Greenhouse Gas Emissions along the Rural-Urban Gradient

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ABSTRACT

This paper investigates how land use relates to greenhouse gas emissions, using data sources that are readily available to municipal planners. It presents a causal framework linking settlement patterns to greenhouse gas emissions via landscape impacts (deforestation, carbon sequestration by soils and plants, urban heat island), infrastructure impacts (transportation-related emissions, waste management-related emissions, electric transmission and distribution losses), and buildings (residential, commercial). This is not a full accounting because it does not include impacts from industrial activities, agriculture, and consumer behavior not related to land use, such as food consumption and air travel. Exploratory case studies of municipalities lying along a gradient of increasing population density suggest that per-capita carbon dioxide emissions vary widely, following an inverted “U” shape, with post-war suburbs riding the pinnacle. Reflecting their central regional roles, municipalities with good jobs-to-housing ratios have higher per-capita emissions because they host both residential and commercial buildings. Buildings typically contribute more emissions than personal transportation. Vehicle-miles traveled per capita shrink most dramatically at very high population densities and where transit options exist. Changing land-use patterns is a political challenge because localism and outdated zoning ordinances subvert regional solutions. Technical fixes, especially green buildings, must be part of the solution.

INTRODUCTION

State and local governments have taken the lead in addressing global warming while a federal consensus for action slowly builds in the United States. Land-use planning is one of the primary public policy tools available at the local level. Policy entrepreneurs are touting “location efficiency” (Holtzclaw et al 2002), “cool spots” (Steuteville 2008), “post-carbon cities” (Lerch 2007), and other planning-based approaches for reducing greenhouse gas emissions. Although the most important national sources of these emissions are well documented, their relative importance at the local level is less well understood. Given the diversity of land-use patterns present in any metropolitan area, it is reasonable to suspect that different emissions sources dominate in different localities. If so, perhaps the solutions should also vary by location.

This paper explores the variation in greenhouse gas emissions across a set of case study municipalities lying along the rural-to-urban gradient. In an acknowledgement of the exploratory nature of this project, and to encourage replication, this paper uses data sources that are readily available to U.S. municipal planners. These case studies illustrate how land-use choices and settlement patterns seem to influence greenhouse gas emissions. The analytical differences among cases lying on a density gradient carry over into prescription, in line with the New Urbanist transect planning framework embodied in the Smartcode (DPZ 2008).

This paper focuses on land-use planning because it belongs to local governments, not because it is the only policy tool available for mitigating global warming. To make a difference, such local action must ultimately nest within a framework of international treaties, national energy and environmental policies, and state policies. While debates over global greenhouse gas emissions caps, national carbon taxes, appliance and vehicle efficiency standards, and innovation policy play out, local planners can get to work on their part of the problem.

Illustrative of state and local actions, the governor of New Jersey signed an executive order (EO 54) setting ambitious goals for the reduction of greenhouse gas emissions in February 2007. The goals were adopted by the state legislature in June and signed by the governor in July 2007 (New Jersey Office of the Governor 2007). The legislation calls for the reduction of greenhouse gas emissions to 1990 levels by 2020 (a 20 percent reduction) and an 80 percent reduction below 2006 levels by 2050. In developing plans to meet these targets, many parties want to know how land use policies influence greenhouse gas emissions and what land-use policy changes could help reduce emissions in the long run, by 2050.

The next section of this paper describes the research design and framework used to analyze the relationship between greenhouse gas emissions and municipal land use. The third section summarizes the findings from a set of detailed case studies in New Jersey. The final section offers conclusions and recommendations to help municipalities reduce their greenhouse gas emissions. An appendix provides methodological details.

FRAMEWORK LINKING LAND USE AND GHG EMISSIONS

Urban metabolism studies have documented a strong correlation between settlement patterns and per-capita greenhouse gas emissions (Kennedy, Cuddihy and Engel-Yan 2007). Personal carbon footprint calculators highlight the determining role of everyday behaviors (e.g., Carbonfootprint.com 2008). In order to understand current linkages between emissions and municipal land use, and to begin thinking systematically about the future, we develop an explicit causal framework. This research extends a conceptual framework linking urban sprawl to residential energy use developed by Rong (2006) and elaborated in Ewing and Rong (2008).

Rong's framework identifies three connections between sprawl and residential energy use. The first link is through the transmission and distribution of electricity (T&D). Energy loss through T&D is greater in spread-out areas because longer low-voltage wires are needed to connect electricity uses. Rong identifies the second link as the housing stock itself. Energy usage varies based on the housing type and size with smaller, denser units requiring less energy than larger, spread out units. The age and quality of the unit also impacts its energy needs. The third link is between urban density and the creation of urban heat islands (UHIs). Urban heat islands increase localized temperatures, causing both positive and negative effects on residential energy use. Higher temperatures can mean less energy use for heating during the winter, but more energy use for cooling in the summer. Rong's framework excludes vehicular emissions.

Newman and Kenworthy (1999) are emblematic of another line of research that focuses chiefly on the transportation part of the equation. Ewing et al (2007) summarize this research, showing that sprawling land-use patterns and low population densities correlate with higher vehicle miles traveled (VMT) per capita, greater gasoline consumption, less use of public transit, and higher per-capita greenhouse gas emissions.

For this paper, we pursue a more complete model that accounts for the impacts on greenhouse gas emissions of landscape, infrastructure, and buildings. Figure 1 shows the multiple pathways by which land use influences emissions. Low-density residential and commercial development requires more energy both directly for operating the physical structures and indirectly by increasing vehicle miles traveled between residential and commercial areas. Sprawling development may increase the amount of electrical energy lost in transmission and distribution. The impact of urban sprawl on the landscape and urban heat islands has mixed effects. Preserved forest landscapes sequester carbon, whereas sprawling development releases carbon from soils and plants, and increases the amount of impervious surface. At the same time, higher density development does create an urban heat island effect (UHI) that has both positive and negative contributions to the climate temperature. Thus, settlement patterns influence greenhouse gas emissions by means of landscape changes, infrastructure choices, and building characteristics.

Note that a full accounting of greenhouse gas emissions would also track items not tallied here including industrial activities, freight transportation and agriculture. It would also include items not associated with settlement patterns such as food consumption and air travel. The following points summarize the methodology used to implement the framework. An appendix provides a worked example. Full details are available from the author.

