Modeling and visualizing urban sprawl and carbon footprints in Phoenix metropolitan area*

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Abstract

Urban planners are dealing with problems of urban sprawl and CO_2 emissions. The multidimensional character of these phenomena requires new analysis and visualization tools that are unavailable in platforms like the Geographical Information Systems (GIS). This paper, first, presents an approach for measuring and monitoring urban sprawl and carbon footprints. Second, it offers a three-dimensional visualization method that takes into account the multi-dimensional nature of the data. The visualization of the data is based on an intuitive approach involving B-Splines and Bezier techniques to create three-dimensional surfaces. Finally the paper introduces an analysis tool for planners and decision makers to examine household carbon footprints in relation to their direct spatial neighborhood based on unstructured census data.

Keywords and phrases Urban Sprawl, GHG Emissions, Visualization, Case Studies

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1 Introduction

In the era of globalization and climate change urban planners are dealing with problems related both to urban sprawl and increasing CO_2 emissions and even their interrelationships. Given the multidimensional and multidisciplinary aspects of these problems, the conceptual and visualization tools planners have typically employed are often inadequate [1]. This paper demonstrates how high bandwidth of visualization methods in computer science, especially the techniques developed in the field of information visualization, can be applied in planning problems related to urban sprawl and carbon emissions. The advances in computer technology provide a unique opportunity to use digital visualization techniques to represent planning issues especially in public communication and participation programs [2] [3].

While taking advantage of an existing method [4] to measure urban sprawl, the paper applies a new model for calculating carbon footprints at the level of individual households, which includes emissions from electricity use as well as from consumption behavior. By using a new form of three-dimensional visualization to present the results of both applications, the paper demonstrates how this form of analysis and visualization can support urban planning. The remainder of the paper is structured as follows. First, the paper introduces and describes the first application topic, urban sprawl, in section 2. In section 2.2, a new visualization

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tool using Coons Patches is presented in order to visualize the parameters of urban sprawl developed in section 2.1. The second application topic, carbon footprints at the level of individual households, follows in section 3. Here the paper presents a new model to measure carbon footprints at the level of individual households followed by an introduction of a visual analysis tool presented in section 4. The paper concludes by a short summary and a future outlook in section 5.

2 Urban Sprawl

2.1 Introduction urban sprawl

The term suburbanization is used to describe the process of movement of population from central areas of cities and towns to peripheral areas. This phenomenon can have a number of reasons associated with it such as high density of cities, pollution by industry or high levels of traffic. Suburbanization causes an increase urban sprawl. Urban sprawl is reported to be a significant contributor to traffic congestion, job-housing mismatches, racial and income segregation and environmental degradation [5]. The literature in urban sprawl is vast and there have been several efforts to define urban sprawl. An acceptable definition is found in Clawson [6]: "[the] rapid spread of suburbs across the previously rural landscape, tendency to discontinuity [...]". In other words urban sprawl can be defined as low density, leapfrog, commercial strip development and discontinuity [4] [7]. These common definitions bring us to one of the essential parts of this work; that is to develop quantitative indicators to measure urban sprawl. There are several studies that have derived indicators of urban sprawl [5] [8]. The research applies some of the measures introduced by Galster et al. [4], as a basis for indicator calculations in this study. Galster et al. defined urban sprawl as [...] a pattern of land use in an urban area that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity. The research reported in this paper uses three of these dimensions: density, continuity and diversity.

2.2 Visualizing indicators of urban sprawl

Based on Galster et al. [4] sprawl indicators were calculated and forecasted for Maricopa County, AZ, for 2000 to 2030. The study area is subdivided into one square mile grid cells. The analysis is based on the demographic projection data from a software-based simulation model called UrbanSim [9]. UrbanSim delivers those data on a household-per-grid-cell basis for the period of projection. Among others the data include the number of households by type, number of workers, and land use. The available simulation results over the next 30 years offer the possibility of visualizing trends in urban sprawl indicators over a medium-term future. As already mentioned in section 2.1, the most significant indicators for urban sprawl are density, continuity and diversity. The following definitions are adapted from Galster et al. [4]. Density is defined as "[...] the average number of households per square mile of developable land in the total area." That means in this case the number of residential units per grid cell. Density is the most widely used indicator of sprawl. Continuity is defined as "[...] the degree to which developable land has been developed in an unbroken fashion throughout the total area." In other words, leap-frog areas are considered to be more sprawl-like. Diversity is defined as "[...] the degree to which substantial numbers of two different land uses exist within the same area." Greater diversity values of land uses within a given area are considered as the opposite of sprawl. In other words, the interpretation of this indicator is the average density of a particular land use (measured by number of households) in another land use's (measured by the number of employments) area. For each of those three indicators the higher indicator numbers indicate less sprawl. One main objective of this paper is to provide a compact visually pleasing three-dimensional visualization of urban sprawl. The research uses the location co-ordinates of the grid cell centre points as well as the calculated indicator values as a basis for our surface construction. First, a height-field comprised of the centres of the grid cells and the selected values as their heights is generated. Second, based on this height-field, a surface with C^0 continuity is constructed [10]. Figure 1 shows an example with a regular grid marked in green, its height field in red/orange, and the resulting surface in yellow.

