Journal of Agriculture, Food Systems, and Community Development
ISSN: 2152-0801 online
www.AgDevJournal.com

Mapping the cost of a balanced diet, as a function of travel time and food price

Nathan Hilbert,[a] Jennifer Evans-Cowley,[b] Jason Reece,[c] Christy Rogers,[c] Wendy Ake,[c] Casey Hoy[d] *
The Ohio State University

Submitted April 30, 2014 / Revised July 18 and August 20, 2014 / Accepted August 24, 2014 / Published online December 6, 2014

Citation: Hilbert, N., Evans-Cowley, J., Reece, J., Rogers, C., Ake, W., & Hoy, C. (2014). Mapping the cost of a balanced diet, as a function of travel time and food price. *Journal of Agriculture, Food Systems, and Community Development, 5*(1), 105–127. http://dx.doi.org/10.5304/jafscd.2014.051.010

Abstract

We present a new method for analyzing spatial variation in the cost of a balanced diet, as an alternative to food desert classification. Our specific hypothesis is that the cost of a balanced diet varies according to where one lives, as a function of travel and food item costs. We collected price data for the USDA Thrifty Food Plan from approximately 30 percent of food retail outlets of various kinds in the three Gulf Coast counties of Mississippi, and these prices were extrapolated to the remaining stores. Transportation costs were calculated for both driving by automobile and the combination of walking and public transportation by bus, accounting for both the shoppers' time and the cost of automobile mileage. We developed a "traveling purchaser problem" algorithm to estimate the lowest-cost combination of travel and food costs for purchasing all items in the Thrifty Food Plan for each residential parcel in the study area, and mapped the resulting costs and examined their variation. Estimated costs varied more because of transportation costs than food prices, and ranged from US$109 to US$215 for automobile travel and from

[a] Agroecosystems Management Program, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, Ohio. Current address: 7600 Wisconsin Avenue, Bethesda, Maryland, USA; nathan@gisrs.net

[b] City and Regional Planning Section, Austin E. Knowlton School of Architecture; The Ohio State University; 275 West Woodruff, Columbus, Ohio, USA; +1-614-292-0479; cowley.11@osu.edu

[c] The Kirwan Institute for the Study of Race and Ethnicity, The Ohio State University, Columbus, Ohio

[d] Agroecosystems Management Program, Ohio Agricultural Research and Development Center, The Ohio State University, Wooster, Ohio

* *Corresponding author:* Casey Hoy, Agroecosystems Management Program, The Ohio State University, Ohio Agricultural Research and Development Center, 1680 Madison Avenue, Wooster, Ohio 44691 USA; +1-330-263-3611; hoy.1@osu.edu

US$111 to US$439 for a combination of walking and public transportation. In general, costs were lowest in the more populated areas near the coast and higher in more rural areas further inland. Results of this analysis demonstrate that the cost of acquiring a balanced diet varies considerably and more or less continuously. Food is not equally cheap for all; it depends on where one lives. For any given location, an estimate of the cost of a balanced diet, including both food price and transportation, is more useful than a classification as food desert or not in understanding access issues and needs. Furthermore, policy alternatives that are intended to influence access should be evaluated based on how much they influence costs, and for whom, depending on where people live.

Keywords
economics, food access, food desert, optimization, policy, spatial analysis, traveling purchaser problem

Introduction

In the past 15 years, interest in and concern about food deserts, food environments, and food access for public policy, community development, and community health policy have grown. Food price, diet, and health outcomes are clearly linked (e.g., Duffey, Gordon-Larsen, Shikany, Guilkey, Jacobs, & Popkin, 2010; Sharkey, 2008). From a policy perspective, ensuring affordable, healthy food may improve social equity and foster community development. The concept of a food desert, where healthy and affordable food is relatively scarce, has emerged as a way of communicating the geographical disparities in food access, particularly as they relate to income. A plethora of methods and definitions have been used to identify food deserts at multiple geographic scales in many different research fields, as demonstrated in recent literature reviews (Charreire, Casey, Salze, Simon, Chaix, Banos, Badariotti, Weber, & Oppert, 2010; McEntee, 2009; McKinnon, Reedy, Morrissette, Lytle, & Yaroch, 2009). However, classification imposes arbitrary binary or ordinal criteria on an essentially continuously varying challenge: variation among locations (typically locations of households) in the challenge of acquiring a healthy diet. This paper first reviews methods for classifying food deserts and areas of low access to food, then proposes an innovative method to address some of the shortcomings of the classification methods. Our proposed method does not classify or label, but rather estimates and maps the cost of acquiring a balanced diet for any household location as a continuous variable. In this way we avoid the pitfalls of describing food access as a pathological state in need of a cure for a particular place (Shannon, 2014); instead, we estimate one of the critical patterns of variation with which people must contend in relating to their neighborhoods. Our assumption is not that cost alone governs diet, but rather that it is one very important consideration in shaping what people eat and how they acquire it (Alkon, Block, Moore, Gillis, DiNuccio, & Chavez, 2013). Therefore we offer one very important step beyond food desert classification and toward a more complete understanding of disparities in food access.

The term "food desert" has been defined in various ways in the recent literature. The term was popularized by a British study suggesting that millions of households did not have adequate access to grocery stores, resulting in undernourishment (Cummins & Macintyre, 2002). The U.S. government formalized the definition in the 2008 Farm Bill as follows: "an area in the United States with limited access to affordable and nutritious food, particularly such an area composed of predominately lower income neighborhoods and communities" (2008 Farm Bill, Title VI, Sec. 7527). Ambiguities in the definition include what constitutes "nutritious food" and "limited access" (Bitler & Haider, 2011). In one study, the area classified as a food desert varied from 17 percent to 87 percent of the study area depending on how the term was defined (Rose, Bodor, Swalm, Rice, Farley, & Hutchinson, 2009).

This study focuses on an alternative to food desert classification to overcome its shortcomings; we estimate the variation among residents in the cost of acquiring food, as a relatively continuous variable that can be mapped. Food access depends at least in part upon the affordability or price of a complete and balanced diet, the distance or cost of transportation to acquire it, and information about what healthy food is and where it can be acquired and at what price (McEntee, 2009; McEntee & Agyeman, 2010). Bitler and Haider (2011) provide an economic perspective by separating the issues into demand- and supply-side issues. Most studies solely focus on the supply side (Alkon et al., 2013), asking what area is served by a given set of stores. Others, described below, have focused on the demand side in terms of affordability and access to consumer information, by comparing income levels to prices paid at stores. One study has included elements of both the demand and supply sides by looking at both the price that given households would pay for a balanced diet and the cost of transportation to acquire it (Rose et al., 2009), which would have to be combined to calculate the full cost to the household while ignoring any additional costs such as information about prices. Even when food desert classification is accepted as a valid representation of food access disparity, the quality of methods used varies widely among studies (Beaulac, Kristjansson & Cummins, 2009).

A community's diet is associated with the food in its environment, but changing the available food may not immediately change the community's diet (Ver Ploeg et al., 2009). Some question whether the food environment is the outcome of market forces (i.e., businesses providing goods and services that consumers demand) rather than a systemic issue of businesses that are unwilling to offer healthy food in certain areas. Some researchers question the value of examining the food environment at all, because providing access to a particular set of food items does not guarantee that the surrounding population will acquire them (Apparicio, Cloutier & Shearmur , 2007; McEntee 2009). Perception is a challenge as well, as households may not have the access to information to know what adequate food access entails (Morton & Blanchard, 2007). In a systematic review of 38 studies of food environment and diet, however, Caspi, Sorensen, Subramanian, and Kawachi (2012) found that both food availability and price were associated with diet and that inconsistency in studies of the relationships between food access and diet stemmed from arbitrary and varying use of often overly simplified classification techniques, such as distance buffers.

Most researchers have agreed that food access issues and food deserts are associated with physical places (Leete, Bania, & Sparks-Ibanga, 2012; Sparks, Bania, & Leete, 2011), despite the challenges of identifying or placing boundaries on those places. Geographical information systems (GIS) are a useful tool to measure and better understand food access and the food environment. Researchers have embraced GIS and have effectively analyzed multiple variables associated with food over many geographic areas (Charreire et al., 2010), although their methods have varied. Charreire and colleagues note that the ideal GIS study would measure proximity, diversity, availability, affordability, and perception (2010). If these were examined along with the demand and supply dimensions raised by Bitler and Haider (2011) and McEntee's (2009) core components of food access, then a more comprehensive analysis of food access would be available. Based on the conceptual issues raised in the studies described above, we pose four questions regarding spatial variability, transportation costs, store variety, and overall cost calculations that should be resolved in improved methods:

1. How well do buffers (the area encompassed by a particular radius around a point or grid cell) or network service areas reflect the transportation cost of acquiring a healthy diet for a household, considering differences between rural and urban areas and between walking and driving?