Residential Buildings

The impact of the residential building stock on greenhouse gas emissions varies by housing unit type, size, and location. Using data on electricity, natural gas, fuel oil, and other energy use by residential buildings in the Mid-Atlantic region from the Residential Buildings Energy Consumption Survey (RBECS) (EIA 2004), we develop per-household energy use measures. We multiply those times the number of households of various types in each case study municipality as shown in the 2000 Census (U.S. Census Bureau 2007) to get total residential energy use. We then convert energy use to carbon dioxide emissions using conversion factors from the U.S. Department of Energy (EIA 2008). Large units in lower density areas, e.g. single-family detached units that are also the most popular type, create the most emissions in both their construction and operation. Smaller units in multifamily complexes use less energy and therefore create fewer emissions. Because the RBECS data do not resolve at a fine enough level of geographic detail to distinguish between (often smaller) suburban and (often larger) exurban single-family detached houses, this study may understate the variation in emissions along the gradient. Residential buildings affect emissions in other areas such as transportation (discussed below) because higher-density residential areas can reduce auto trips. However, there are also many opportunities across all housing types for reducing emissions through more efficient technologies and designs.

Commercial Buildings

Similar to the residential building stock, the emissions from commercial buildings vary by building type, size, and location. Using data on electricity, natural gas, fuel oil, and other energy use by commercial buildings in the Mid-Atlantic region from the Commercial Buildings Energy Consumption Survey (EIA 2006), we develop per-employee energy use measures. We multiply those times the number of employees on payroll in each case study municipality as shown in Zip Code Business Patterns (U.S. Census Bureau 2007), adjusted by the total employment data from the American Community Survey (U.S. Census Bureau 2008), to get total commercial energy use. We then convert energy use to carbon dioxide emissions using conversion factors from the U.S. Department of Energy (EIA 2008). We thereby capture some industrial activities too, specifically those taking place in standard buildings. However, we do not capture the full range of industrial activities, especially those located in heavy industrial facilities. If there are systematic variations in commercial building types along the gradient, this study may understate those variations. There are substantial opportunities to reduce greenhouse gas emissions through the use of more efficient construction materials and optimized appliances, lighting, heating and cooling systems.

Transportation

We rely on the National Household Travel Survey (NHTS) Transferability study for census tract-level estimates of daily vehicle miles traveled (ORNL 2007). We annualize those estimates and convert them to carbon dioxide emissions using the fleet-average miles per gallon (EPA 2005). The NHTS Transferability study extends a national sample survey of travel behavior to census tracts nationwide by categorizing households into clusters based on settlement patterns (urban, suburban, rural), household characteristics (e.g., median household income, vehicle ownership), and census tract characteristics (e.g., employment rate), and extrapolating travel behavior to similar households in all census tracts (McGuckin 2005).

The NHTS transferability study produces modeled rather than measured local vehicle miles traveled (VMT). As such, it probably understates the actual variation in VMT across towns. VMT measurements at the local level do not exist on a national basis, hence localities must resort to second-best measures. Figure 2 confirms that related measures from the decennial census do show more variation than the modeled VMT from the NHTS Transferability study. Increased use of village-style, and especially, transit-oriented development has the potential to reduce auto trips, and therefore emissions, by encouraging people to take public transit, walk or use forms of transportation other than driving.

Electric Transmission and Distribution Losses

Approximately 9% of the electrical energy that is generated in the United States is lost during transmission and distribution (EIA 2007). Variation in that percentage across settlement patterns is unknown, but probably minor, and at the local scale it is driven more by loading on network elements than by the length of electric lines. More important, however, is that sprawl precludes the possibility of using highly efficient cogeneration of electricity, heating, and cooling to serve district energy networks such as are found in dense downtowns, college campuses, and military bases (Andrews 2008). Compact, mixed-use developments, by contrast, are ideal hosts for cogeneration and district energy systems.

Waste Management

Wastewater management and solid waste management both cause greenhouse gas emissions. Septic systems and sewage treatment plants release methane and nitrous oxide, landfilling of solid waste releases methane, and incineration of solid waste releases nitrous oxide and carbon dioxide. To a first order, the quantities track population (Andrews 2001). Using statewide estimates developed from an inventory of landfills, incinerators, septic systems, and sewage treatment plants (NJDEP 2008) and normalizing by the state population, we develop per-capita estimates of CO_2-equivalent emissions due to waste management. We multiply these by the number of residents in each municipality. Waste reduction, re-use, and recycling can all reduce the greenhouse gas emissions associated with waste management.

Landscape

Impermeable surfaces, farming techniques, and land use changes are all factors in a municipality's contribution to global warming. Land Use/Land Cover data sets provide a basis for evaluating land use changes over time (NJDEP 1930, 1986, 1995, and 2002a). Using a modified Anderson classification system (NJDEP 2002b), and a method for temporal comparisons based on Hasse and Lathrop (2001), we track changes in land use in New Jersey.

Soil and trees are two of the most important sources of natural carbon sequestration. While both are still plentiful in New Jersey, the fast rate of build-out and land-use change has severe consequences on the amounts of carbon that soils and trees sequester. Soil is the largest terrestrial sink for storing carbon, however changes in land use such as cropland establishment and cultivation, abandonment of agricultural practice, and subsequent forest re-growth dictate the release of carbon by soil (Chen et al 2006). Likewise, the disturbance of soil during the process of constructing buildings, parking lots, and roads initially causes a large release of carbon into the atmosphere, and the subsequent compaction and covering of the soil eliminates sequestration entirely. Sequestration rates for New Jersey municipalities are based on measured averages from the literature (Sampson and Hair 1996) that distinguish types and ages of trees, and the significant role of street trees which grow larger and faster than those in forests (Nowak and Crane 2002). Following NJDEP (2008) we assume that undisturbed freshwater wetlands support tree growth and treat carbon sequestration in agricultural areas as negligible because it so rapidly turns over its carbon content.

The rapid rate of development and clearing of forests will only continue to lessen the amount of carbon sequestered per year. Street and shade trees also play an important role in the sequestration of polluting emissions, as each individual tree sequesters approximately 19 lbs (8.6 kg) of CO2 per year (Akbari 2002). Urban and suburban tree-planting programs are a step in the right direction, but in most places they do not come close to making up for the loss of carbon that was sequestered each year by the lost open space. American Forests (2003) has developed a methodology to help jurisdictions think through these landscape-related decisions.

