Applied Geography 78 (2017) 12–21

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

A comparison of raster-based travel time surfaces against vector-based network calculations as applied in the study of rural food deserts

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ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form
16 October 2016
Accepted 30 October 2016
Available online 14 November 2016

Keywords:
Food insecurity
Food proximity
Geographic information systems
Raster GIS
Travel-time
Travel-time surface

ABSTRACT

While the term food insecurity is gaining popularity in contemporary literature, there is debate as to how tenets of this phenomenon can be quantitatively measured. One of these tenets, proximity to food resources, which is used to measure food deserts, can be measured within a digital GIS (Geographic Information System). Metrics such as Euclidean and network distance represent planimetric distance measurements between locations and resources, but do not truly represent the empirical cost that serves as a barrier, most notably time and/or money, to those who must decide to travel to these resources. While the vector data model has been the standard by which these calculations are done within a GIS, raster-based travel time surfaces can serve as a faster, replicable and scalable alternative. However, little research has been done to test the efficacy of these surfaces and their alignment with vector-based network calculations. In this research, we developed two travel-time surfaces for a rural region in southeastern North Carolina. One represented travel times to grocery stores and while the other represented travel time to convenience stores. We found that the travel times derived from this surface were statistically consistent with vector-based counterparts for sample sizes at a 95% confidence. When utilized correctly using an appropriate scale and spatial resolution, these surfaces have the potential to be effective tools in the study of food deserts.

1. Introduction

Increased interest in reducing the occurrence of food deserts has been a popular topic in contemporary literature within the geographic, information, health and social sciences (Coleman-Jensen, Rabbit, Gregory, & Singh et al., 2015; Morton & Blanchard, 2007; Morland., Wing, & Diex-Roux, 2002). The term food desert has been applied to areas with "limited access to healthy and affordable food" (USDA, 2009). The USDA considers a food desert to be a low-income census tract where a substantial portion of the residents has low access to a supermarket or large grocery store (Ver Ploeg et al., 2009). Most food desert studies have been conducted in urban neighborhoods; rural food insecurity more generally is particularly understudied in the United States.

Proximity is a key tenet to help assess food security, or one's ability to have "physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). However, it is not the only one. Food insecurity is also a byproduct of unemployment, underemployment, education, income, vehicle ownership and commuting patterns (Dutko, Ver Ploeg, & Farrigan, 2012) as well as food utilization, which entails one's ability and desire to consume a proper diet in conjunction with provisions for water sanitation, health education and health services (FAO, 1996).

GIS (Geographic Information Systems)-based spatial analysis has become an essential tool for food system research and proximity of residences to large supermarkets or supercenters is a commonly used proxy for access (Morton & Blanchard, 2007; Sharkey & Horel, 2008). However, the contribution of spatial analysis to our understanding of food system dynamics has been somewhat limited by methodological challenges. Different studies vary considerably in the type of data used and in the spatial delineation methodology; even the definition of proximity is subject to debate. Metrics such as Euclidean and network distance

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http://dx.doi.org/10.1016/j.apgeog.2016.10.006

highlight linear distance measurements between a particular address and resource, but do not adequately represent the empirical costs, most notably time and/or money, that serve as a barrier to food access.

Most food desert studies using GIS techniques implement the vector data model to measure proximity. This approach represents real-world phenomena using points (e.g., addresses and food sources), lines (e.g., roads and isochrones) and polygons (e.g., census tracts and zip codes). Van Hoesen, Bunkley, and Currier (2013) looked at the quality of food in conjunction with point-to-point (individual home address to food source) distances along a vector road network in Vermont and grouped these results by towns, represented as polygons. Proximity measures using vector data can be vulnerable to error if individual addresses of residents and resource locations are not updated, properly geocoded, or the center of the enumeration unit is used to represent the entire unit. Another source of error is introduced when different types of data are combined. In the vector data environment, measures to express proximity are typically grouped within census-defined units such as block groups and tracts to align with explanatory socio-economic variables such as race/ethnicity, poverty, income and access to transportation available at that scale. This introduces problems when larger, littoral or oddly-shaped enumeration units are used for analysis. Wieczorek, Delmerico, Rogerson, and Wong (2011) showed this with points agglomerated within zip codes versus computer generated (hexagon and lattice) polygons. These problems limit the usefulness of GIS analysis for identifying significant causal relationships among the many factors potentially contributing to food insecurity.