In the review of 29 GIS studies on food access issues by Charreire et al. (2010), 18 of the studies used buffers around store locations as an indicator of store accessibility. Of these 18 cases, 11 used a circular buffer or "as the crow flies" distance, and seven used the network service area (Charreire et al., 2010). The network service area restricts the representation of distance to travel along a road network only. The assumption is that the buffers or service areas allow one to classify particular places as meeting (within a buffer or service area) or not meeting (outside of all buffers or service areas) as a criterion of availability. In addition, there were 16 cases in which the distance from a particular place to the nearest store that sold food (i.e., not necessarily a grocery store) was taken as a measure or classifier of availability. A few studies highlight the use of these different methods. Block and Kouba (2006) used the circular buffer method around independent grocery stores in comparing two neighborhoods in Austin, Texas. They examined concentric buffers of ¼ (.4 km), ½ (.8 km), ¾ (1.2 km), and 1 mile (1.6 km), and found that 74 percent, 92 percent, 97.3 percent, and 98.7 percent, respectively, of the population of Austin have access to an independent grocery store. The authors conclude that walkable access was acceptable for a majority of the population. Apparicio, Cloutier & Shearmur (2007) used a network service buffer method as one of three measurements of food access. The method drew a 1 km (.6 mile) network service area using the street network around the center of each of the census blocks examined and counted the number of stores that fell within this area. An average of 1.220 supermarkets were found within 1 km of all of the census blocks examined, although in this case the variance or percentage of blocks with no supermarkets may be more meaningful than the average. Mulangu & Clark (2012) used a similar method and found that approximately 75 percent of the rural Ohio population fell outside any buffer or service area and, therefore, are more than 1 mile (1.6 km) from a grocery store. An alternative to classifying locations as being within or outside a buffer or service area is to simply calculate the distance from a given point, representing a household or population center, to the nearest supermarket or grocery store. Ver Ploeg and colleagues used the 2010 U.S. census data nationwide and distance to store measures to calculate that 41.2 percent of the population was at least one mile away from a supermarket. Similarly, Morton & Blanchard (2007) found that nearly half of the U.S. population lives more than 10 miles (16 km) from the nearest large food store. In sum, studies that use the circular buffer, network service, or distance measures to the nearest store all represent the single aspect of proximity, thus not accounting for diversity, availability, affordability, and perception. Many of these studies did include other variables to complement the proximity measure. For example, Block and Kouba (2006) examined the price of a market basket of items to explore affordability; Apparicio, Cloutier, and Shearmur (2007) used average distance to the three closest supermarkets to examine diversity; and Morton and Blanchard (2007) used interviews to note perception. In each case, however, the various components of access were addressed separately and tradeoffs among them could not be explored.

Sparks, Bania, and Leete (2011) demonstrated that the circular buffer and network service methods provide similar results. Based on a lack of differences resulting from the two methods, they concluded that researchers should use whatever method is easily accessible to them. Unfortunately, the comparison was entirely within an urban data set, where road networks are more uniform and dense than in a rural setting, where physical barriers like lakes, farms, and mountains can dramatically increase driving time. Therefore the importance of the network service area approach outside of urban areas, for regional or national analyses for example, remains a subject of research (Ver Ploeg et al., 2009). And ultimately these measures of distance alone have been very inconsistently associated with dietary outcomes (Caspi et al., 2012).

2. Does the price of transportation need to be included in the total cost of acquiring food?

Bitler and Haider (2011) have called for more accurate measures of affordability by including the price of transportation for households; omitting the cost of transportation has been noted as a major limitation of some studies (McEntee & Agyeman, 2010; Mulangu & Clark, 2012; Ver Ploeg et al., 2009). As noted earlier, Rose et al. (2009) is the only study reviewed that calculated both the cost of transportation, using available transportation and network distance to the nearest supermarket to calculate cost, and the availability of food item categories within a given network distance, to improve the description of food access to encompass a balanced diet. If parts of a balanced diet are not available within a given distance, however, they still need to be acquired. The distance measures discussed above are likely correlated with cost, but the transportation cost of a balanced diet would need to include the cost, given available transportation, to the nearest set of stores at which the entire diet can be acquired, or transportation to the set of stores at which the entire diet can be acquired at lowest cost with transportation included. Transportation cost should include vehicle mileage and public transportation fares paid, and it should also factor in time spent in transit. This cost varies depending on the modes of transportation available to each household and its location. Based on 2010 census data, 2.2 percent of the U.S. population live more than 1 mile (1.6 km) away from a supermarket and do not own a vehicle (Ver Ploeg, Breneman, Dutko, Williams, Snyder, Dicken, & Kaufman, 2012). This population may spend a great deal of time walking to acquire food and may be limited in how much and of what they can procure by the weight and bulk of the items purchased. Again, based on the 2010 Census, 0.3 percent of the population use public transportation and 4.8 percent use taxis or share rides to a grocery store, while another 4.8 percent walk (Ver Ploeg et al., 2009). Data was not available to determine the distance to grocery stores for these groups. Nevertheless, people use various means of transportation that have different costs in terms of actual dollars and time expended, which should be considered in estimating the full cost of obtaining a balanced diet.

3. What types of stores should be included in measurements of food access?

Supermarkets of greater than US$2 million dollar revenue have been the accepted proxy for availability of fresh, healthy food in a neighborhood (Apparicio, Cloutier, & Shearmur, 2007; Hubley, 2011; Leete et al., 2012; Sharkey & Horel, 2008). Fresh produce has been shown to cost less and be more broadly available in supermarkets (Hubley, 2011). In fact, in Buffalo, New York, a set of food items representing a balanced diet was found to cost US$132.64 on average if purchased in supermarkets and US$162.47 if purchased in convenience stores (Raja, Ma, & Yadav, 2008). However, small grocery stores offered prices similar to supermarkets, US$133.39 (Raja, Ma, & Yadav, 2008). In addition, these small grocery stores tend to be found more often in low-income areas, and could be missed in food accessibility measures if only supermarkets are considered (Block & Kouba, 2006; Raja, Ma, & Yadav, 2008; Ver Ploeg et al., 2009). Based on national census data, 75 percent of food is purchased in supermarkets and supercenters that on average have 10 percent lower prices than smaller food stores, and low-income households only spend 2 to 3 percent of their food dollars at convenience stores (Ver Ploeg et al., 2009). Farmers markets have been noted to have an effect on increasing accessibility and lowering the average price for fresh produce, but are rarely used in food environment studies (Larsen & Gilliland, 2009). Although supermarkets provide a good and simple estimate for most people, such alternative outlets as farmers markets and smaller grocery stores could be critically important for some populations and locations. Furthermore, preferences for particular stores, based on a range of characteristics from food quality to characteristics of the surrounding neighborhood, may be as important as store type (Caspi et al., 2012). In any case, obtaining accurate data can be challenging. For example, a research group in Texas verified the locations of food stores by driving every road in their study area. They found a total of 208 food stores, including convenience, small grocery, and superstores, although only 169 food stores were in publically listed databases (Sharkey & Horel, 2008).

4. How can food access be measured as a combination of transportation cost and price of all food items needed for a balanced and healthy diet?

None of the studies described above takes the critical step of combining the various costs and calculating the cost of what people would need to do to acquire a balanced diet, which is to acquire balanced food items consistently regardless of how far or how many outlets are needed to do so. This question goes beyond a simple classification of locations into food deserts and not food deserts. Our hypothesis is that the total cost of a balanced diet varies considerably depending upon where people live, the resources they have available to them, and how they use those resources, and that the distribution of costs is a better measure of the variance in food access than a bivariate classification. Note that this cost would include both supply- and demand-side elements of food access, that is, both the availability of food items and their spatial distribution and cost of purchase, and the steps and behaviors taken by a given household to acquire them. For this study, we had access to data for the first four measures proposed by Charreire et al. (2010), allowing us to focus on how to combine these data in an improved measure of food access. We seek better methods to incorporate consumer choice and perception as called for by McEntee (2009) and to better understand why food access varies, not just where food deserts exist according to a particular definition (Bitler & Haider, 2011). Furthermore, the typical policy objective is to improve access by lowering the cost of a balanced diet. But many outcomes in terms of changes in the distribution of costs could be possible, from decreasing cost equally everywhere for everyone, to much larger decreases in costs but only in some places or times or for some people. For food desert classification to be useful as a policy evaluation tool, it would need to distinguish among these possible outcomes, but changes in the size and shape of classified food deserts may do little to distinguish between them. Our ultimate goal is a more continuous measure of total cost of a balanced diet that allows policy-makers to conduct cost-benefit analyses of options for improving food access for a given population in a given area.

Methods

We used GIS and optimization techniques to estimate the lowest cost of acquiring all food items required for a balanced diet, including transportation cost and the cost of the food items. This case study for the proposed method was conducted in a three-county area of Mississippi. Transportation costs included walking, public transportation, and private automobile transportation in conjunction with parcel centroids, road networks, and verified store locations. Cost of the items at each store was based on the USDA Thrifty Food Plan pricing data collected from a sample of the stores in the study area. First we will describe the study area, then we will outline the data acquired and used in the analysis, and finally we will describe the optimization techniques used to estimate the lowest-cost combination of transportation and stores.

The Mississippi Gulf Coast includes three coastal counties: Hancock, Harrison, and Jackson. The three counties have a combined population of 330,702 people, based on the 2010 census (U.S. Census Bureau, 2010). Much of the population is concentrated south of Interstate Highway 10, but there are also significant rural populations in the northern areas of the counties. In 2005, Hurricane Katrina destroyed many of the food stores that were located closest to the coast. Due to changes in insurance prices, many of these stores chose not to rebuild, leaving newly formed gaps in food access that have been slow to be filled. In the rural areas, there are limited numbers of grocery stories, meaning that many residents' closest food sources are convenience stores. Food access became a pressing issue emphasized in a number of the post-hurricane plans (Evans-Cowley, 2011).

Food environment studies commonly use population blocks, including census tracts, census blocks, counties, and 0.5 km (.3 mile) grid cells (Leete et al., 2012; Morton & Blanchard, 2007; Ver Ploeg et al., 2009). Parcel maps were available from the Southern Mississippi Planning and Development District for the three-county area and were used as the basic unit for mapping food access cost. Parcels identified as industrial, public use, right-of-way, school, parking lot, office, institutional, and parks were excluded from the data set, leaving 36,732 residential parcels, corresponding to at least one household at each residential parcel for which food would be acquired at a cost unique to that parcel.

The road network was obtained from 2010 U.S. Census Tigerline data (U.S. Census Bureau, 2012). Two road network data sets were developed using ArcGIS 10, one for driving and one for a combination of walking and public transportation. The driving network used road classifications to attribute speed limits to all the roads. For the walking/public transportation network, major highways with an "A1" classification were ignored; we assumed they did not have walkable sidewalks. The bus route was digitized into a separate shapefile and walking and bus transportation were compiled as a multimode network. According to the managing authority of public transportation, buses in the area will pick up and drop off passengers anywhere along the route. Therefore, we assumed that individuals would walk to the nearest point on the nearest bus route, or to the nearest store if it was closer. Buses were assigned an average speed of 20 miles per hour (MPH), and the rest of the walking/public transportation network was assigned a speed of 3 MPH.