Urban Heat Island

The urban heat island phenomenon makes urban and suburban temperatures measurably warmer than surrounding rural areas. This happens when a large fraction of the natural land cover in an area is replaced by built surfaces that trap incoming solar radiation and then re-radiate it at night slowing the cooling process. Harmful effects of the UHI problem are increased energy consumption, air conditioning costs, heat related illnesses and mortality, as well as air pollutants (Stone 2005). UHI increases summer air-conditioning burdens while reducing winter heating demands, and the net energy cost depends on location. In New Jersey it nets out to approximately zero change in energy use (Rong 2006). This is not the case in other regions, so future applications of this method should more thoroughly tackle UHI. Mitigation and policy strategies include the introduction of green roofs, high-albedo surfaces, additional tree planting and a reduction in impervious surfaces.

Complex Causality

The categories in the framework illustrate the complexity of quantifying the relationship between various land uses and greenhouse gas emissions in order to develop targeted policy changes. For example, greater residential density decreases auto use but it also diminishes opportunities for carbon sequestration. What is the net effect? Can design or regulation change the market demand for single-family detached units on large lots? Household income, occupational choices, and diverse personal preferences muddy the causal story and constrain the public policy options.

Varied Settlement Patterns

Land-use patterns vary along a gradient of increasing population density, and the rural-to-urban transect is a useful analytical tool for studying urban morphology. It also forms the basis for a normative theory of urban planning that is “based on universal ecological principles” (Duany & Talen 2002). This theory has roots, first, in concepts of regional optimality associated with Geddes, and second, in MacHarg’s sense that development needs to fit appropriately in a place. New Urbanists have developed this theory into a model form-based land use ordinance called the Smartcode (DPZ 2008). The Smartcode calls land-use categories along the rural-to-urban gradient “sectors” at the regional level, and “transects” at the local level. Good design, therefore, introduces variety at both the regional and local scales (see Figure 3). Smartcode sector categories include preserved, reserved, controlled/restricted growth, intended growth, and infill growth. Within regional Smartcode sectors, the local transect categories include natural, rural, sub-urban, general urban, urban center, and urban core. Each specifies a sequence of appropriate land uses from less dense to more dense development patterns.

The next section applies the land use-emissions analysis framework to case studies of nine municipalities and the overall State of New Jersey. U.S. Census data, state geographic information system data, and local land use planning documents provide the grist for this analysis. Case study towns are selected across a range of land use categories that lie along the population-density gradient that is associated with planning area types in the New Jersey State Development and Redevelopment Plan (NJSPC 2001). The spectrum of planning areas includes environmentally sensitive, rural, fringe, suburban, and metropolitan categories. These New Jersey categories are approximately equivalent to the Smartcode sector and transect categories (see Table 1).

Although there are only five planning area types, more than five case studies are included in recognition of additional factors that may influence greenhouse gas emissions. These factors include income levels, transit access, and jobs/housing balance (see Table 2). Specifically, for their positions in the population density gradient, Neptune and Highland Park provide contrasting lower-income cases, Cherry Hill has transit access, and Jefferson is an exurban bedroom community.

The case studies use detailed analysis of local conditions to estimate emissions. Each case study analyzes common framework categories—buildings, infrastructures, and landscapes—to estimate current greenhouse gas emissions based on appropriate per-housing unit, per-acre, per-person, or per-job multipliers. Master plans, redevelopment plans, and zoning ordinances for most of the case study municipalities are online (CGS 2008), with the remainder available from local officials. Demographic data come from U.S. Census (2007a) and NJDOL (2001). Maps and case study reports are available from the author.

Research Limitations

Before discussing the results, it is useful to consider the many limitations of this exploratory research. The cases studied here do not represent the full range of U.S. or even New Jersey municipalities. The emissions calculations rely heavily on the literature and are not based on detailed primary research, hence they should not be viewed as definitive. The variation in transportation- and building-related emissions is probably understated. A number of second-order phenomena are ignored, such as the effects of settlement patterns on electric line losses and on CO_2 emissions by garbage trucks. The methodology employed here should be viewed as a first approximation using widely accessible data, and as better information becomes locally available, it can be inserted to support more precise estimates of greenhouse gas emissions. In the future, the needed data should be measured, not estimated.

The emissions estimates resulting from this modeling framework do lie within 6% of the official New Jersey greenhouse gas emissions inventory (NJDEP 2008), once adjusted for items not included here: freight and air transportation, industrial processes, and agriculture. Much of the remaining discrepancy is due to divergent assumptions about carbon sequestration rates associated with specific landscape types, and reliance on a different data set to characterize buildings.

RESULTS

Two sets of results follow. First is an examination of statewide trends in population growth and land-use changes. It is followed by a summary of municipal case studies.

Statewide Trends

According to the U.S. Census (2007a), New Jersey has seen continued population growth over many decades, with the greatest jumps prior to 1970 and then again between 1990 and 2000, when the population reached 8.4 million. This growth has driven a demand for housing, infrastructure, and economic activities that produce greenhouse gas emissions. Looking forward, continued population growth is expected to increase greenhouse gas emissions even if per-capita emissions rates stabilize. A reasonable projection for New Jersey's population in 2050 is over 11 million people (NJSSI 2007).

As one of the most affluent of the U.S. states, New Jersey is responsible for a significant amount of greenhouse emissions associated with its high levels of consumption of nondurable goods, durable goods, transportation and housing. New Jersey has the highest population density of any U.S. state at 1,135 persons per square mile (438 persons per square kilometer). The U.S. average is 80 persons per square mile (31 persons per square kilometer), and higher than average commute times (30 minutes compared to a national average of 26) (U.S. Census 2007a). As a result of this density there are numerous competing interests for land use within the state. In the context of global warming emissions, the various land uses have both positive and negative impacts. The urban areas of the state contribute tremendously to overall greenhouse gas emissions, while the forests provide a method of sequestering some of the CO2 emissions.

Reviewing recent changes in state land use, it is evident that New Jersey's largest land use growth is in the urban category, mostly at the expense of agricultural land, forested land, and wetlands. Between 1986 and 2002, New Jersey's urban land grew by 19.2% to 1.44 million acres (582,936 hectares), agricultural land shrank by 19.8% to 0.60 million acres (241,518 hectares), forested land shrank by 4.0% to 1.58 million acres (637.470 hectares), wetlands shrank by 3.8% to 1.01 million acres (408,548 hectares), barren land increased by 7.2% to 0.06 million acres (24,828 hectares), and water increased by 2.2% to 0.80 million acres (323,981 hectares) (NJDEP 1986, 1995 & 2002). From 1986 to 1995, the state gained 126,037 acres (51,005 hectares) of urban land, and from 1995 to 2002 it gained 105,874 acres (42846 hectares) of urban land, indicating that the rate of land conversion is continuing at a rapid pace (NJDEP 1986, 1995 & 2002).When the forest data are dissected a bit further, it appears that the rate of carbon sequestration may be slowing because an increasing fraction of the forests are mature rather than rapidly growing.