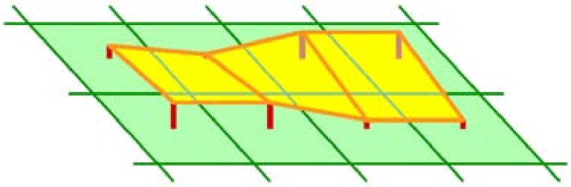

Figure 1 Regular grid (green), dedicated height-field (red/orange) [13].

The surface is built by tessellating the faces of the height-field using linear Coons Patches (a mathematical technique to describe and construct surfaces) [11]. With this approach the appearance of a smooth surface is maintained even though the surface is only C^0 continuous. It remains visible at the silhouettes, which is not the applications focus. Therefore, this method achieves a very good trade-off between the visualization's speed and quality. One advantage of this approach is its flexibility and adaptability. For example, the perspective and color of the surface can be changed (also see Figure 5 and 6). Furthermore the user is able to switch between a plain background and our background (Figure 2), created by using Google Earth [12].

This approach also offers the possibility to compare the results of different years by overlaying different surfaces by using different layers or transparency (see section 3.3: Figure 5 and 6).

3 Carbon footprints

3.1 Introduction carbon footprints

The urgency of reversing climate change is among the most pressing international concerns. One of the major anthropogenic contributors to the changing climate is carbon dioxide emission from burning fossil fuels. Given that global energy needs are overwhelmingly dependent on fossil fuels, reducing its use would require finding alternative energy sources together with increasing energy efficiency. Energy is needed for every aspect of human production and consumption - from extraction, to manufacturing, to transportation and finally for disposal of waste products. Therefore knowing what humans consume and the total energy required for making this consumption possible would provide a reasonable estimate of the carbon footprint of individuals. This paper offers a method to determine carbon footprints of cities and urban regions from consumption patterns of households and offers novel ways of visualizing this footprint. In this study the term "carbon footprint" describes the total amount of CO_2 emitted into the atmosphere by individuals and organizations

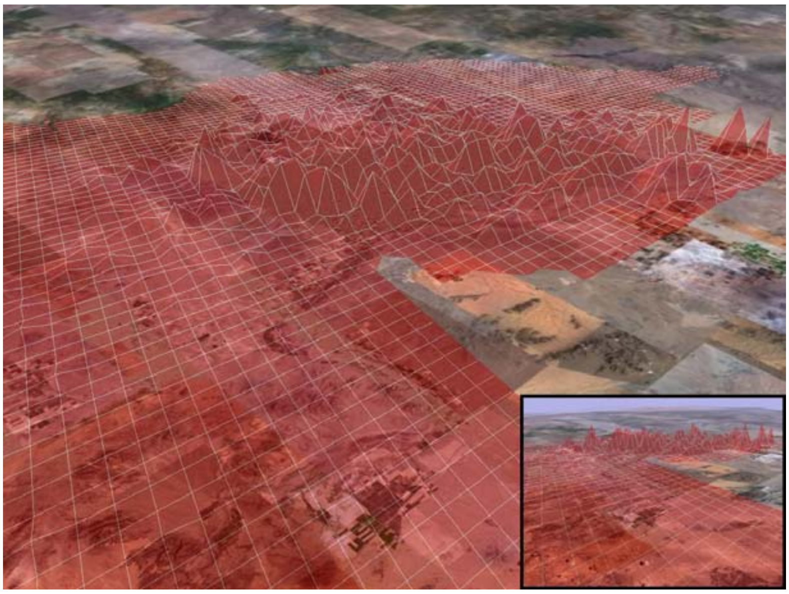

Figure 2 Density values for the year 2005 with "Maricopa County" background as well as different perspectives [10].

through the use of fossil fuels [13]. The paper describes an approach for estimating carbon footprints for different types of households and for different scenarios of housing development.

