Dasymetric Mapping for Disaggregating Coarse Resolution Population Data

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ABSTRACT

This research describes a new dasymetric mapping technique where population data are redistributed from choropleth map zones to dasymetric map zones based on a combination of areal weighting and the estimated population density of each ancillary class. The analyst may specify the density estimate using domain knowledge, derive the density estimate from patterns embedded in the data using a variety of empirical sampling techniques, or combine the two methods. If the population density estimate cannot be derived from sampling, the technique uses information about the other ancillary classes for which densities can be determined to make an estimate. We demonstrate the utility of our dasymetric mapping technique using U.S. Bureau of the Census population data and remotely-sensed land cover data. The dasymetric mapping algorithm may be downloaded as a VBA script for ArcGIS (ESRI, Inc.) at http://astro.temple.edu/~jmennis/research/dasymetric.

INTRODUCTION

A statistical surface is a quantity that varies continuously over a two-dimensional space. There are many geographic phenomena that can be modeled as statistical surfaces, such as elevation and population density. The idea of a statistical surface bears a close relationship to the concept of ‘field-like’ geographic phenomena, as opposed to ‘object-like’ geographic phenomena, that has been the topic of discussion in the geographic information science literature (Peuquet et al., 1998). A dasymetric map is an approach to the cartographic depiction of a statistical surface in which the surface is represented as an exhaustive tessellation of zones. The nature of the tessellation reflects the underlying variation in the variable being mapped, so that within zone homogeneity is maximized and the boundaries between zones occur at steep escarpments in the surface (McCleary, 1969). A dasymetric map can be distinguished from the more common choropleth map. Whereas choropleth maps also depict zones, the zone boundaries do not reflect the properties of the statistical surface but rather are derived from some convenience of data collection or aggregation, for instance in maps depicting population density by census or other administrative units. While a dasymetric map could theoretically be used to represent any geographic phenomenon that can be modeled as a statistical surface, it has been almost exclusively applied to population data.

Statistical surfaces can be encoded using a variety of approaches, including raster grids, triangulated irregular networks (TINs), isolines, and regular and irregular lattices. Dasymetric maps can be generated from such data by classifying the surface values into ranges that form zones on the map, though transformations such as interpolation may be required to derive such zones from surface data encoded as sparse point samples, as is typically the case with irregular lattice encoding. Typically, however, dasymetric maps are generated from transformations of data encoded in a choropleth map format. This transformation can be considered the process of dasymetric mapping, and it involves the overlay of the choropleth map with an ancillary spatial data set, typically an area-class map (Eicher and Brewer, 2001; Mrozinski and Cromley, 1999).

Dasymetric mapping is applicable to a variety of situations where spatial data disaggregation from choropleth map encoding is desirable, for instance in mapping population distribution where population data are encoded in relatively coarse-resolution administrative units. Unfortunately, dasymetric mapping methods are not widely accessible to casual geographic information users. This research describes a new dasymetric mapping technique and its implementation as a free extension to a popular geographic information systems (GIS) package. We demonstrate the utility of our dasymetric mapping technique using U.S. Bureau of the Census population data and remotely-sensed land cover data.
LITERATURE REVIEW

The work of Wright (1936) is often cited as particularly influential in developing the dasymetric mapping approach in the USA. Since that time, however, dasymetric mapping has been addressed somewhat sparingly by cartographers. For example, though most introductory cartography textbooks give some attention to dasymetric mapping (e.g. Dent, 1999), its treatment is typically limited to a few paragraphs, and often simply as a contrast to the more common choropleth mapping. The historical lack of emphasis on dasymetric mapping in cartographic research is likely because the dasymetric mapping method was extremely cumbersome prior to the widespread use of computers for spatial data handling. As GIS software has become more accessible, however, and as interest in population estimation for environmental and demographic computational modeling has grown, dasymetric mapping has reemerged as an important topic of research.