Transportation networks were used to calculate the total cost of transportation, based on distance traveled, and would account for assumed consumer behavior and the value of their time. For the driving network, cost was determined by multiplying US$0.585 (based on a recent federal mileage reimbursement figure) by the number of miles traveled plus the driving time (assuming speed limits were strictly observed) multiplied by a standard value for time (US$10.00/hour). Variables that were calculated incidentally and could be useful in other research included the number of hours in transit and total distance traveled. For the walking/public transportation network, the only cost assumed was time spent (at US$10.00/hour). The US$1.50 bus fare for public transportation was assumed to be negligible in the calculations and was ignored. Supplemental variables that were calculated for the walking network included the number of hours traveled and the distance traveled by bus.

The optimization algorithm required a matrix of transportation costs between all parcels and stores and between all stores. Two origin-destination (OD) cost matrices were developed using ArcGIS 10 Network Analyst. The OD cost matrix calculates the cheapest route along the network from each of the input origin values to each of the destination values. The first calculation created a 6.1 million value (36,732 parcels by 167 stores) matrix for the total cost of transportation from each parcel to each store. The second calculation created a 167 x 167 matrix for the total transportation cost from each store to each of the other stores. These cost matrices were constructed for both the driving and the walking/public transportation network data sets.

The store data was obtained through a multi-step process. First the telephone business directory was examined to create an initial list of potential stores. This was then matched with store data from ESRI's Business Analyst Database. This list was then visually confirmed through a review of Google Satellite Imagery to make sure that a store appeared on the site. A number of the businesses listed were no longer at the location due to the hurricane. The refined list was then sent to a sample of city planning officials who reviewed the list for their community to determine if any were missing or should be removed. A letter was sent to each store on the list requesting permission to visit their store to conduct the pricing survey. A total of 45 stores indicated willingness to be surveyed. Teams of two students per store completed the store audits during March 2011. The students entered the store and asked to speak to the store manager. They requested permission of the store manager to conduct the survey. Two stores declined to participate upon the visit by the students. Each student team completed the USDA Thrifty Food Plan (TFP) survey instrument for each store visited. In sum, 43 of the 167 identified stores were surveyed, including 24 convenience stores, 13 grocery stores, and 6 superstores. The surveyed stores were also geocoded using the Google Geocoding Service into an ArcGIS shapefile, and then verified once more using aerial imagery and the Google Map Business Listing.

The TFP includes a set of 87 food items that were judged to provide a healthy and complete low-cost diet for a family of four (Cohen, 2002). The TFP is assumed to represent a typical American diet, and does not consider variations based on ethnicity. We assume that the variation in cost of these items would be similar for other balanced diets, such as those representing other ethnic preferences, although this would be worth examining in future research. Where more than one brand or quantity was available for a given item, the lowest unit price was recorded. If the product was not available, the price was recorded as zero, signifying that the item was not available. The prices of goods were calculated for a standardized unit. The weekly cost for each of the items was calculated according to recommended consumption of 28 categories of the 87 TFP food items for two adults and two children (Carlson, Lino & Fungwe, 2007). Recommended amounts were multiplied by price per unit to estimate the total cost of each food item for one week for a family of four at a given store. Stores that were not surveyed included 98 convenience stores, 22 grocery stores, and 4 superstores. Following Rose et al., the price for each item in unsurveyed stores was selected at random from the range of prices for that item among the surveyed stores in the same category.

The algorithm to estimate the lowest-cost combination of transportation and food prices for the entire diet was based on the traveling purchaser problem (TPP), which has been well documented in operations research (Boctor, Laporte, & Renaud, 2003; Laporte, Riera-Ledesma & Salazar-González, 2003). Given a set of markets and the prices of goods within each of the markets, the objective function is to minimize the overall cost of purchasing a complete set of items from any of the markets in the set. No restrictions were assumed on which items could be purchased from a given store, other than that the item must be available at the store. For the sake of simplicity, supplies of the items in each of the stores were assumed to be unlimited, making this an uncapacitated TPP (Boctor et al., 2003). Once the item has been purchased, however, we assumed that the item would not be purchased in any other market (Riera-Ledesma & Salazar-González, 2005). The cost of the TFP for any given household and set of stores was calculated as the sum of the price of each of the purchased items, given the prices in the stores at which those items were purchased, plus the cost of transportation from the starting parcel to and among each of the stores required to acquire all items and back to the starting point. The objective function was solved when the combination of transportation and food costs had been minimized for any given parcel.

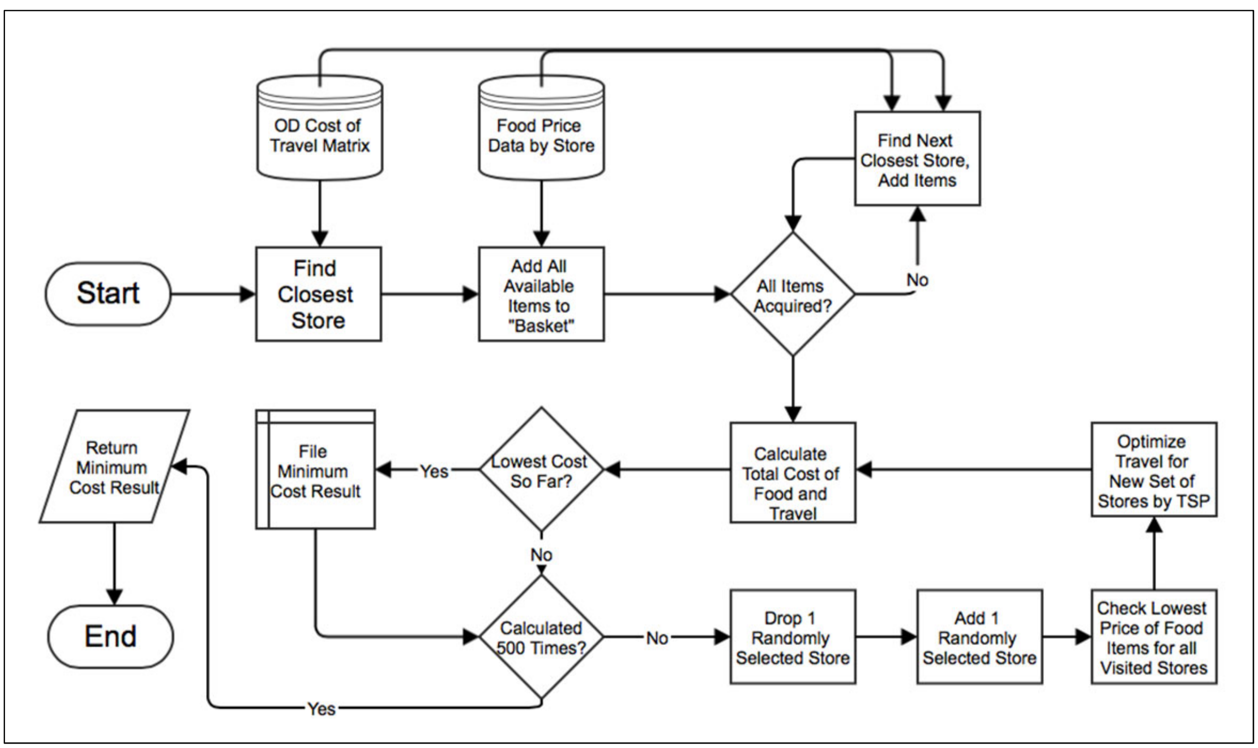
A number of algorithms have been presented over the past 20 years to solve the TPP problem with either global or approximate, near-optimum solutions. A global solution, the absolute minimum of the objective function, requires intensive calculations that are not feasible for more complex applications of the TPP. For example, we estimated that our optimization problem would take 127 days with a relatively fast personal computer to solve by evaluating all possible combinations of stores and routes from each starting point in our study area. Laporte, Riera-Ledesma, and Salazar-González (2003) proposed a global-solution algorithm that reduced the number of calculations required by using the branch-and-cut method, which branches and calculates many solutions, preserving the minimum and cutting the branches that yield solutions greater than the minimum until no additional branches are possible. Near-optimum solutions rely on heuristics to more quickly find a solution that is close to the global minimum. Voß (1996) presented a dynamic tabu search as a heuristic approach to solve problems with many markets and items. The dynamic tabu search keeps a record of all combinations of markets and items and randomizes the combinations many times, skipping any combinations that were already calculated, while calculating, storing, and ranking the value of the objective function for each combination. The iterations stop after a specific number of iterations or when new combinations become infrequent. More recent algorithms have used biomimicry, such as ant-colony optimization techniques that mimic ants following pheromone trails to optimize paths to food sources (Bontoux & Feillet, 2008). Goldbarg, Bagi, and Goldbarg (2009) used a transgenetic algorithm that merges two near-optimal parents many times, keeping only the offspring of those parents that represent improved solutions.

For our problem of 167 stores each with 87 food items to be procured 73,464 times (36,732 parcels run once for walking/public transportation and again for driving), relatively fast heuristics were required to estimate solutions. Our algorithm followed Boctor, Laporte, and Renaud (2003), heuristics of market exchange for an uncapacitated TSP, with modifications. Boctor et al. (2003) first calculated the minimum cost of all commodities and the cost of transportation in an initiation phase. They then used an improvement phase by first dropping one market from the feasible solution if it yields a cost savings, then adding unvisited markets that minimize the travel cost. If through the series of dropping and adding markets the solution is less than the original feasible solution, they then used the new solution and repeated the drop/add market functions. Finally, they ran the traveling purchaser problem heuristic on each of the feasible solutions to minimize total travel cost. Multiple perturbation heuristics were used, including an added parameter to weight the travel cost against the commodity cost, removing two markets and replacing them with one, and varying the criterion for stopping the search for a solution, which was the number of successive iterations with no improvements.

We initialized our algorithm (Figure 1) by first selecting the nearest stores until the market basket was full, then selected the store from which each item was obtained based on the prices among all stores visited, following Riera-Ledesma and Salazar-González (2005). Starting from the centroid of each parcel, all available food items were purchased from the nearest store, then the algorithm repeated the process of searching for the next closest store and purchasing all available items still required until a complete set of the 87 food items had been purchased.