The focus of this approach is on the neighborhood scale. Thus the paper provides information about the distribution by type of households. The growing interest in monitoring and measuring carbon footprints has resulted in several studies across the globe. Among the path-breaking projects for monitoring CO_2 in the United States is The Vulcan Project [14], funded by NASA and led by a research team at Purdue University. It has achieved in quantifying United States fossil fuel CO_2 emissions at the scale of individual factories, power plants, roadways and neighborhoods. The results are represented on a common 10 km grid to facilitate atmospheric modeling. Weber [15] [16] defined 13 broad consumption categories of household level carbon footprints, for example education, home energy, and private transport. His study demonstrates, among other things, that the CO_2 emissions are proportional to the household expenditures. For 2004 household consumption totaled 8100 billion dollars and resulted in 5700 million-tons of CO_2, for an average CO_2 intensity of consumption of about 0.7 kg CO_2 per dollar. This suggests that each American household would have been responsible for 50 tons of CO_2 in 2004, if all of the production took place in the U.S. (without implicating import and export). Referring to studies focusing on national average results, he also concludes that global and distributional aspects would be important to consider in order obtaining an accurate picture of carbon emissions. Other studies such as Sovacool and Brown [17] and Wentz et al. [1] also offer alternative approaches for the calculation of carbon footprint.

3.2 Measuring carbon footprints at the level of local neighborhoods

When focusing on household carbon footprints this research distinguishes between different contributors of CO_2 emissions, namely energy (electricity) and consumption behavior. To complete a total household carbon footprint, future work will also include transportation emissions. The basic information for the emission caused by the consumption behavior of different households is derived from the Consumer Expenditure Diary Survey (CES) for the year 2006 [18]. The CES provides detailed data about the consumption items per household as well as information about different types of household units. In other words we know how much is spent on a particular item by a certain category of household. These categories are generated for different family sizes, by different classes of income as well as by different races. The carbon intensity of each consumption item for each type of household was provided by the CES and the Berkeley institute of the environment [19] (Economic Input-Output Life Cycle Assessment EIO-LCA 10). Particular emission estimates were done for 42 different household types [13]. In this approach the consumption component is calculated based on the amount of money spent by a household for a particular item and the CO_2 emissions coefficient of for this item. With the variables KR, KF, KI in our matrix we can choose between the different values for income class, race and family size. C is a constant which does not depend on time.

$$\begin{bmatrix} E_R \\ E_F \\ E_I \end{bmatrix} (t) = \begin{bmatrix} K_R \times coeff \\ K_F \times coeff \\ K_I \times coeff \end{bmatrix} = C \times \begin{bmatrix} K_R \\ K_F \\ K_I \end{bmatrix} (t)$$

$$R = race, F = familysize, I = incomeclass, t = certainyear$$

Figure 3 shows an example of the expenditure distribution and the resulting CO_2 emissions for the household type 612. These resultant emissions give us baseline figures for the daily consumption decisions of specific household types. Comparisons can be made of carbon emissions of different consumables as well as the total emissions for different types of households.

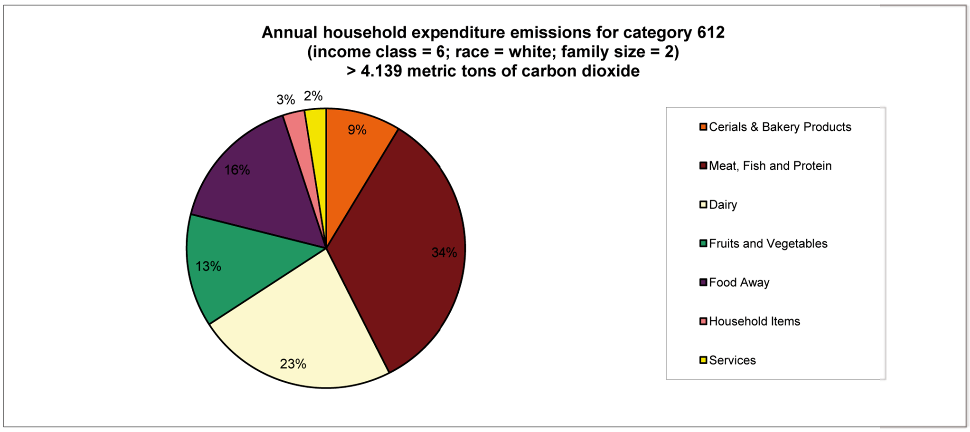

Figure 3 Household emissions for category 612 [13].