As an approach to the transformation of data from one set of areal units to another, i.e. from the enumeration zones of the choropleth map to the surface-derived zones of the dasymetric map, the process of dasymetric mapping can be considered a type of areal interpolation. The simplest form of areal interpolation is areal weighting, in which a homogeneous distribution of population is assumed to occur throughout each original choropleth map zone. In the context of dasymetric mapping, where data are redistributed to sub-choropleth map zone units via overlay with an area-class map, the areal weighting calculation may be expressed as

\[ \hat{y}_t = \frac{y_s A_t}{A_s} \]  

(1)

where \( y \) is the observed population, \( \hat{y} \) is the estimated population, \( s \) is a choropleth map zone, \( t \) is the area of overlap of zone \( s \) and an area-class map zone, and \( A \) is the area.

Unlike with simple areal weighting, however, the goal of dasymetric mapping, is to characterize the relationship between population density and the classes encoded in the area-class map to obtain an improved representation of the underlying population density surface. A number of methods have been proposed for this purpose. Eicher and Brewer (2001) provide an overview of traditional dasymetric mapping techniques described by Wright (1936) and McCleary (1969), including the ‘binary’, ‘class percent’, and ‘limiting variable’ methods, as well as the implementation of these techniques in GIS using raster and vector data modeling approaches. In the binary method, an ancillary data set describing inhabited and uninhabited regions is used to redistribute population. In the class percent method, each ancillary class is assigned an a priori percentage value to which that fraction of a choropleth zone’s population is assigned. The limiting variable method enforces upper limit population density thresholds; if the threshold is exceeded in a given spatial unit during the population redistribution procedure, population is redistributed in an iterative procedure. Other researchers have adopted statistical approaches to characterize the population density of the area-class map classes. These approaches include various regression-based techniques (Goodchild et al., 1993; Langford et al., 1991), expectation maximization (Flowerdew and Green, 1994), and a heuristic sampling method (Mennis, 2003).

DASYMETRIC MAPPING METHOD AND IMPLEMENTATION

In the dasymetric mapping technique described here, population data are redistributed from choropleth map zones to dasymetric map zones by overlaying the choropleth map with an area-class map. Population data are redistributed to dasymetric map zones based on a combination of areal weighting and the estimated population density of each ancillary class. The basic premise of the technique can be expressed as

\[ \hat{y}_t = y_s \sum_{c \in s} \frac{A_c D_c}{\hat{A}_c D_c} \]  

(2)
where \( c \) is a class in the area-class map (comprising one or more individual zones) and \( \hat{D}_c \) is the estimated population density of class \( c \). The value of \( \hat{D}_c \) may be set manually or it can be derived by sampling those zones \( s \) that can be spatially associated with each class \( c \). This association may be defined by noting which zones \( s \) are contained entirely within class \( c \) or which zone centroids fall within class \( c \). A third approach identifies all zones \( s \) which are covered by class \( c \) to an extent greater than a threshold percent, say 90%.

Once a sample of choropleth map zones has been selected as representative of a particular class, the population density of an ancillary class can be calculated as

\[
\hat{D}_c = \frac{\sum y_s}{\sum A_s}
\]

where \( n \) is the number of sampled choropleth map zones associated with class \( c \). The dasymetric mapping also has the ability to account for the fact that the population density of class \( c \) may vary from one location to another. To account for this variation, a third spatial data layer that partitions the area under investigation into regions may be introduced so that \( \hat{D}_c \) is calculated individually for each class \( c \) within each region. If \( \hat{D}_c \) is not set manually nor can an adequate sample be obtained, \( \hat{D}_c \) is estimated by using information about the other ancillary classes for which population densities can be determined to make an estimate. Note that this dasymetric mapping method preserves Tobler’s (1979) pycnophylactic property which specifies that the total population contained within an original choropleth map zone remains within the boundaries of that zone following the dasymetric mapping.

The dasymetric mapping technique was implemented as a VBA script which can be run within the GIS software package ArcGIS (Environmental Systems Research Institute, Inc.). The script ingests a header file that specifies path and file names for the input choropleth and area-class maps, as well as user-defined parameters such as the manually set values of \( \hat{D}_c \) and preferred sampling strategy. Upon completion, the script returns a comma delimited text file that can be read into a spreadsheet package and which summarizes the results of the dasymetric mapping. This file describes, for each class \( c \): the method of deriving \( \hat{D}_c \); the number of zone \( s \) samples taken; the total area of the zone \( s \) samples taken (expressed as a percent of the total area sampled for all classes); the total population of the zone \( s \) samples taken (expressed as a percent of the total population sampled for all classes); the mean, minimum, maximum, and standard deviation of the population density for the set of zone \( s \) samples; the estimated population density (\( \hat{D}_c \)); and the mean, minimum, maximum, and standard deviation of the population density for the set of dasymetric zones.