Following Boctor, Laporte, and Renaud (2003), after the initial feasible solution was found with the nearest store search, we used market drop and add functions to search for a lower-cost solution. This function removed one store, selected at random, from the set of stores that led to the current estimated solution to the objective function. Then a market add function was used to restore the full set of food items by searching the 30 closest stores to the removed store that were not already included in the solution to test whether inserting one or more of these alternate stores into the solution set would lower the overall cost. The order of the closest stores was randomized to remove the possibility of calculating the same solution repeatedly. All sequences generated using this randomization technique were recorded using a dynamic tabu method, where each subset of the stores is included in calculating the value of the objective function. If a new sequence of stores resulted in a lower total cost, then it became the new estimated solution for the objective function. The minimum prices were verified by reviewing the selection of the lowest cost of each food item in all of the stores visited. A traveling salesman problem algorithm using simulated annealing and the hill climb method (Lundy & Mees, 1986) was then used to ensure the optimal route to each of the visited stores and back to the parcel. The algorithm

Figure 1. Flow chart for the algorithm used to determine the lowest-cost combination of travel and food item cost to purchase all items in the USDA Thrifty Food Plan for each residential parcel in the study area



stopped after 500 substitutions of stores into the initial solution, or if no additional substitutions were possible. It then returned the approximate minimum for the total cost of all food items plus the transportation.

We compared the results of this analysis with food desert classification using a network service area defined by 15 minutes of travel time, consistent with Apparicio, Cloutier, and Shearmur (2007). For all 36,732 parcels in the study area, we then counted the total number of times that, according to the optimal cost algorithm, the shoppers from those parcels would have left the assumed network service area to purchase an item for a complete and minimal-cost TFP. The percentage of parcels from which one would never need to leave the assumed service area to purchase a complete and low cost-diet was taken as an estimate of how well the network service area buffers, based on time of travel alone, represented the cost of food access.

Results

As hypothesized, the minimized-cost algorithm resulted in a wide distribution of total costs for the TFP among parcels in the study area for both the driving and walking/public transportation methods, as shown in Figures 2 and 3. Figures 4 and 5 show the spatial pattern of variation in the estimated minimum cost of obtaining the TFP during spring 2011, including both transportation and the cost of the food items. This image was generated using the inverse distance-weighted interpolation function of ArcGIS based on cost data for travel from parcel centroids. For either driving or walking/public transportation, the minimum total cost of obtaining the TFP was less in the more populated areas along the coast, and quickly increased as food store density declined in the rural areas and transportation distances increased. For either mode of transportation, the cost of a minimum balanced diet shows a skewed distribution, with most parcels having a minimum cost near the average but with variation leading to longer tails of the distribution on the higher-cost side (Figures 2 and 3). Most of the residential parcels are in areas with high population densities, for which the same set of stores would be used and the transportation differences among parcels would be relatively small. A smaller percentage of parcels, in the tails of the distribution, would be found either very close to supermarkets or at great distances from a set of stores from which the entire food plan could be purchased. Those parcels that are at the greatest distances or must visit the most stores to acquire the entire diet were estimated to have 1.5 to 3 times the average minimum cost of the TFP, depending on mode of transportation.

In this three-county area, stores are located close to population centers, suggesting that there may be a difference in the minimum total TFP cost between the urban and rural areas. Figures 6 and 7 display histograms of the frequency of food costs alone for all parcels and show that the distributions of food costs are similar for either mode of transportation. Comparing rural and urban populations using walking and public transportation (Table 1) and focusing on the food cost alone, the maximum food cost was the same, US$193.39, whereas the rural population's minimum food cost was slightly lower, US$95.43, than the urban population's minimum cost, US$97.88. Time required to obtain all items in a balanced diet, however, was approximately four times greater on average for rural than urban areas (Table 1), and travel costs were substantially different between rural and urban parcels. To achieve minimum cost of transportation, we estimated that 24.5 percent of the rural population and 49.9 percent of the urban population would travel by bus. The remaining population was estimated to find lower cost by walking, although taking a median of approximately 2 hours and 45 minutes in urban areas and 8 hours and 30 minutes in rural areas. The time requirements to gather a TFP appeared more feasible in the driving model, with about 45 minutes round-trip required for rural areas and 15 minutes for urban areas. Differences between rural and urban areas in median estimated total cost (transportation plus food items) were much greater for those walking and taking public transportation than for those with access to an automobile (Table 1). For the walking/public transportation mode, the cost of transportation was 41.0 percent of the estimated median minimal cost of obtaining the TFP in rural areas and 18.4 percent in urban areas. For the driving mode of transportation the costs were 15.2 percent and 6.0

Figure 2. Variation in total cost of the USDA Thrifty Food Plan in the Gulf Coast counties of Mississippi, during spring 2011, assuming that all items are purchased and the shopper uses an automobile for transportation and achieves the lowest cost for the combination of food price and travel.

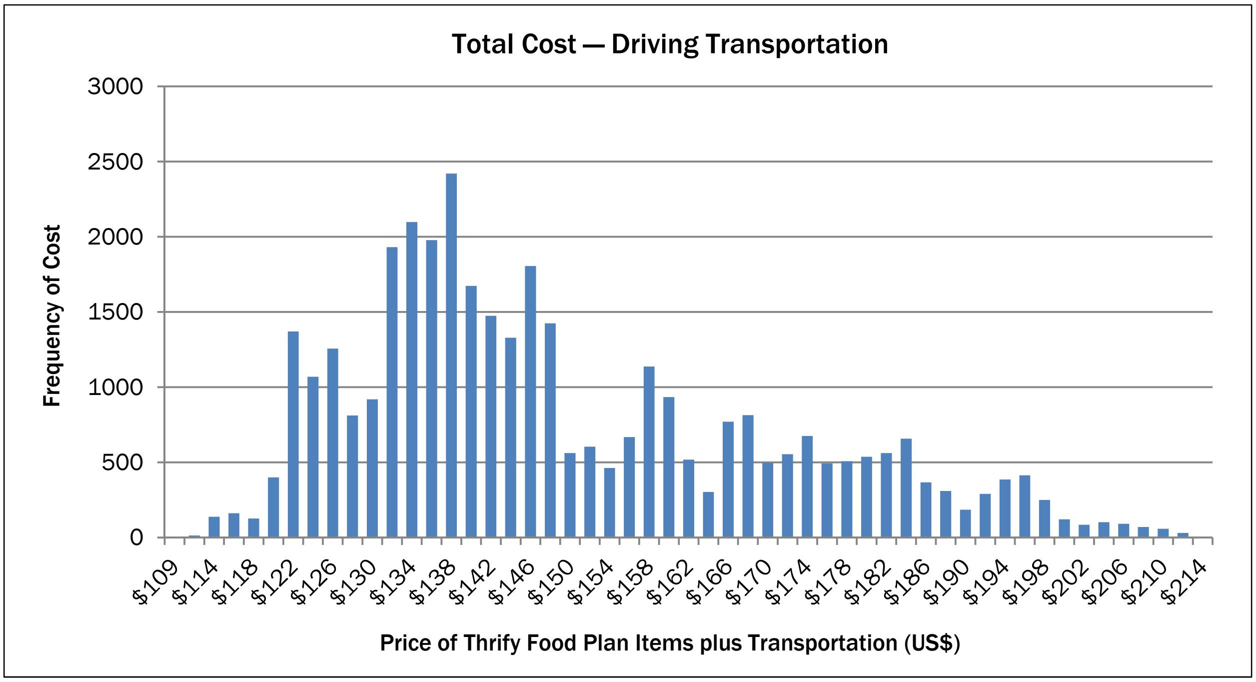


Figure 3. Variation in total cost of the USDA Thrifty Food Plan in the Gulf Coast counties of Mississippi, during spring 2011, including both the cost of the food items and transportation to acquire them, assuming that all items are purchased and the shopper uses a combination of walking and public transportation by bus to achieve the lowest cost for the combination of food price and travel.

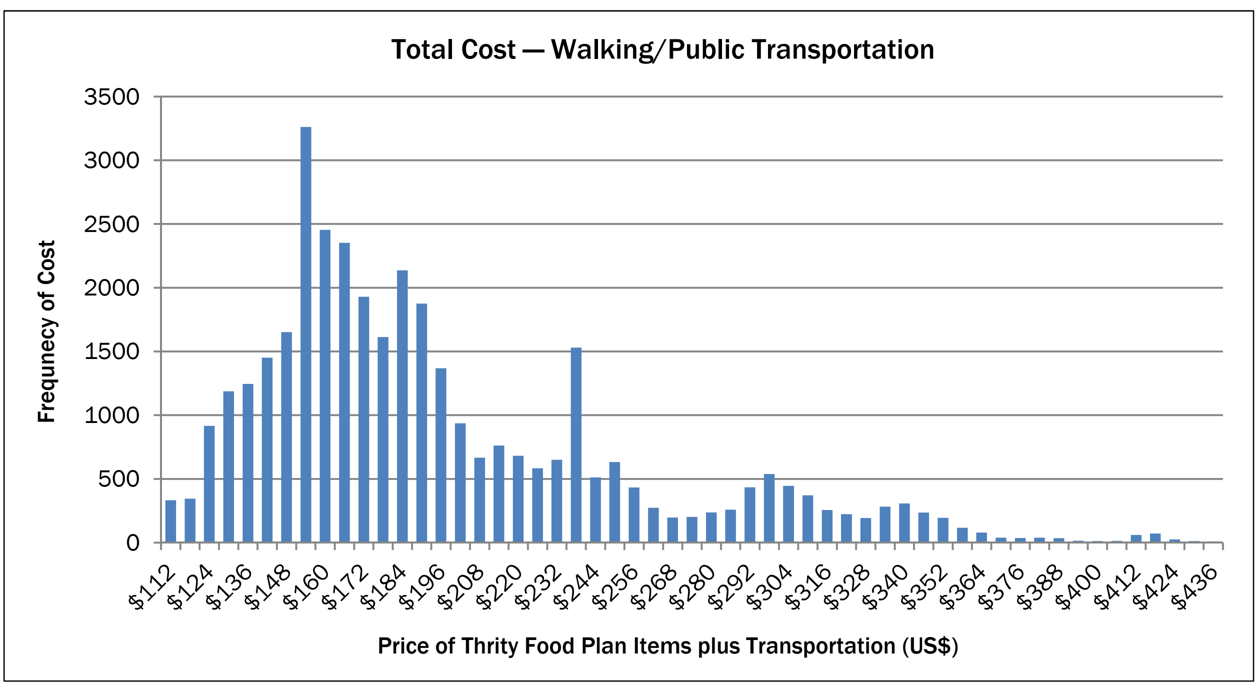


Figure 4. Map of the minimum total cost of the USDA Thrifty Food Plan in the Gulf Coast counties of Mississippi, during spring 2011, including both the costs of the food items and transportation by automobile to acquire them.