The following section summarizes the major findings from the case studies. As discussed earlier, the communities studied represent a variety of categories. The cases are ordered from lower density, rural communities to higher density suburban and finally urban communities, with additional cases included that vary income, transit access, and jobs/housing ratios (see Table 2).

Municipal Case Studies

By comparing New Jersey municipalities arrayed along the rural-to-urban gradient, we observe significant differences in greenhouse gas emissions, land-use laws, and potential for change. Table 3 summarizes estimated greenhouse gas emissions by category and municipality. Figure 4 shows per-capita emissions rates. See the appendix for more on the calculation methodology. Detailed writeups on each municipality are available from the author.

Figure 4 shows that current per-capita carbon dioxide emissions vary by a factor of two across the gradient in New Jersey, but there is a rough inverted “U” shape and not a monotonic relationship between population density and per-capita emissions. This shape is the net result of several countervailing patterns, so that as density increases, carbon sequestration decreases, but also deforestation decreases, residential energy use decreases, and transportation energy use decreases. Carbon sequestration on preserved forest lands outweighs anthropogenic greenhouse gas emissions in Washington, the least-dense township. Because exurban development is taking place mostly on former agricultural lands, leaving forested areas intact, sequestration outweighs the higher transportation- and housing-related emissions in Woolwich and Jefferson. The post-war suburbs in the middle (East Brunswick and Cherry Hill) have the highest net emissions rates, because they lack forests, depend on automobiles, and have large, single-family detached houses. Inner-ring suburbs (Neptune, Montclair, Highland Park) have smaller and more attached housing units, more walking and transit use. Hoboken, the most-dense city, has relatively small per capita emissions because of smaller, multifamily housing units, walkable streets, and access to public transit.

Unlike some other factors, commercial activities do not vary systematically along the population density gradient, and really should be studied in their regional context. Bedroom towns such as Jefferson and Highland Park have few commercial buildings, and hence lower per-capita emissions from buildings, than towns with more balanced growth such as East Brunswick and Cherry Hill. Of course, the residents of bedroom towns also suffer under higher property tax burdens. There is also an important transportation-related consideration because per-capita vehicle miles traveled (VMT), and hence CO_2 emissions from driving, are lower when jobs and housing are more balanced, and when retail and housing are well mixed (Cervero and Duncan 2006). In short, greenhouse gas emissions from commercial activities should be considered at the larger, regional scale.

According to the National Household Travel Survey Transferability estimates (ORNL 2007) used in this study, transportation-related emissions per capita do not drop dramatically until reaching the very high population density and superb transit access of the Hoboken case. Access to rail transit also seems to play a role in reducing transportation-related per-capita emissions in Montclair below those of the other inner-ring suburb (Highland Park) and its economic peers (East Brunswick, Cherry Hill, Woolwich, Jefferson). Income also seems to play a role, with less wealthy Washington and Neptune having relatively lower per capita transportation-related emissions than wealthier communities. These results may be understated, making it essential that local studies commence to better understand the land use-transport link.

Buildings (residential and commercial) are a larger contributor of carbon dioxide emissions than transportation in all case study municipalities, just as they are nationally (EIA 2007b). Also notable are the relatively small impacts on emissions due to waste management, electric line losses, and the urban heat island. Carbon sequestration in soils and forests is significant in rural towns, and deforestation is relatively insignificant in these case studies.

CONCLUSIONS AND RECOMMENDATIONS

This research confirms that the causal relationship between land use and greenhouse gas emissions is complex. Settlement patterns affect building practices, infrastructure designs, travel behavior, and landscape performance. Numerous interrelated factors, such as income and household size, also affect emissions levels, making it difficult to isolate the net effects of individual policies. Future research should focus on developing well-documented, data-driven, usable models for use in planning support systems and policy analysis. Surveys of actual local energy usage in buildings, infrastructure elements, and vehicles will be particularly valuable.

Nonetheless, there are clear lessons regarding the most important factors affecting greenhouse gas emissions along the urban density gradient. Coincident with New Urbanist principles embodied in the Smartcode, some lands should be preserved in forest, because they are valuable carbon sinks. Likewise, regions need densely urban areas that are walkable and have rail transit service, because they support a lower-carbon lifestyle. Further, sprawling suburbs are a carbon-intensive form of land use.

The forest-based sequestration strategy has clear limits, however, in this small and densely populated state. Using just its own land area, New Jersey could only support 450,000 residents living today’s lifestyle on a carbon-neutral basis. The Census Bureau puts the 2007 population at 8,685,920.

Transportation-related greenhouse gas emissions decrease along the gradient, but only exceptionally high densities coupled with transit access and walkable destinations yield dramatic reductions in per-capita emissions. In walkable, inner-ring suburbs that lack rail transit and employers, such as Highland Park, it appears that many residents rely on their cars almost as much as they do in sprawling, post-war suburbs. The particular data source used in this study probably underestimates the variability, so the transportation results should be treated with caution.

Two lessons are orthogonal to, rather than in agreement with, the principles of the Smartcode and the transect planning approach it embodies. First, buildings in all locations are significant greenhouse gas emitters, and need to become much more efficient. Second, the non-transportation infrastructure factors such as waste management and electric line losses are only second-order greenhouse gas emitters, and therefore warrant less attention.

The Smartcode approach offers simple guidance on what to do with existing automobile-dependent suburbs: encourage infill development. While helpful, this is a limited and politically challenging prescription. Needed are much stronger regional planning frameworks, and an embrace of technical fixes.

New Jersey, for example, has pursued a statewide development framework through the adoption of the State Plan and its cross acceptance process. Statewide growth management concerns are also addressed through the creation of the Highlands, Pinelands, and Meadowlands protection areas. Most development decisions, however, still remain in the hands of individual communities. Most towns are extremely resistant to higher density due to concerns that it decreases adjacent property values. To the extent that these development decisions remain in the hands of voters, in many places densification proposals will fail politically. Thus, states like New Jersey, that are home to many small communities with a tradition of home rule, need to encourage regional optimality through transit infrastructure investments, workforce housing requirements, and redevelopment.