**CASE STUDY: DELAWARE COUNTY, PENNSYLVANIA, USA**

The dasymetric mapping technique is demonstrated by disaggregating 2000 U.S. Bureau of the Census tract level population data for Delaware County, Pennsylvania, USA to sub-tract units. The choropleth map ingested into the dasymetric mapping script is thus population density by tract (Figure 1). Delaware County serves as a good case study region for dasymetric mapping because it lies on the urban-rural fringe of the city of Philadelphia, Pennsylvania, USA, a metropolitan area encompassing approximately five million people. Delaware County thus contains a wide range of population density values, with population density generally decreasing from east to west. The area-class map used in the dasymetric mapping is a land cover data set extracted from the National Land Cover Data (NLCD) program administered by the U.S. Geological Survey. The data are derived from 2001 Landsat Enhanced Thematic Mapper Plus (ETM+) imagery and made available as classified 30 meter resolution raster data. These land cover data were preprocessed by passing a focal majority filter over the raster and then transforming the subsequent grid to vector format. The resulting polygon boundary lines were then smoothed (Figure 2).
Figure 1. Population density by tract.

Figure 2. Land cover.
Table 1 presents the abridged tabular dasymetric mapping script output generated using a preset value of zero population density for agriculture, bare, water, and wetland land covers, and using centroid sampling to estimate the population density for the developed and forest land covers (assuming forest encompasses sparsely distributed single-family homes). Note that to estimate $\hat{D}_{\text{developed}}$ and $\hat{D}_{\text{forest}}$ 125 and 13 samples were taken, respectively. In other words, 125 tracts have centroids falling within developed land cover and 13 tracts have centroids falling within forest land cover. The mean and standard deviation of the population density for those samples are given and provide a rough characterization of the distribution. As one would expect, developed land cover has a higher sampled mean population density than forest. Note that the actual values of $\hat{D}_c$ differ from the means because, unlike the means, $\hat{D}_c$ is calculated by dividing the sum of all the sampled population by the sum of the sampled areas for each class (Equation 3). Thus, the fact that $\hat{D}_{\text{developed}}$ is significantly below its analogous sampled population density mean indicates that there are a number of developed samples with very high population densities and small areas; the larger samples of developed tend to have lower population densities. The table also indicates that just over half the county is occupied by developed land cover, and the dasymetric mapping script distributed approximately 90% of the population to developed land. The distribution of population density for forest and developed classes in the dasymetric map are indicated by the last two columns of the table. Ideally, one would expect these to roughly match the population density mean and standard deviation of the samples.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>Method</th>
<th>SNO</th>
<th>SMN</th>
<th>SSD</th>
<th>EPD</th>
<th>%AR</th>
<th>%TP</th>
<th>DMN</th>
<th>DSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Preset</td>
<td>0</td>
<td>17.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bare</td>
<td>Preset</td>
<td>0</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Developed</td>
<td>Centroid</td>
<td>125</td>
<td>3,032</td>
<td>1940</td>
<td>1993</td>
<td>50.7</td>
<td>90.0</td>
<td>1348</td>
<td>1129</td>
</tr>
<tr>
<td>Forest</td>
<td>Centroid</td>
<td>13</td>
<td>787</td>
<td>347</td>
<td>835</td>
<td>26.1</td>
<td>10.0</td>
<td>667</td>
<td>475</td>
</tr>
<tr>
<td>Water</td>
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<td>0</td>
<td>3.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wetlands</td>
<td>Preset</td>
<td>0</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

SNO is the number of samples, SMN is the sample population density mean, SSD is the sample population density standard deviation, EPD is the estimated population density ($\hat{D}_c$), %AR is the percent of total area, %TP is the percent of total population, EMN is the dasymetric population density mean, and DSD is the dasymetric population density standard deviation.