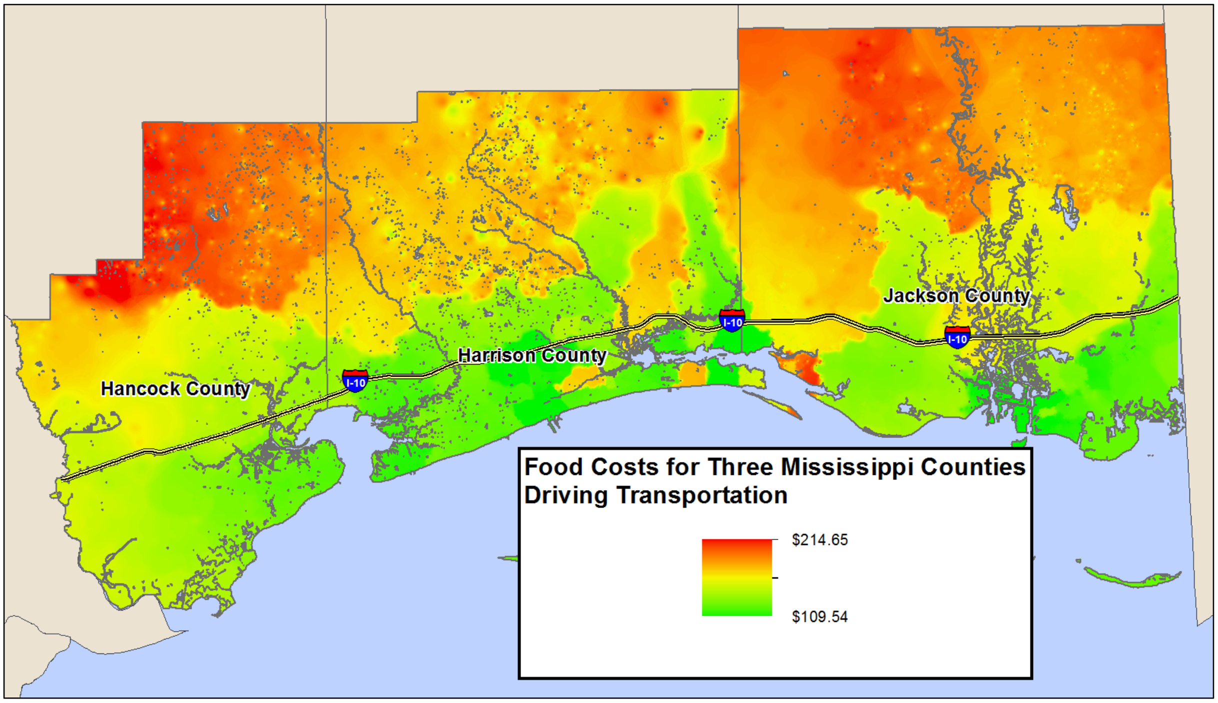


Figure 5. Map of the minimum total cost of the USDA Thrifty Food Plan in the Gulf Coast counties of Mississippi, during Spring 2011, including both the costs of the food items and transportation by a combination of walking and public transportation by bus to acquire them.

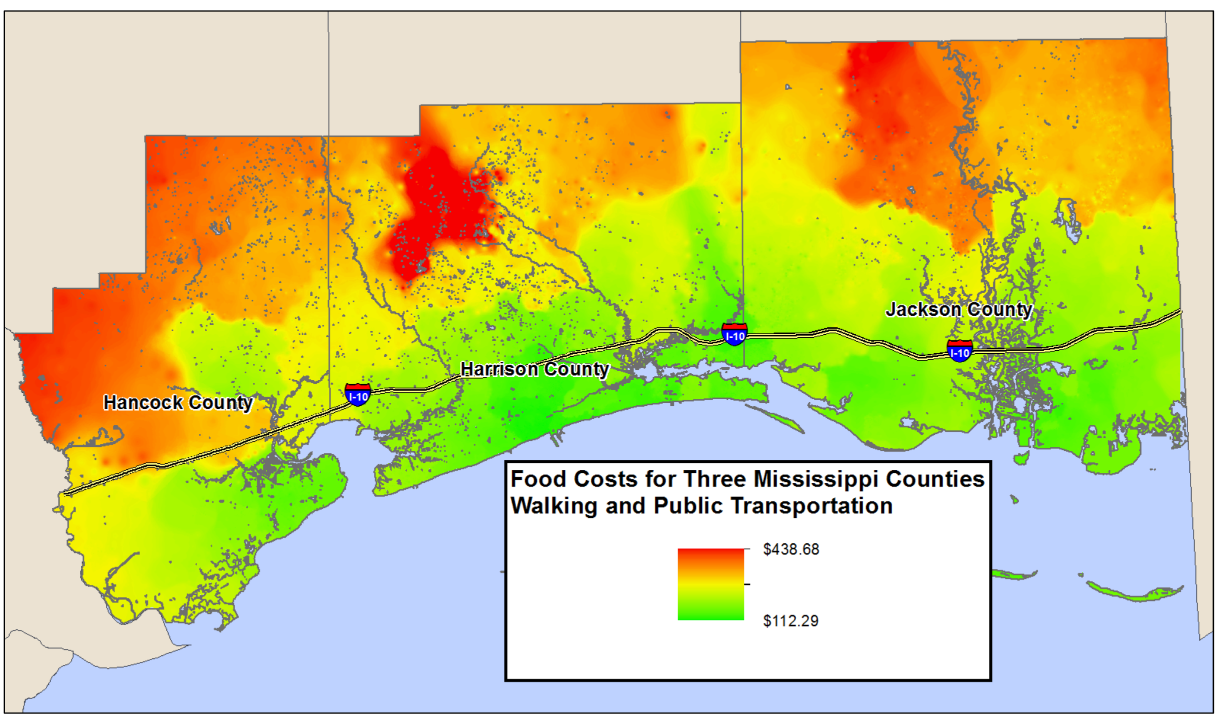


Figure 6. Variation in total cost of the USDA Thrifty Food Plan for the food items alone in the Gulf Coast counties of Mississippi, during spring 2011, assuming that all items are purchased and the shopper uses stores that provide the lowest cost combination of food price and transportation cost by automobile.

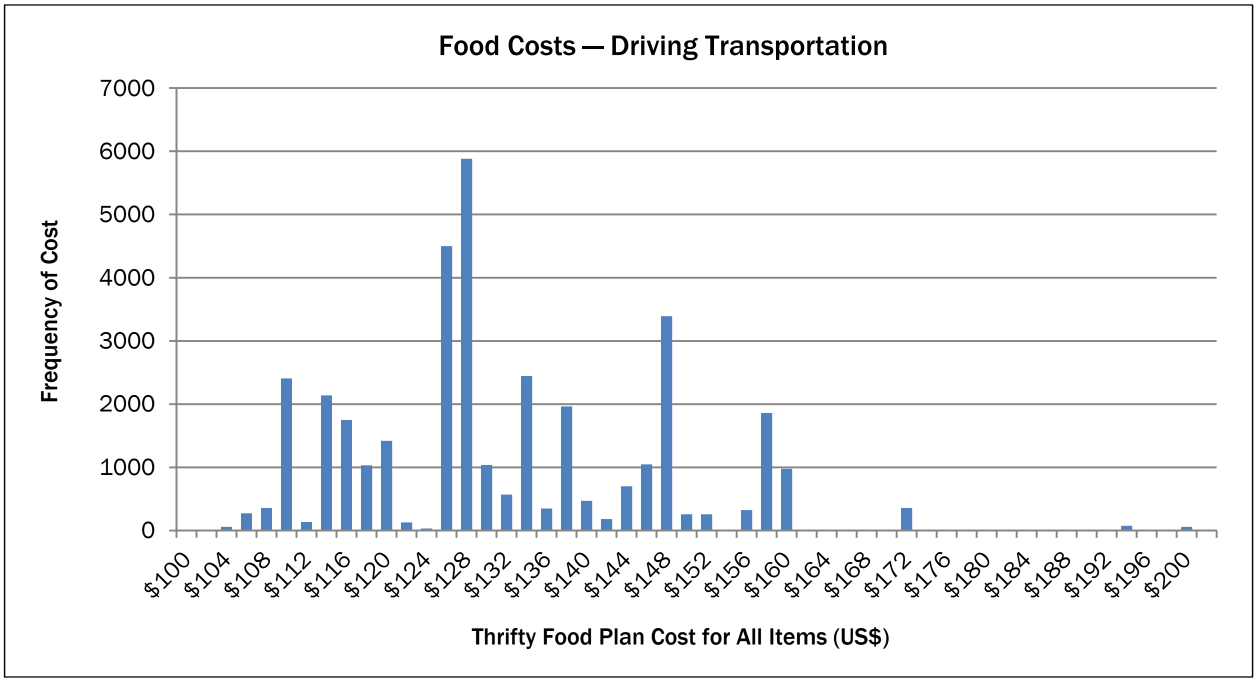


Figure 7. Variation in total cost of the USDA Thrifty Food Plan for the food items alone in the Gulf Coast counties of Mississippi, during Spring 2011, assuming that all items are purchased and the shopper uses stores that provide the lowest cost combination of food price and transportation cost by walking and public transportation by bus.