The raster data model offers an alternative approach to spatial analysis. In contrast to the vector data model, the raster data model represents the earth using uniformly spaced pixels or cells. Raster models are useful for representing data that varies continuously across space such as temperature or elevation. Distance or travel time to some point also varies continuously across space and thus can usefully be represented using a raster model as a distance or travel-time surface.

In this paper we present an improved spatial analysis methodology for food security studies that uses the raster GIS data model to create continuous travel-time surfaces. Each surface is generated from vector-based GIS data using a road's speed limit as an indirect cost, land cover data, and relatively simple cost-distance algorithms to calculate a pixel's travel time in minutes to the nearest specified resource (grocery stores, for example). We demonstrate how readily travel time surfaces can be combined with other spatially continuous datasets, or can be agglomerated to census units as needed for integration with socio-economic and other potentially explanatory data. We show that a raster-based approach is particularly suitable for the study of food security in sparsely-populated rural areas. This can be important because of the relative simplicity, in terms of time, algorithms and resources, used to process raster data when compared to its vector counterpart.

Finally, we present evidence that, given an appropriate pixel resolution and scale, raster-based techniques are a suitable alternative to vector-based processing. While raster-based techniques have previously been identified as novel, faster, scalable and easily modeled, most food security studies have used the vector data model because of the large size and related computational and storage requirements of raster datasets. The increasing capabilities of desktop computers has substantiated the feasibility of raster-based approaches, but there has been little research to determine their accuracy or how well the results align with those of vector-based studies. Therefore, comparison of raster- and vector-based analyses is an important component of our study.

2. Literature review

The use and application of the raster data model in travel-time calculations has been largely overshadowed by vector data applications. Powerful tools to calculate new routes, service areas and O-D (origin-destination) matrices have been developed specifically for vector data and used for practical applications such as vehicle routing problems, creation of market areas, response times and determining closest facilities utilized by both public agencies and businesses interested in the efficient delivery of goods/services, advertising, logistics and supply chain management (Camm et al., 1997; Weigel & Cao, 1999).

Vector-based studies tend to aggregate results and represent them as single points centered within polygonal enumeration units or as polygonal units themselves. The most commonly used enumeration units are those defined by the U.S. Census Bureau for reporting of demographic and socio-economic data, ranging in scale from the census block (Gallagher, 2006) to the block group (Mulangu & Clark, 2012), tract (McEntee & Agyeman, 2009) and county (Morton & Blanchard, 2007; Sisiopiku & Barbour, 2014) levels. While powerful, these groupings may add to uncertainty if phenomena are grouped in such a way that breaks up clusters and thus obscures underlying patterns in the data (Lam, 2012).

A particular challenge in rural food availability studies is that any food proximity metric will likely be low regardless of explanatory factors such as socio-economics due to large distances and low population density (Bell & Standish, 2009). Identifying differences in rural accessibility using travel time in minutes to the nearest healthy food source requires additional information or analysis. Gallagher (2006) tackled this challenge by developing a unitless *food balance score* which represents the ratio of distance to grocery stores versus the distance to fast food.

Creation of raster-based travel-time surfaces can address the challenges of agglomeration, potential error, and processing time for large-scale regions. However, relatively little work on food insecurity has been done using a raster-based approach. Julião (1999) modeled travel time as a cost along highways in Central Portugal with 100-m pixel resolution to both the centers of municipalities and the city of Lisbon. Pozzi, Robinson, and Nelson (2009) did this at coarser resolution for the Horn of Africa. Balstrøm (2002) derived a walk-time surface in mountainous regions based on slope (i.e. people will walk slower on high slopes). The National Park Service (2010) developed a travel-time surface model that not only takes into account slope, but land-cover, proximity to streams and trails, where that each impedance represents a percentage (75% for example) of normal travel speed. An innovative study by Hallett and McDermot (2011) used a raster model to derive a cost surface in dollars to secure food based on the distance to full-service outlets via the IRS value of cost to operate a motor vehicle ($.505/mile).

Travel-time surfaces are a subset of cost-based surfaces in which each cell represents the acclimated cost between a cell and the nearest source. With the creation of these surfaces, a simple point-in-raster function can extract the value of the travel-time surface at a particular location (addresses or neighborhoods, for example) much faster than vector-based networking tools. Early pioneers of GIS (Clarke, 1985; Congalton, 1997; Veregin, 1989) recognized the importance of understanding the propagation of error as one migrates between vector and raster processing models. For example, the IBM (Increasing Buffer Method), devised by Haklay (2010) measured vector-on-vector error using Survey Ordnance GIS data to measure the accuracy of OSM (Open Street Map) GIS data in England. However, few studies have been done to determine the alignment of data intended to measure the same