates (Table 3).

Settlement category accounted for the balance between household emissions and vegetation carbon assimilation (Table 1). Estimated by carbon flux density, urban and suburban densities appear to be net carbon sources, whereas exurban and rural densities are associated with slight carbon sinks (Table 2). Estimated by per capita measures, urban and suburban densities are shown to be net carbon sources at a much smaller magnitude compared to the size of net sinks at exurban and rural densities (Table 3).

Policy Implications and Future Research Directions

Consumption-based emissions analyses offer an approach to capture the carbon sources principally associated with household activities, a key driver of fossil fuel use. This study investigates emissions from home energy use and transportation sectors. Going forward, future research might consider including other household-level fossil fuel–related consumption items. These might include goods and products such as food and apparel as reported through consumer spending surveys. These analyses would provide further information to support emission trading programs, especially those involving household emission credit transfers based on fossil fuel consumption (Niemeier et al. 2008).

Another avenue could incorporate information on the commercial sectors for more comprehensive emissions accounting at (supra)national levels. This type of analysis would further contribute to helping set emissions targets and distribute responsibilities, which are top priorities for policymakers concerned with carbon emissions reductions and climate change mitigation (Hepburn and Stern 2008). Related to this, time series analysis of energy consumption and consumption-based emissions would provide insights for the efficacy of emissions reduction practices.

Per our results, the highly concentrated energy and fuel consumption levels recorded in urban and suburban areas, accompanied by lower amounts of vegetation carbon sinks, suggest the need for emissions reduction in high-density areas through cutbacks in energy use (possibly through renewable resources or new forms of mass transportation) and the utilization of carbon-efficient plant species. Exurban densities are characterized by highly efficient vegetation carbon assimilation, yet they are associated with the highest per capita household transportation demand. This suggests that lowering transportation emissions in low-density areas is a need, although the strategies for doing so are not clear. These environments tend to be unsupportive of travel reduction initiatives such as carpooling campaigns, because the complex spatio-temporal patterns of individual movement among disparate activity locations limit cooperative transport opportunities (Horner 2004). At the same time, mass transit options in these locations are also very limited.

Besides examining the spatial and temporal patterns of carbon emissions and sequestration, future research might wish to explain these patterns as a function of socioeconomic variables such as housing-unit characteristics (Newton, Tucker, and Ambrose 2000), household income levels (Druckman and Jackson 2008), or even the lifestyle characteristics of household members themselves (Lutzenhiser 1993). This contributes to a better understanding of social and economic drivers of
Table 1. Effects of settlement category (consisting of urban, suburban, exurban, and rural densities) on consumption and CO2 estimates according to the univariate analysis of variance

<table>
<thead>
<tr>
<th>Type of measures</th>
<th>Dependent variable</th>
<th>Adjusted $R^2$</th>
<th>$df$</th>
<th>$F$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per unit area</td>
<td>Energy consumption</td>
<td>0.377</td>
<td>3</td>
<td>420.252</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Vehicle miles of travel</td>
<td>0.404</td>
<td>3</td>
<td>470.183</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>CO2 emissions</td>
<td>0.418</td>
<td>3</td>
<td>498.143</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Vegetation CO2 assimilation</td>
<td>0.469</td>
<td>3</td>
<td>613.584</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>CO2 balance</td>
<td>0.430</td>
<td>3</td>
<td>523.918</td>
<td>0.000</td>
</tr>
<tr>
<td>Per capita</td>
<td>Energy consumption</td>
<td>0.023</td>
<td>3</td>
<td>17.436</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Vehicle miles of travel</td>
<td>0.001</td>
<td>3</td>
<td>1.645</td>
<td>0.177</td>
</tr>
<tr>
<td></td>
<td>CO2 emissions</td>
<td>0.002</td>
<td>3</td>
<td>2.385</td>
<td>0.067</td>
</tr>
<tr>
<td></td>
<td>Vegetation CO2 assimilation</td>
<td>0.352</td>
<td>3</td>
<td>376.186</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>CO2 balance</td>
<td>0.353</td>
<td>3</td>
<td>378.564</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 2. The per unit area household energy and fuel consumption and carbon emissions and sinks by settlement densities in Florida, 2001