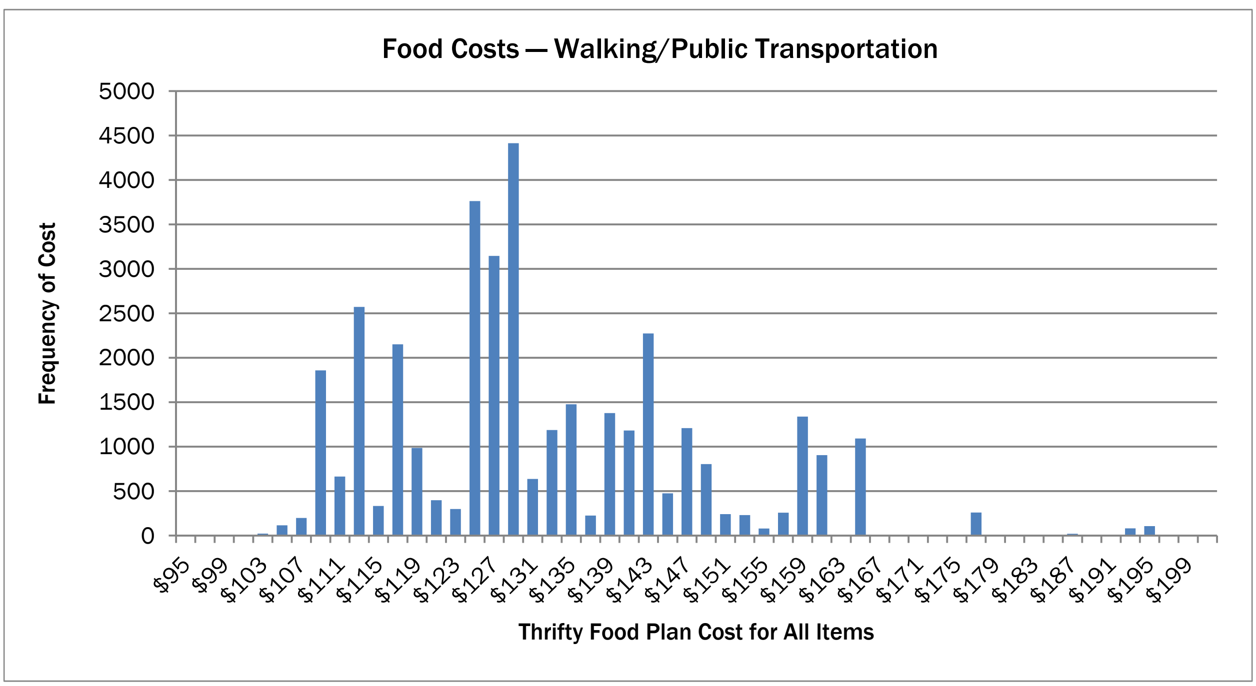


Table 1. Average minimum costs of the USDA Thrifty Food Plan in rural and urban areas in the Gulf Coast Counties of Mississippi during spring 2011, considering both the cost of the food items and the cost of transportation to acquire them (all costs in US$).

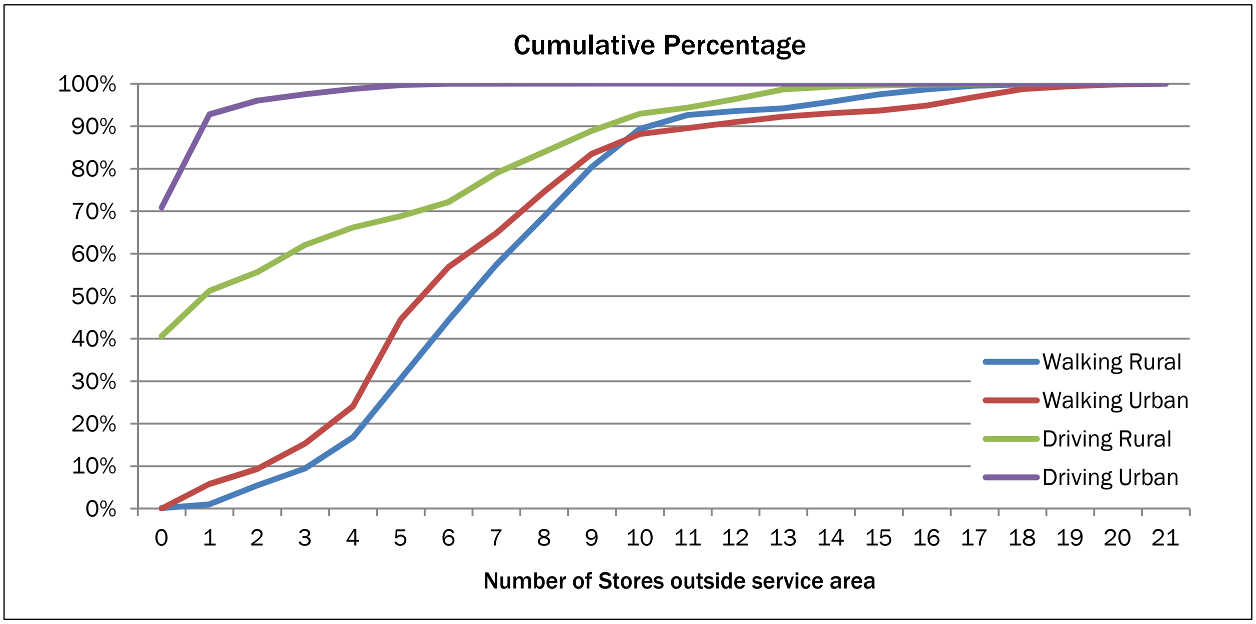
Driving	Maximum	75%	Median	25%	Minimum
Total Cost					
Urban	$204.63	$144.03	$135.22	$127.91	$108.71
Rural	$214.65	$178.96	$157.42	$142.02	$115.86
Travel Cost					
Urban	$58.21	$14.04	$9.63	$6.65	$.02
Rural	$80.24	$42.99	$25.88	$16.12	$.63
Time Spent (hours)					
Urban	1.5	.37	.24	.17	.01
Rural	2.1	1.0	.71	.42	.02
Food Cost					
Urban	$199.88	$133.41	$127.06	$115.39	$100.51
Rural	$199.88	$146.90	$133.41	$124.97	$102.67
Walking/Public Transportation					
Total Cost					
Urban	$291.82	$177.53	$155.76	$143.24	$111.36
Rural	$439.26	$288.22	$224.67	$186.71	$121.46
Bus Usage (miles)					
Urban	38.1	10.2	0	0	0
Rural	34.44	0	0	0	0
Time Spent (hours)					
Urban	17.4	3.9	2.6	1.64	.01
Rural	30.82	14.55	8.52	5.32	.05
Food Cost					
Urban	$193.39	$136.21	$127.06	$115.89	$97.88
Rural	$193.39	$146.90	$132.54	$124.97	$95.43

percent of the median values for rural and urban residents, respectively. Based on the assumptions inherent in our algorithm and the available data, the median cost of walking and public transportation in our three-county research area is US$35.31 more than the median cost of driving to acquire all items in the TFP at the lowest cost, assuming the shoppers' time is worth US$10/hr.

Assuming that a typical service area is defined by a 15 minute travel time from the centroid of a given parcel (Apparicio, Cloutier, & Shearmur, 2007), service areas enclosed an area within 0.75 mile (1.2 km) for walking/public transportation and 10 miles (16 km) for driving at 40 MPH along the area road network. Our results showed that approximately 30 percent of urban residents and 60 percent of rural residents with access to an automobile would have to travel outside this service area to acquire the entire TFP (Figure 8). Without an automobile, very few or no residents would be able to acquire the entire TFP within a 0.75 mile service area. However, we did not calculate the number or proportion of the TFP that residents would be able to acquire within this service area because the items making up this proportion could vary widely. Based on the available data describing what items were available at which stores, large percentages of residents, particularly those without access to an automobile and those in rural areas, would have to visit as many as 10 stores outside of their service area to acquire all items in the TFP. Those walking and using public transportation in

Figure 8. Percentage of residential parcels from which a shopper would have to visit up to a given number of stores that are outside of an assumed service area to acquire all items in the USDA Thrifty Food Plan at the lowest cost.

The shopper from each parcel is assumed to acquire all items in the Gulf Coast counties of Mississippi, during spring 2011, and use the combination of stores that provide the lowest cost combination of food price and transportation cost. The assumed service area, based on Apparicio et al. (2007), was 15 minutes in travel time from the centroid of the parcel, which equals approximately 0.75 mile (1.2 km) for walking or 10 miles (16 km) for driving at 40 miles per hour (64 km/hour) along the road network in the area.



an urban area would need to visit fewer stores outside the assumed service area than those in rural areas, but the differences are fairly small and the overall pattern is the same: most residents would have to travel to several stores outside the service area that has been assumed in previous food desert studies. For urban residents with access to an automobile, most could acquire the TFP at the lowest cost by visiting only a few additional stores outside of their assumed service area. For those without an automobile and those in rural areas, however, up to approximately 10 percent would have to travel to more than 10 stores to acquire the entire TFP at lowest cost, probably reflecting much greater frequency of small food retail outlets with a relatively limited selection of items in the TFP.