Furthermore detailed information on the total electricity consumption (in kWh) of every mentioned household category [20] is available. In conjunction with the energy coefficient for Arizona, precise amount of CO_2 emissions for each type of household as well as for all households in Maricopa County is calculated. The calculation of the household electricity component of emissions was based on the electricity consumption of each household category (KX) and the energy coefficient (C) for Arizona. Finally the emissions from household energy use and the emissions from the consumption items are combined for a total carbon footprint at the household level. The distribution of the CO_2 emissions in metric tons by all of our 42 different household types is shown in Figure 4.

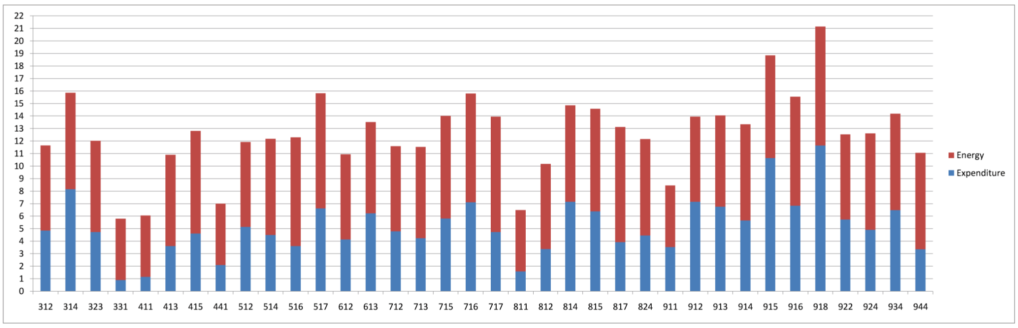

Figure 4 Distribution of CO_2 emissions in metric tons by household type [13].

3.3 Visualizing carbon footprints

Using the visualization tool, described earlier in section 2.2, results for household carbon footprints are shown three-dimensionally. To demonstrate the utility of this visualization method, calculations of carbon footprint in Maricopa County were made for two different development scenarios (emission values are in tons of CO_2 per grid-cell). The scenarios chosen for this exercise show the difference in development patterns between allowing state lands to be auctioned as per current rules ("BAU" scenario) and the alternative of freezing all state owned lands in Maricopa county to 2005 levels ("Stateland" scenario).

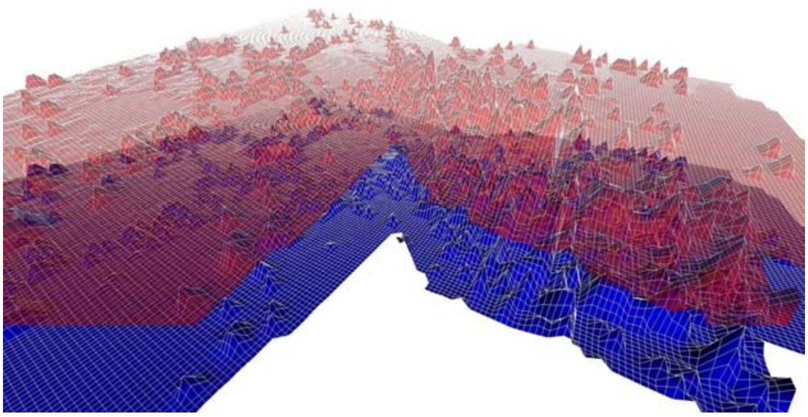

Figure 5 Transparent overlay of household emissions in tons of CO_2 per grid-cell for BAU 2020 and Stateland 2020 [21].

Using transparency and different surface layers (Figure 5), two datasets are compared in a way that shows specific areas of CO_2 pikes and how they are different in the other scenario. Figure 6 illustrates the differences between the total carbon footprints for BAU and Stateland in 2010. The grid cells are colored in blue if the BAU emissions are higher than the Stateland emissions and red in the opposite case. The height of each grid cell illustrates the absolute difference between the two scenarios. As expected, the BAU scenario provides more sprawling and leapfrog development while the scenario Stateland (with no development on state lands) shows higher CO_2 emission values in the urban area of Maricopa County [13].

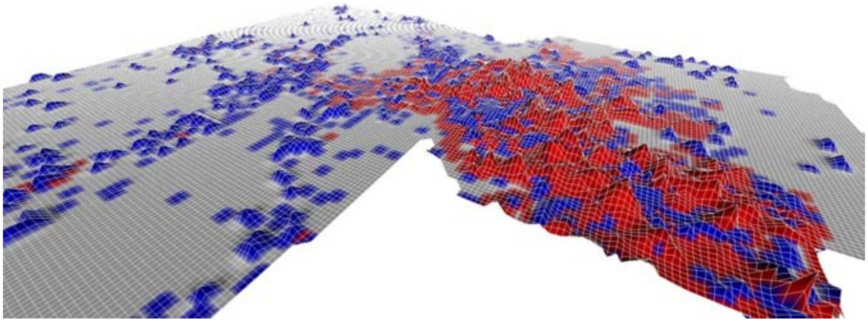

Figure 6 Differences between scenario emissions BAU and Stateland in 2010 [13].