Given the large contributions of residential and commercial buildings to local greenhouse gas emissions, jurisdictions nationwide should actively encourage green, energy-efficient building. This means establishing performance standards for state and municipal facilities, updating building codes, incorporating energy-efficient design requirements into permit approval processes, and providing incentives for the use of green building technology in new, existing, and rehabilitated structures.

The process of reorienting settlement patterns toward smarter growth and greenhouse gas emissions reductions is complicated and slow. Many institutional and legal barriers exist, but they are not insurmountable. While state and national governments slowly develop more appropriate policy frameworks, municipalities can begin to act now to reduce their greenhouse gas emissions. They should act in ways that are appropriate to their placement along the rural-to-urban gradient.

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Appendix: Emissions Calculations (using example of Highland Park, NJ)

Residential CO_2 Emissions Calculation Steps

1. Download the RBECS Microdata file. See EIA (2004).
2. Sort by Census Division and Housing Unit Type, delete all records not in the Census Division in which jurisdiction is located.
3. Multiply all other fields by the weighting factor field do scale survey results to actual regional housing stock.
4. Sum the weighted number of housing units and delivered energy consumption by category for each cell in the table below.
5. The table shows total fuel use by housing type (Mid-Atlantic Division in 2001). Note that U.S. data sources are not in SI units. Therefore, the conversion to SI units (metric tons) occurs in the final step of each calculation.

Housing Unit Type	Units	Kerosene (gal)	Electricity (kWh)	Nat. Gas (100 CF)	Fuel Oil (gal)	LPG (gal)
Mobile Homes	487,669	91,051,345	4,411,782,975	69,014,330	11,806,845	89,417,540
Single-Family Detached	6,114,069	9,067,728	66,883,237,850	3,445,740,440	1,507,395,909	203,719,352
Single-Family Attached	2,403,792	-	14,833,021,301	1,942,206,338	159,421,163	-
Apartments in Buildings with 2 to 4 Units	2,026,419	405,675	11,373,110,976	1,369,325,253	210,850,993	714,071
Apartments in Buildings with 5 or More Units	3,814,649	22,562	18,290,581,993	898,613,670	306,886,635	2,503,002

6. Divide total fuel use in each cell above by the number of housing units to get the regional average fuel use per housing unit by housing type (Mid-Atlantic Division in 2001).

Housing Unit Type	Kerosene (gal)	Electricity (kWh)	Nat. Gas (100 CF)	Fuel Oil (gal)	LPG (gal)
Mobile Homes	186.71	9046.68	141.52	24.21	183.36
Single-Family Detached	1.48	10939.24	563.58	246.55	33.32
Single-Family Attached	0.00	6170.68	807.98	66.32	0.00
Apartments in Buildings with 2 to 4 Units	0.20	5612.42	675.74	104.05	0.35
Apartments in Buildings with 5 or More Units	0.01	4794.83	235.57	80.45	0.66

7. Get conversion factors from fuel use to CO2 emissions. The table shows coefficients from EIA (2008), except for electricity (see below).
8. Electricity conversion factors are state-specific, based on EIA (2007), adjusted for electricity imports if necessary.

Kerosene	Electricity	Natural Gas	Fuel Oil	LPG
(lb CO2/gallon)	(lb CO2/kWh)	(lb CO2/100 CF)	(lb CO2/gallons)	(lb CO2/gallons)
21.54	0.85	12.06	22.38	12.81

9. Calculate CO2 emissions in pounds per household by fuel type and household type (Mid-Atlantic Division in 2001).

Housing Unit Type	Kerosene	Electricity	Natural Gas	Fuel Oil	LPG
Mobile Homes	4,021.11	7,693.43	1,706.62	541.93	2,347.89
Single-Family Detached	31.94	9,302.89	6,796.33	5,518.67	426.66
Single-Family Attached	-	5,247.63	9,743.63	1,484.52	-
Apartments in Buildings with 2 to 4 Units	4.31	4,772.88	8,148.91	2,329.08	4.51
Apartments in Buildings with 5 or More Units	0.13	4,077.59	2,840.80	1,800.78	8.40

10. Add across rows above to get total CO2 emissions per household (pounds/year) by household type (in Mid-Atlantic Division in 2001). To get metric tons/year divide by 2200.
11. For a jurisdiction (Highland Park, NJ in this example), get the number of housing units by type (U.S. Census SF3, Housing, Structural Characteristics, Units in Structure). This table based on U.S. Census (2007a).
12. Multiply the number of housing units by type times the CO2 emissions per household calculated above to get total residential CO2 emissions.

Housing Unit Type	CO2 emissions per household (Pounds/year)	CO2 emissions per household (metric tons/year)	Units in Jurisdiction	Residential CO2 Emissions in Jurisdiction (metric tons)
Mobile Homes	16,311	7.4	0	0
Single-Family Detached	22,076	10.0	2,246	22,538
Single-Family Attached	16,476	7.5	69	517
Apartments in Buildings with 2 to 4 Units	15,260	6.9	1,691	11,729
Apartments in Buildings with 5 or More Units	8,728	4.0	1,893	7,510
Total Residential CO2 Emissions in Jurisdiction				42,294

Commercial CO_2 Emissions Calculation Steps

1. Download the CBECS Microdata file. See EIA (2006).
2. Sort by Census Division, delete all records not in the Census Division in which jurisdiction is located.

3. Multiply all other fields by the weighting factor field do scale survey results to actual regional building stock.
4. Sum the weighted number of employees and delivered energy consumption by category for each cell in the table below.
5. The table shows total fuel use in commercial buildings (Mid-Atlantic Division in 2003).

Employees	Electricity (kWh)	Nat. Gas (100 CF)	Fuel Oil (gal)
11,750,679	115,738,566,587	3,426,240,557	763,647,568

6. Divide total fuel use in each cell above by the number of employees to get the regional average annual fuel use per employee.

Electricity (kWh)	Nat. Gas (100 CF)	Fuel Oil (gal)
9,850	292	65

7. Get conversion factors from fuel use to CO2 emissions. The table shows coefficients from EIA (2008), except for electricity (see below).
8. Electricity conversion factors are state-specific, based on EIA (2007), adjusted for electricity imports if necessary.