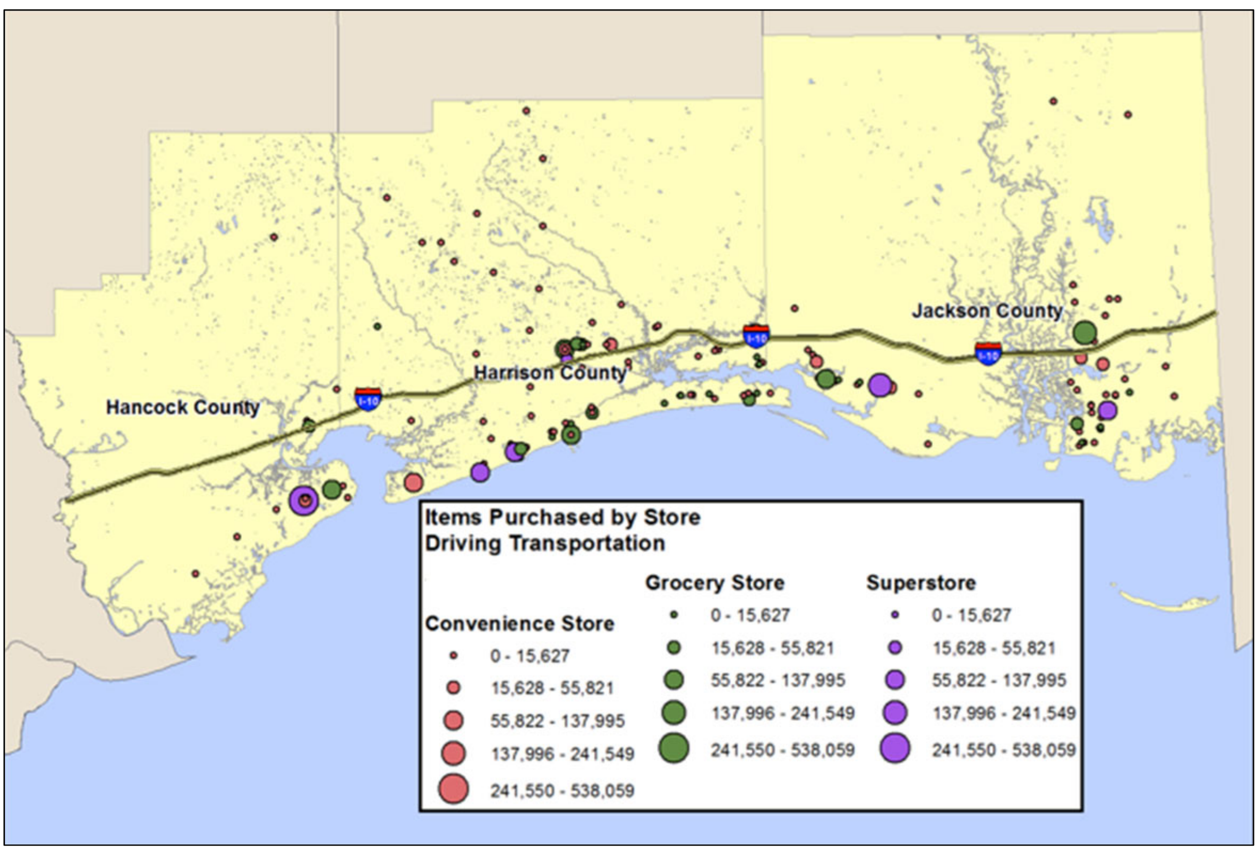
Table 2. Percentage of items purchased by residents using driving and walking/public transportation according to store category and location.

	Driving	Walking/Public Transportation
Store type/location	**% of the TFP**	**% of the TFP**
Convenience Store	28.64	26.58
Rural	6.52	6.48
Urban	22.12	20.10
Grocery Store	31.19	35.04
Rural	0.34	1.65
Urban	30.85	33.39
Superstore	40.17	38.39
Urban	40.17	38.39

The contribution of stores and store types to the minimum cost TFP, recorded as the percentage of items in the TFP that would be acquired from all parcels at each store, according to the least-cost algorithm, varied among store types and locations (Table 2, Figures 9 and 10). Mode of customer transportation, driving or walking and public transportation, made little difference in the percentage of items that would be purchased at the different store types and locations to achieve the minimum-cost TFP. Regardless of mode of transportation, and perhaps not surprisingly, the largest percentage of items would be purchased at urban superstores and the smallest percentage at rural grocery stores. Urban superstores, however, still account for only approximately 40 percent of items in the least-cost TFP, suggesting that it is less expensive to get 60 percent of the items elsewhere. Convenience stores in urban areas accounted for almost as large a percentage of items as grocery stores in urban areas, but those in rural areas contributed a relatively small percentage (Table 2). Most of the items purchased by residents in the study area would be expected to be purchased in stores in the more populated areas close to the Gulf (Figures 9 and 10).

We recognize that using the heuristics approach resulted in approximate solutions for each parcel, because there were random selections of stores that were dropped or added to test for an improved solution. To examine the variation in solutions returned by the algorithm, we performed 100 estimations for eight parcels selected from areas with high store density, medium store density, and low store density throughout the research area. For six of the eight parcels, the standard deviation of the estimates was less than one dollar, indicating that the algorithm consistently returned a near-optimal solution to the objective function (Table 3). The two parcels for which the solutions varied by more than one dollar were in rural areas and were roughly equidistant to two clusters of stores. In these cases, the estimated solutions varied according to which cluster was included first, after which the other cluster tended to be ignored because the travel cost would increase for travel between the two clusters. In these cases the average solution values tended to be closer to the maximum than the minimum of the range of solutions, suggesting that in some cases the heuristic algorithm could miss relatively rare

Figure 9. Map of the stores and their estimated frequency of usage (number of items purchased per store) by residents in the Gulf Coast counties of Mississippi, if they were to purchase all items in the USDA Thrifty Food Plan during spring 2011 at the lowest cost, including both the costs of the food items and transportation by automobile to acquire them.



lower-cost solutions (by as much as US$27 for the parcels examined) that did not fit the mechanics of the algorithm well.

Discussion

The method we have described does what we initially expected it to do; it provides an estimate of

Figure 10. Map of the stores and their estimated frequency of usage (number of items purchased per store) by residents in the Gulf Coast counties of Mississippi, if they were to purchase all items in the USDA Thrifty Food Plan during spring 2011 at the lowest cost, including both the costs of the food items and transportation by a combination of walking and public transportation by bus to acquire them.

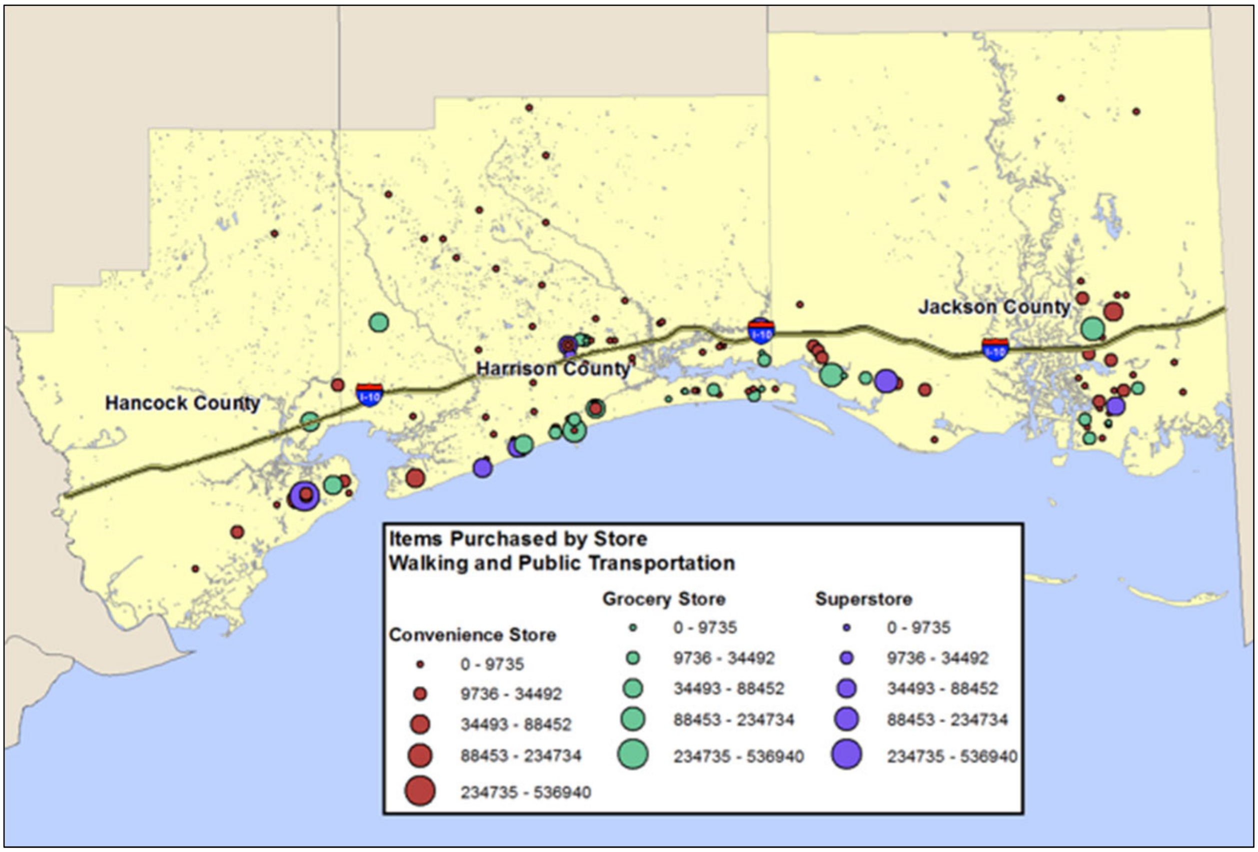


Table 3. Analysis of variation in heuristic algorithm solutions for an objective function of the minimum total cost of the USDA Thrifty Food Plan for selected residential parcels in the Gulf Coast Counties of Mississippi during spring 2011, considering both the cost of the food items and the cost of transportation to acquire them (all in US$).