4 Visual analysis tool

In this part of the paper the visualization toolbox is extended with a visual analysis tool which is able to demonstrate different quantities of CO_2 emissions for specific household categories in relation to the neighborhood. The visualization method presented earlier relies on an underlying grid-cell-based structure (one square mile grid cells). The motivation for this work is to create a visual analysis tool that is based on census tracts in order to cut down the workflow and to directly access census data. A novel type of diagram for a two-dimensional space subdivision in cells with weighted generator points is developed which builds on the original geometric construction of a Voronoi Diagram [22]. The weighting of each generator point is based on the calculated carbon footprints (section 3.2) for different household categories. The objective is to illustrate the differences in weights to the nearest neighbors. By doing so, differences depending on different household attributes or different numbers of households are shown. The analysis focuses on cell deformations depending on neighborhood values. The sizes of the new resulting cells represent the carbon footprint distribution for the census tracts in relation to the direct neighborhood cells. Figure 7 shows these resulting spatial subdivision diagrams based on average results of household carbon footprints for a particular part of Phoenix.

This distribution represents the typical household category in each census tract. To provide a better orientation, an underlying background map of this particular sector of Phoenix, adopted from Google Earth, is also included. By restricting this weighted approach to direct neighbors, the resulting cells always stay within the original borders of the study area which makes it easy to understand and reconstruct. Thus any other possible application within the same study area (within the same census tracts), such as visualizing urban sprawl indices, can be achieved by this method. Since this approach is based on U.S. census data, it can be adapted to any other metropolitan area in the United States.

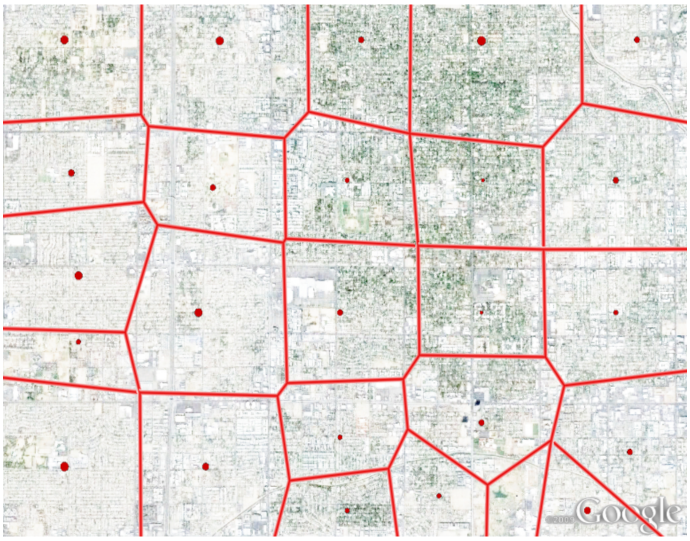

Figure 7 The resulting diagram for average household carbon footprint values per census tract [22].

5 Conclusion

The visualization approach presented in this paper provides an efficient way to visualize urban sprawl indicators as well as carbon footprint values three-dimensionally. Height fields were selected because in order to show multidimensional data (using different layers or multidimensional data within one layer). Possible alternatives, like the use of different colours, have to be considered carefully because of possible difficulties with coloured single spots that are hard to detect. Furthermore the paper presented a model to calculate carbon footprints at the level of urban neighborhoods. The high number of different household categories makes this model unique and gives the user a detailed tool for estimating the impacts of daily consumption decisions by household type as well as the resulting amount of CO_2 emissions. To complete a total carbon footprint at the level of households, future work will also include emission parameters from the transportation sector, for which we distinguish between different modes of transportation, the spatial locations of different household categories as well as different purposes of trips. By developing a novel approach for two-dimensional space subdivision in cells using weighted generator points, household carbon footprints in relation to their neighborhoods can be represented visually. This will enrich the toolbox for urban planners in analyzing and counteracting the causes of carbon footprints within a defined local area. As mentioned before, future work will contain other applications such as visualizing urban sprawl indices and combining both urban sprawl and carbon footprint results to see possible causes and correlations.

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