Electricity	Natural Gas	Fuel Oil
(lb CO2/kWh)	(lb CO2/100 CF)	(lb CO2/gallons)
0.85	12.06	22.38

9. Calculate CO2 emissions in pounds per employee by fuel type (Mid-Atlantic Division in 2003).

Electricity	Natural Gas	Fuel Oil	Total	Total
(lb CO2/emp)	(lb CO2/emp)	(lb CO2/emp)	(lb CO2/emp)	(metric ton CO2/emp)
8,376	3,516	1,454	13,347	6.1

10. For a jurisdiction (Highland Park, NJ in this example), get number of employees from Zip Code Business Patterns (U.S. Census Bureau 2007b).
11. Multiply the number of employees times the total CO2 emissions per employee to get total commercial CO2 emissions in jurisdiction.

Employees	CO2 Emissions	CO2 Emissions
	(lb CO2)	(metric tons CO2)
1,829	24,406,702	11,094

Landscape CO_2 Emissions Calculation Steps

1. For a jurisdiction (Highland Park, NJ in this example), perform a land cover classification analysis using a GIS tool. The following is based on NJDEP (2002a).
2. Calculate total acreage for each land cover category.

3. Get annual carbon sequestration rates per acre by land cover category.
4. Calculate carbon sequestration by land cover category. Example ignores ignores grasslands and built-up areas.

Land Cover Category	Acres	Sequestration Rate (lbs CO2/year)	Note	CO2 Sequestered (lb/year)
Deciduous Forest 10-50% Crown Closure	6.73	(1,760)	[1]	(11,845)
Deciduous Brush/Shrubland	18.04	(1,760)	[1]	(31,750)
Mixed Forest (>50% Deciduous with 10-50% Crown Closure)	0	(1,760)	[1]	(0)
Deciduous Forest > 50% Crown Closure	53.5	(3,909)	[2]	(209,132)
Mixed Forest (>50% Deciduous with >50% Crown Closure)	12.38	(3,909)	[2]	(48,393)
Coniferous Forest 10-50% Crown Closure	0	(9,826)	[3]	(0)
Coniferous Brush/Shrubland	0	(9,826)	[3]	(0)
Mixed Forest (>50% Coniferous with 10-50% Crown Closure)	0	(9,826)	[3]	(0)
Coniferous Forests >50% Crown Closure	0	(7,516)	[4]	(0)
Mixed Forest (>50% Coniferous with >50% Crown Closure)	0	(7,516)	[4]	(0)
Freshwater Wetlands	40.17	(4,275)	[5]	(171,722)
Urban	892.17	(3,919)	[6]	(3,496,748)
Total Sequestered (lb CO2/year)				(3,969,590)
Total Sequestered (metric tons CO2/year)				(1,804)

Notes:
[1] Sequestration rate based on 25 year old northeast maple-beech-birch forests in Sampson & Nair (1996).
[2] Sequestration rate based on 120 year old northeast maple-beech-birch forests in Sampson & Nair (1996).
[3] Sequestration rate based on 25 year old northeast white and red pine forests in Sampson & Nair (1996).
[4] Sequestration rate based on 120 year old northeast white and red pine forests in Sampson & Nair (1996).
[5] Sequestration rate based on NJDEP (2008).
[6] Sequestration rate based on Nowak and Crane (2002).

5. For the jurisdiction (Highland Park, NJ in this example), calculate carbon emissions due to land use changes by comparing land cover maps from two time periods. The following is based on analysis of NJDEP (1995 & 2002) and Hasse & Lathrop (2001). It excludes conversion of agricultural land.
6. Annualize the loss of forested acreage.
7. Get an estimate of CO2 released per acre. Estimate shown is from NJDEP (2008).
8. Multiply acres lost times CO2 released per acre to get total CO2 emissions from land use changes.

Acres lost (1995-2002)	Average annual loss (acres/year)	CO2 released (metric tons/acre)	Total CO2 released (metric tons)
2.31	0.33	141	46

Transportation CO_2 Emissions Calculation Steps

1. For the jurisdiction (Highland Park, NJ in this example), get daily Vehicle Miles Traveled (VMT) per household for relevant census tracts (ORNL 2007).
2. Multiply by 365 to get annual VMT per household.

Daily VMT per household	Households	Total Daily VMT	Total Annual VMT
42	5,899	250,240	91,337,714

3. Get an estimate of fleet average miles per gallon of fuel use for autos and light trucks, plus the split. Based on EPA (2005).

Vehicle Type	Miles per gallon	Split	Weighted MPG	CO2 emissions rate (lb/gal)	CO2 emissions rate (lb/mile)
Automobiles	22.1	0.64	20.48	19.4	0.947265625
Light trucks	17.6	0.36			

4. Multiply total annual VMT times the CO2 emissions rate to get total annual CO2 emissions.

CO2 emissions (lb)	CO2 emissions (metric tons)
86,521,077	39,328

Electric Transmission and Distribution Loss-related CO_2 Emissions Calculation Steps

1. For state in which jurisdiction is located, get total annual electricity used.
2. For state in which jurisdiction is located, get total population.
3. Calculate annual per capita electricity consumption by dividing [1] by [2] above.
4. For jurisdiction (Highland Park, NJ in this example), get population from U.S. Census (2007a).

State electricity use (kWh/yr)	State Population	State kWh/capita-yr	Jurisdictional population
79,680,947,000	8,414,350	9,470	13,999

5. Estimate electricity use in jurisdiction by multiplying per capita use by population.
6. Get an estimate of percent losses by the T&D system from EIA (2007).
7. Estimate energy lost by multiplying electricity use times percent losses.

Jurisdictional electricity use (annual kWh)	T&D Loss rate	T&D Losses (kWh/yr)
132,565,626	0.09	11,930,906

8. Calculate CO2 emissions associated with lost electricity. Emissions factors are state-specific, based on EIA (2007), adjusted for electricity imports if necessary.

CO2 emissions rate (lb/kWh)	CO2 emissions (lb)	CO2 emissions (metric tons)
0.85	10,146,221	4,612

Waste Management-related CO2 Emissions Calculation Steps

1. Conduct inventory of solid waste disposal facilities and wastewater treatment plant greenhouse gas emissions (in CO2 equiv.). The table below uses NJDEP (2008).
2. Get population of inventory area.
3. Calculate annual per capita greenhouse gas emissions by dividing [1] and [2] above.
4. For jurisdiction (Highland Park, NJ in this example), get population from U.S. Census (2007a).