Table 1. Tabular output of the dasymetric mapping script.

Figure 3 shows the dasymetric map associated with Table 1. Note the differences between Figures 1 and 3. Figure 3 contains significant within-tract variation in population density, particularly in the western part of the county where intermixed forest and agricultural land covers dominate. The distribution of population density for much of the more densely populated far eastern part of the county appears similar in Figures 1 and 3, as many of these tracts are occupied nearly completely by developed land cover. Consequently, the upper bound of the range of population density for the dasymetric map (12,138 people/km$^2$) is nearly identical to that of the original choropleth map (12,119 people/km$^2$). Note also that a number of tracts in the southeastern part of the county extend into the Delaware River (Figure 2). The dasymetric mapping script takes this into account and redistributes the population into the non-water cover portion of the tract.

A regions layer was introduced to account for the fact that the population density of certain classes may vary across the county. For instance, developed areas in the eastern, urban areas adjacent to the city of Philadelphia may have generally higher population densities than developed areas in the west, which may capture small towns or residential subdivisions. The regions layer partitions the county into three regions: urban, suburban, and exurban (Figure 4). These regions were generated by manually categorizing tracts into one of these three regions. The dasymetric mapping script was run again with similar settings as were used in the previous run, but this time also incorporating the regions layer.

The tabular output associated with this dasymetric mapping run consists of three tables similar to that reported in table 1 – one table for each individual region. These results indicate that the ratio of developed population density to forest population density is approximately three for both the urban and suburban regions, but drops to approximately one for
Figure 3. Results of dasymetric mapping using a preset value of zero population density for agriculture, bare, water, and wetlands land covers, and centroid sampling for developed and forest land covers. Tract boundaries are overlaid in bold.

Figure 4. Regions used in the dasymetric mapping.
the exurban region (though it should be noted only two samples were used to estimate $\hat{D}_{\text{developed}}$ in the exurban region). The associated dasymetric map (Figure 5) reflects this by assigning a greater proportion of population to forest land cover in the exurban region as compared to the previously generated dasymetric map (Figure 3). A close-up view of the area delineated by the red box in Figure 5 is shown in Figure 6, alongside a comparative view of the same area from the choropleth map of tract-level population density shown in Figure 1. One can clearly see the within-tract variability that the dasymetric map captures in the suburban and exurban regions as compared to the choropleth map. For example, the choropleth map encodes a population density of 287 people/km$^2$ for the southwestern-most tract shown in Figure 6, whereas the dasymetric map encodes population densities ranging from 0-582 people/km$^2$ over the same area.

CONCLUSIONS

Informal tests of our dasymetric mapping technique suggest that it performs consistently better than areal weighting. Informal tests have also shown that the application of a preset $\hat{D}_c$ value, even for a single area-class map class, can substantially improve the accuracy of the resulting dasymetric map. Caution is advised, however, in estimating $\hat{D}_c$ through sampling. While dasymetric mapping assumes a priori that there are significant population density differences among area-class map classes, it is possible that population density varies widely even within individual classes. We certainly found this to be the case in using USA land cover data as the area-class map in the dasymetric mapping. If the within-class population density variance is indeed high, a low number of samples may yield a non-representative estimate of $\hat{D}_c$, and hence an inaccurate dasymetric map. The tabular output from the dasymetric mapping script provides some clue as to the within-class distribution of population density as estimated from the sampling. In addition, although we did not discuss it in the case study presented here, the script also allows the analyst to establish a minimum threshold for number of samples; if the threshold is not exceeded, the script will abandon the sampling approach and instead resort to a local areal weighting to estimate $\hat{D}_c$. The dasymetric mapping script is available for public download at http://astro.temple.edu/~jmennis/research/dasymetric.

REFERENCES

Figure 5. Results of dasymetric mapping using a preset value of zero population density for agriculture, bare, water, and wetlands land covers, centroid sampling for developed and forest land covers, and using regions. Box outlined in red shows area depicted in Figure 6. Tract boundaries are overlaid in bold.

Figure 6. Close up of area shown red box in Figure 5: the dasymetric map of population density depicted in Figure 5 (left) and the choropleth map of population density by tract depicted in Figure 1 (right).
BIography

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