<table>
<thead>
<tr>
<th>Settlement densities</th>
<th>Urban</th>
<th>Suburban</th>
<th>Exurban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption (billion Btu/km²)</td>
<td>64.26 (1.37)</td>
<td>9.68 (0.22)</td>
<td>1.12 (0.04)</td>
<td>0.27 (0.02)</td>
</tr>
<tr>
<td>Vehicle miles of travel (million miles/km²)</td>
<td>9.84 (0.19)</td>
<td>1.62 (0.05)</td>
<td>0.20 (0.01)</td>
<td>0.05 (0.00)</td>
</tr>
<tr>
<td>CO2 emissions (thousand tons/km²)</td>
<td>7.62 (0.15)</td>
<td>1.21 (0.03)</td>
<td>0.15 (0.00)</td>
<td>0.03 (0.00)</td>
</tr>
<tr>
<td>Vegetation CO2 assimilation (thousand tons/km²)</td>
<td>0.14 (0.00)</td>
<td>0.31 (0.00)</td>
<td>0.51 (0.01)</td>
<td>0.51 (0.03)</td>
</tr>
<tr>
<td>CO2 balance (thousand tons/km²)</td>
<td>7.48 (0.13)</td>
<td>0.90 (0.03)</td>
<td>-0.36 (0.02)</td>
<td>-0.47 (0.03)</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses are standard error of mean.

Table 3. The per capita household energy and fuel consumption and carbon emissions and sinks by settlement densities in Florida, 2001

<table>
<thead>
<tr>
<th>Settlement densities</th>
<th>Urban</th>
<th>Suburban</th>
<th>Exurban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption (million Btu/person)</td>
<td>36.91 (0.14)</td>
<td>36.53 (0.17)</td>
<td>35.85 (0.33)</td>
<td>32.36 (1.05)</td>
</tr>
<tr>
<td>Vehicle miles of travel (miles/person)</td>
<td>5,862.85 (58.91)</td>
<td>5,865.64 (110.13)</td>
<td>6,314.17 (274.53)</td>
<td>5,608.84 (481.39)</td>
</tr>
<tr>
<td>CO2 emissions (kg/person)</td>
<td>4,468.87 (28.05)</td>
<td>4,450.45 (49.66)</td>
<td>4,611.58 (122.45)</td>
<td>4,123.03 (234.11)</td>
</tr>
<tr>
<td>Vegetation CO2 assimilation (kg/person)</td>
<td>1,192.00 (128.21)</td>
<td>2,057.51 (90.84)</td>
<td>19,408.97 (1,041.00)</td>
<td>91,689.51 (17,085.57)</td>
</tr>
<tr>
<td>CO2 balance (kg/person)</td>
<td>4,340.66 (28.04)</td>
<td>2,392.94 (108.51)</td>
<td>-14,797.40 (1,037.89)</td>
<td>-87,566.48 (17,051.87)</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses are standard error of mean.

consumption and carbon emissions for effective emissions reductions.

Summary and Conclusions

In this study, we presented a new approach for spatially detailed carbon balance accounting and applied this approach to investigate the carbon balance between household emissions and vegetation assimilation by Census tract for the state of Florida. Household carbon emissions in the presented Florida study were composed of CO2 released through residential consumption of energy and transportation fuels. We excluded carbon emissions from the commercial sector for this inventory. The tract-level residential energy and fuel consumption estimates were constructed based on Census household characteristics and the U.S. Department of Energy household consumption survey. Vegetation carbon sinks were measured as plant net photosynthesis using biophysical remote sensing techniques.

The analysis showed that Florida was able to self-assimilate its residential energy and transportation fuel-related carbon emissions (62 million tons) through the presence of vegetation (88 million tons) according to
estimates in 2001. Household energy and fuel consumption, carbon emissions, and vegetation carbon sinks, however, vary significantly by Census tract across the state. The consumption-based carbon emission sources tend to be separated from vegetation carbon sinks. Consumption measures aggregated by settlement densities showed that the urban and suburban densities (settled at \( \geq 0.1 \) housing units per acre) were associated with the highest per capita energy consumption, whereas the per capita consumption of household transportation fuels tended to be the highest in exurban densities (settled at 0.025–0.1 housing units per acre). Both exurban and rural densities were associated with a significant amount of vegetation carbon sinks. The \( \text{CO}_2 \) balance indicates net carbon sources occurring in the urban and suburban densities, with net sinks in the exurban and rural densities.

This study contributes a spatial inventory of energy consumption and carbon emissions and sinks (Zimmerer 2011). The spatial inventory approach is used to provide baseline carbon fluxes estimates for establishing emission targets, distributing emission responsibilities, and establishing carbon trading programs associated with specific geographic regions or locations. Our methods are broadly applicable and can be integrated with other socioeconomic metrics for sustainability assessments. For example, future efforts might focus on the energy and carbon consequences of various urban development patterns, in particular, the location of individualized communities as well as the constituent densities of residential and commercial development (Horner 2008). This will lead to new insights with respect to sustainable low-carbon energy consumption and transportation behavior.

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