State waste mgmt emissions (lb CO2-equiv./yr)	State Population	State waste mgmt emissions/capita-yr	Jurisdictional population
14,674,000,000	8,414,350	1,744	13,999

5. Estimate equivalent CO2 emissions in jurisdiction by multiplying per capita use by population.

CO2-equiv. emissions (lb)	CO2-equiv. emissions (metric tons)
24,413,214	11,097

Urban Heat Island-related CO2 Emissions Calculation Steps

1. This is a complex calculation not performed here. See Rong (2006) for estimates by U.S. region.
2. Rong (2006) estimates that the net of increased air-conditioning and decreased heating energy use is zero in New Jersey.
3. Thus, net CO2 emissions are also zero in New Jersey.

CO2 emissions (metric tons)
0

Table 1: Land Use Categories

NJ Planning Area Label	NJ Planning Area Category	Equivalent CNU Smartcode Sector	Predominant CNU Transect Category
PA1	Metropolitan	Infill Growth	Urban Center/Core
PA2	Suburban	Intended growth	General Urban
PA3	Fringe	Controlled/Restricted Growth	Sub-Urban
PA4	Rural	Reserved	Rural
PA5	Environmentally Sensitive (Pinelands Forest & Preservation areas also included here)	Preserved	Natural

Table 2: Case Study Summary Characteristics

Municipality Category	New Jersey	Washington	Woolwich	Jefferson	East Brunswick	Cherry Hill	Neptune	Montclair	Highland Park	Hoboken
County		Burlington	Gloucester	Morris	Middlesex	Camden	Monmouth	Essex	Middlesex	Hudson
NJ State Plan Category		P5, Pinelands	P3, P4, P2	P5	P1, P5, P4	P1	P1, P5	P1, P5	P1	P1
Predominant Historic Transect Category (1950)		Preserve	Rural	Rural	Rural	Rural	Sub-Urban / General Urban	Sub-Urban / General Urban / Urban Center	General Urban / Urban Center	Urban Core
Predominant Current Transect Category (2000)		Preserve	Rural / Sub-Urban	Sub-Urban	Sub-Urban / General Urban	Sub-Urban	Sub-Urban / General Urban	Sub-Urban / General Urban / Urban Center	General Urban / Urban Center	Urban Core
Rail Transit Access		No	No	No	No	Yes	No	Yes	No	Yes
Population (2000)	8.4 million	621	3,032	19,717	46,756	69,695	27,690	38,977	13,999	38,577
Density (1950) person/sq. mi.	652	5	64	67	260	429	1655	6969	5287	39,723
Density (2000) person/sq. mi.	1,134	6	145	485	2,130	2,885	3,367	6,184	7,614	30,239
Jobs/Housing ratio (2000)	1.17	1.02	0.69	0.32	1.40	2.18	0.83	0.71	0.35	0.55
Median Household Income ($, 2000)	55,146	41,250	83,790	68,837	75,956	69,421	46,250	74,894	53,250	62,550
Comments		Sparsely populated, preservation area	Rapidly growing exurb	Large-lot, post-war bedroom community	Post-war suburb, commercial strip	Post-war suburb, large employers	Modest-income suburb	Inner-ring suburb, NYC commuters	Modest-income, inner-ring suburb	Gentrified industrial city

Table 3: Case Study CO2-Equivalent Emissions (metric tons/yr, 2000)

Municipality Category	New Jersey	Washington	Woolwich	Jefferson	East Brunswick	Cherry Hill	Neptune	Montclair	Highland Park	Hoboken
Landscape										
Carbon Sequestration	-7,097,304	-285,847	-9,881	-44,958	-22,134	-26,038	-8,830	-7,100	-1,804	-1,362
Deforestation	830,628	0	255	9,064	671	1,847	2,884	340	46	29
Heat Island	0	0	0	0	0	0	0	0	0	0
Infrastructure										
Transportation	29,493,113	1,666	11,334	71,719	150,101	196,684	76,284	95,204	39,328	47,621
Electric Losses	2,772,076	205	999	6,496	15,404	22,961	9,122	12,841	4,612	12,709
Waste Management	6,670,000	492	2,403	15,630	37,063	55,247	21,950	30,897	11,097	30,580
Buildings										
Residential	28,059,382	1,542	9,588	68,625	141,435	232,292	92,965	115,298	42,294	95,950
Commercial	21,809,374	870	3,543	12,250	123,823	307,449	48,571	57,415	11,094	58,012
Total CO_2 Emissions	82,537,269	-281,073	18,241	138,825	446,364	790,441	242,946	304,985	106,666	243,540
CO_2 Emissions per capita	10	-452	6	7	10	11	9	8	8	6

Figure 1: Framework Describing the Influence of Land Use on Greenhouse Gas Emissions