Parcels	Maximum Estimate of Total Cost	Minimum Estimate of Total Cost	Average of Total Cost Estimates	Std Dev of Total Cost Estimates
A	$133.69	$132.93	$133.66	$0.13
B	$119.96	$119.96	$119.96	$0.00
C	$206.66	$172.59	$199.41	$10.35
D	$174.15	$172.07	$173.74	$0.72
E	$182.34	$160.22	$178.95	$4.72
F	$116.35	$116.35	$116.35	$0.00
G	$153.64	$153.64	$153.64	$0.00
H	$134.17	$133.50	$133.82	$0.33

the minimum cost to procure a balanced diet for a given household, given the household's location, mode of transportation, and assuming that all food items are purchased according to an optimal or near-optimal shopping strategy. The resulting map gives more detailed information about food cost than previous food access classifications, based on approximate minimum cost of a balanced diet. Challenges in using this method include the availability of detailed price information and item availability for specific stores, both of which could be dynamic in time. We expect the variation in prices over time to have little impact on the spatial variation among residential parcels in the cost of a balanced diet that these methods estimate, unless the variation is large and aggregates at spatial scales that would significantly shift the optimal set of stores and associated transportation costs for residents.

Data on prices for individual stores, acquired by administering the USDA Thrifty Food Plan Survey in person, required a considerable investment in time and only a limited number of stores were willing to participate. We did not have data for all stores, which would be preferable, but rather estimated the prices for stores that were not sampled. The food price data set was sufficient to demonstrate the methodology and glean useful insights from the results, but a means of collecting these data across all stores in a particular area is needed. Furthermore, food prices can be volatile over time as stores and their suppliers frequently change the price of particular items, according to supply and demand and with the objective of attracting shoppers and maximizing sales revenue. Therefore, access to instantaneous price information, as well as its variation over time, would be ideal. Crowdsourcing, using mobile phone applications that allow shoppers to scan items and input current prices, may be one such opportunity to generate current data in real time, although with quality control depending entirely on the users of the application themselves. If the TPP could be solved in real time, using an algorithm such as the one proposed, then it might suggest alternative shopping strategies that would lower food costs for residents of a given place, and those strategies could be especially important to those with low income and low food security.

Issues that, based on recent literature, have not been addressed using typical representations of food access were better resolved using the methods we have demonstrated. Three important findings were revealed by our study:

(1) The use of the service area buffer does a poor job of representing access to a balanced diet for anyone in the study area, with the exception of urban residents who have an automobile.
(2) Residents of areas conventionally classified as low-access areas, i.e., falling outside all assumed store service areas, may actually be able to purchase the TFP at lower cost than some residents who are not in areas classified as low access.
(3) People may have to travel much farther than previously assumed to purchase a balanced diet, even if they do not live in an area classified as a food desert.

The network service areas are most appropriate as indicators of food access for residents of urban areas who drive, and most previous food-access mapping studies have focused on this demographic (Charreire et al., 2010). However, our analysis suggests that even for urban residents who drive, approximately 30 percent would need to leave their assumed service area to acquire the TFP at lowest cost. Therefore, the service area classification would generally underestimate the areas with limited or more expensive food access, as suggested by Breyer and Voss-Andreae (2013).

In addition to improving on the methods for mapping food-access issues, even this limited demonstration of the method has contributed new insight into disparity in food costs. Residents of urban areas with access to an automobile generally have lower costs of obtaining a balanced diet than rural residents or those without an automobile, but urban populations with automobile access have been the subject of the most research on food access. Urban residents who drive would spend only 6.0 percent (US$8.16) of the total cost of obtaining the TFP on transportation, and this component of the cost would have relatively little bearing on the affordability of food. But for those without access to an automobile or who live in rural areas, the transportation component was estimated to cost from more than two to almost 10 times that of urban drivers, and that kind of additional cost might influence the affordability of food items for many households. Although previous survey data showed that low-income households spend less on the same items as moderate and high-income households (Broda, Leibtag, & Weinstein, 2009), the cost of transportation may be the more important cost. Therefore, studies that attempt to examine food-access issues for the most vulnerable populations must include transportation cost, which is not a simple function of distance to the nearest grocery store, in addition to food cost and the dietary balance of available food items.

It was surprising that the median cost of the food items was similar between rural and urban areas, despite the differences in stores and number of stores in the sample. The variation in cost is probably more important than the median, however, because it identifies disparities. Based on histograms of cost (Figures 2 and 3), the range of estimated costs varied for those with access to an automobile was approximately US$100, but for those without access to an automobile the estimated costs for a significant percentage of parcels was greater than US$300, over US$150 greater than the median estimated cost. Calculating these costs as a percentage of income would be more enlightening, although we would need more complete price data to place confidence in such an analysis.

No restriction was placed on travel time or number of stores visited, resulting in unrealistic walking times of up to 30 hours to obtain one complete set of items in the TFP for a total cost of US$439.26, at US$10 per hour of travel. In reality, people are not likely to spend that much time walking to procure all items in the TFP. A family waiting at a bus stop with their bags of groceries, for example, described to the surveyors that once a month they spend four hours round-trip to walk and ride the bus to go to Walmart (and another grocery store across the street) to stock up on the key food items typically found on the TFP. Because of the time required for this trip, their daily and weekly needs had to be met mostly by convenience stores. Therefore an alternative heuristic approach would be to begin the algorithm by starting at the store with the most items within a maximum radius, or the closest supermarket rather than the closest store of any type. This approach may lead to different estimated minimal costs, a hypothesis that could be tested in future studies. Additional possibilities for modifying the analysis but using essentially the same algorithm include restricting the items procured in the TFP to the more essential items (e.g., ignoring items such as ice cream sandwiches or some of the spices) or placing limits on time spent or distance traveled and examining the proportion of the TFP that could be procured at minimal cost given those limits.

Including more complex rules for consumer behavior is another potential extension of the algorithm. In reality, shoppers do not have perfect information on the price of all items and most stores attempt to attract them with low prices on a limited set of sale items. Therefore, preference for particular stores could be altered in the algorithm as a function of distance, brand, advertising, perceived quality of fresh items, etc. For example, one convenience store manager in a rural area reported that consumers didn't want to have to spend US$7 on gas, using one gallon each way, to get to Walmart. Instead they chose for much of their daily shopping needs to shop at her convenience store. To help meet consumer demand she would go to Walmart once per week and pick up the most commonly demanded items and offer them in her store with a markup over the price she paid at Walmart. This combination of retail outlet practice and consumer behavior is difficult to model because it would require detailed data on characteristics of individual stores and preferences of consumers. Access to food that is not retail market–based could be included in the analysis to examine the relative cost and importance of retail purchase compared with other avenues for food access. Rural residents in particular have been observed to access a large proportion of their diet from alternative sources (Morton, Bitto, Oakland, & Sand, 2008), influenced by access to friends, family, land and knowledge of gardening, fishing, hunting, and gathering. Emergency food supplies likely have an important bearing on how and where people acquire food, as well as ethnic diets and food preferences. Likewise, ready access to fast-food restaurants, or availability of prepared food in general, is assumed to strongly influence diet (Burns & Inglis, 2007). Preferences for particular stores or for particular qualities of the purchased items was not included in the algorithm presented here, but could be added with additional weighting factors on price.

More complex scenarios for transportation, such as limitations on what people can carry either when walking or taking public transportation, could be incorporated into the algorithm's transportation costs. Likewise, limitations on how much people have to spend on food at any given time could place restrictions on how much can be acquired within a given period of time. The algorithm was used to estimate the cost of one purchase of each of the items in the TFP. With data on variation in price over time and consumption rates of the items in the TFP, the analysis could be extended to calculate the cost of maintaining the TFP diet, or other diet, over time. Such an extension of the analysis could identify additional disparities in cost of food access over both time and space. Because the price data we had was incomplete, we did not present results of our cost estimate comparisons with U.S. census variables such as race, ethnicity, age, income, and vehicle access. Calculating these costs by these grouping variables would provide insight into important issues such as structural racism and the actual variation in food cost as a percentage of income.

Of even greater concern in terms of both food access and public health, however, is the likelihood that people forego important parts of a balanced diet in patterns of food purchase, with cost being an important but not the only driver of these choices. These behaviors open a wide range of possible contributing operational factors that determine what food is actually acquired and where. These patterns of acquisition could be quite complex but could be incorporated into our algorithm using a complex set of weighting factors and limits on purchases that varies stochastically among households, perhaps as a function of income or other demographic factors. An alternative would be to use the algorithm's cost estimates as inputs to an agent-based model (e.g. Rice, 2012; Widener, Metcalf & Bar-Yam, 2013) that describes how individuals respond to the food costs they experience in acquisition, diet, and health outcomes. The ultimate goal of our research is to develop this more detailed and nuanced model of the relationships between the food environment, food access, diet, and health.

In this study we have demonstrated methods to more directly address where access to a balanced diet may be limited due to the cost of both the food itself and the transportation cost to obtain it. This methodology can be used to identify places where access is restricted by these economic constraints. Furthermore, the same methods could be used to examine the impact of policy or investment intended to improve food access. Examples could include incentives for new grocery store locations, public transportation, or direct support to particular consumers living in particular places. By comparing the estimated costs of a balanced diet both with and without policy interventions, the impact on costs both areawide and for individuals, neighborhoods, and groups could be estimated. Therefore, use of the proposed methods to evaluate policy and public or private investment should be the focus of additional research.

Conclusions

Methods described in this paper represent a significant step toward an objective measure of food access, defined as the spatially explicit cost of a balanced diet. The example provided in this paper demonstrates that the variation in these costs is large and effectively continuous among residential parcels in the study area. Although examples of clear and sharp boundaries between areas of low and high cost can be found (shifts from green to red over short distances in figures 4 and 5), the gradations are typically much more subtle and diffuse, challenging the notion of discrete food deserts. Further development and implementation of the methods proposed, for improved models to relate the food environment to health outcomes and for better estimates of the impact of policy on food access, could help eliminate disparities and improve public health.

Acknowledgments

This work was supported by The Ohio State University Agroecosystems Management Program, The Ohio State University Food Innovation Center, state and federal funds appropriated to the Ohio Agricultural Research and Development Center, and the U.S. Department of Housing and Urban Development Regional Sustainability Planning grant program. We thank the students who participated in data collection: Brittany Kubinski for her work in identifying stores and requesting permission to visit stores, and Ben Wilson for his work on the data sets.

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