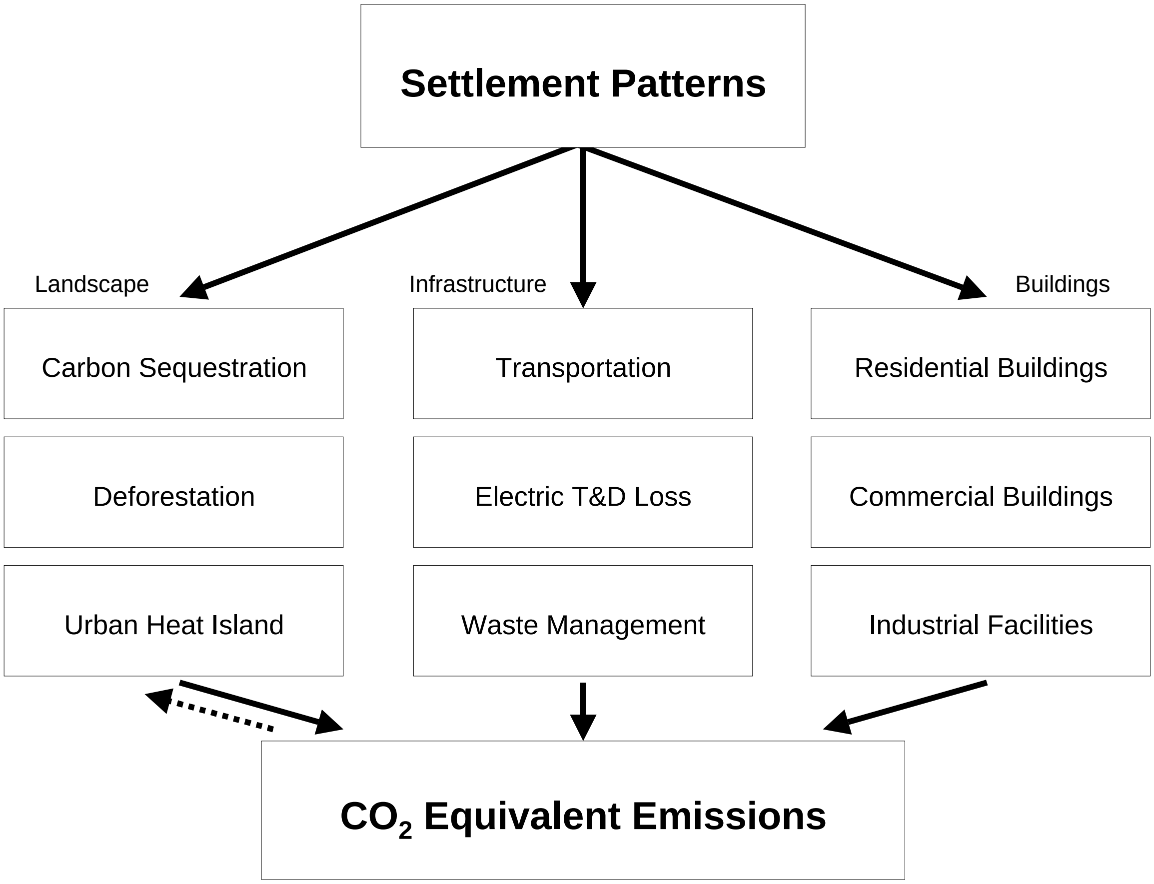
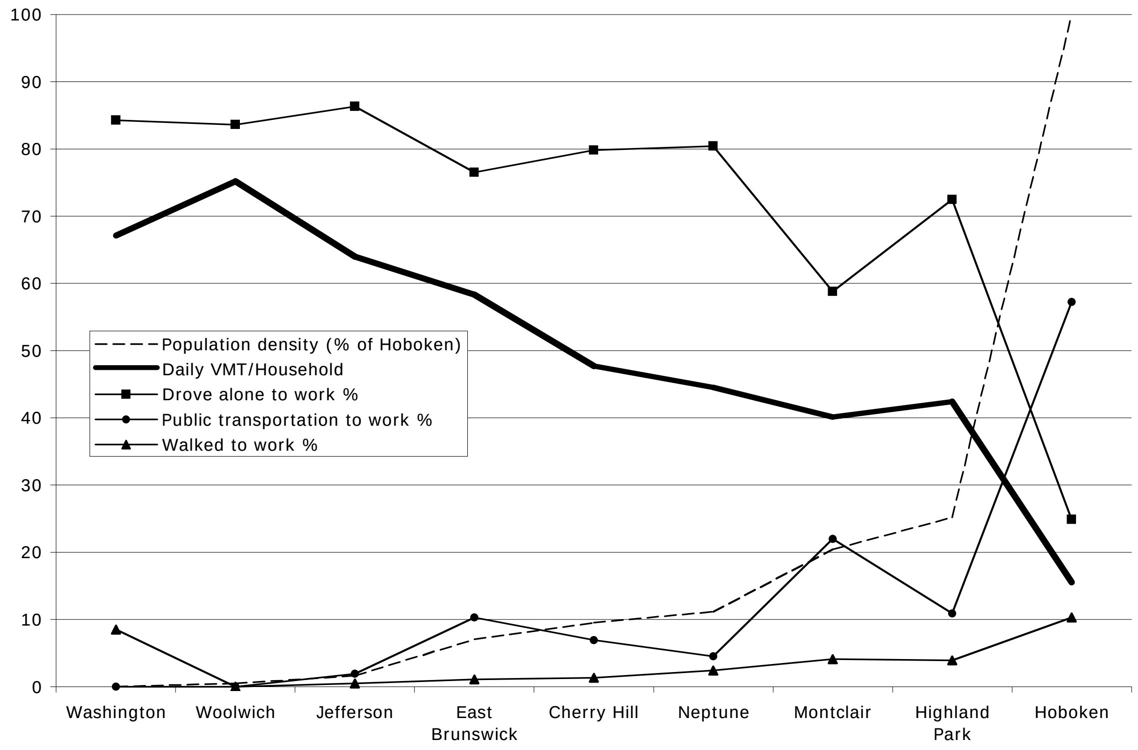


Figure 2: Variation in NHTS VMT Estimates and Census Commuting Measures

Source: Based on data in ORNL (2007) and U.S. Census Bureau (2007a).



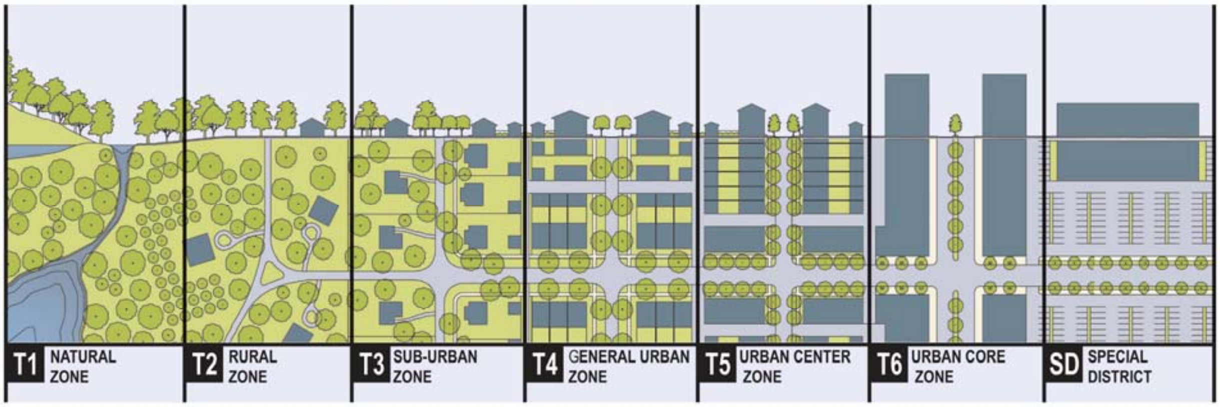


Figure 3: Rural-to-Urban Transect
Source: Courtesy of Duany Plater-Zyberk and Company

Figure 4: Per Capita Greenhouse Gas Emissions along the Rural-Urban Gradient in 2000