Economic Geography

ISSN: 0013-0095 (Print) 1944-8287 (Online) Journal homepage: www.tandfonline.com/journals/recg20

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abstract

Public health researchers have begun to map the neighborhood "food environment" and examine its association with the risk of overweight and obesity. Some argue that "food deserts"—areas with little or no provision of fresh produce and other healthy food—may contribute to disparities in obesity, diabetes, and related health problems. While research on neighborhood food environments has taken advantage of more technically sophisticated ways to assess distance and density, in general, it has not considered how individual or neighborhood conditions might modify physical distance and thereby affect patterns of spatial accessibility. This study carried out a series of sensitivity analyses to illustrate the effects on the measurement of disparities in food environments of adjusting for cross-neighborhood variation in vehicle ownership rates, public transit access, and impediments to pedestrian travel, such as crime and poor traffic safety. The analysis used geographic information systems data for New York City supermarkets, fruit and vegetable markets, and farmers' markets and employed both kernel density and distance measures. We found that adjusting for vehicle ownership and crime tended to increase measured disparities in access to supermarkets by neighborhood race/ethnicity and income, while adjusting for public transit and traffic safety tended to narrow these disparities. Further, considering fruit and vegetable markets and farmers' markets, as well as supermarkets, increased the density of healthy food outlets, especially in neighborhoods with high concentrations of Hispanics, Asians, and foreign-born residents and in high-poverty neighborhoods.

Key words:
food environment
food desert
spatial accessibility
GIS

ECONOMIC GEOGRAPHY

86(4):409–430. www.economicgeography.org

Acknowledgments

The authors thank James W. Quinn for advice on the geographic information system analysis and the National Poverty Center, University of Michigan, for a research grant under the U.S. Department of Agriculture–funded program, "Understanding the Economic Concepts and Characteristics of Food Access." Caitlin Warbelow and Inbar Kishoni provided research assistance for this project. A National Institute of Environmental Health Sciences Individual Research Grant (R01ES014229-01), led by Andrew Rundle, supported acquisition and processing of data used in this study.

Motivated by concern about rising obesity rates, researchers have begun to map the neighborhood "food environment" and examine its association with the risk of overweight or obesity. Some argue that "food deserts"—areas with little or no provision of fresh produce and other healthy food—may contribute to disparities in obesity and related health problems, such as diabetes or hypertension. When access to healthy food is limited, households must expend more time and/or money to eat a nutritious diet; resource-constrained households may be especially likely to substitute unhealthy food for healthy food, which could lead to elevated rates of overweight and obesity. Although concern about "underretailed" neighborhoods is not new, geographic information systems (GIS) software and data have enabled a significant expansion of research on disparities in the food environment and their implications for health.

Despite the growing sophistication of this work, however, a key conceptual question has been neglected: the relationship between physical distance and travel burden. As research by geographers has pointed out, while physical distance offers a simple approximation of travel burden, spatial accessibility may also be affected by both individual/household and neighborhood characteristics. For instance, access to a vehicle greatly extends the range of travel, providing drivers with a much larger retail environment than nondrivers have. On the other hand, high crime rates or hazardous traffic in a neighborhood may deter consumers from shopping at local stores, in effect shrinking their retail environment.

We know little about how adjusting for these conditions would affect our measures of "food deserts." To address this gap in knowledge, we present a series of sensitivity analyses to examine how adjustments for spatial variation in characteristics such as vehicle ownership, crime, and public transit access affect measured disparities in the accessibility of healthy food in New York City. Making both methodological and substantive contributions, this study illustrates straightforward methods for adjusting food environment measures for individual and neighborhood conditions that may affect spatial accessibility; these methods can readily be applied in other cities. The implications of these adjustments for one city are presented in our conclusions about disparities in access to healthy food.

Background

Recent attention to the food environment is motivated by the assumption that differences in food access affect dietary intake and thus body size. "Food deserts," or neighborhood environments with limited access to healthy and affordable food, are believed to contribute to poor diets and to an elevated prevalence of obesity and diabetes in disadvantaged populations (Shaw 2006; Moore, Diez Roux, Nettleton, and Jacobs 2008). While rural areas may be classified as food deserts because of the distance residents must travel to reach a grocery store, urban areas are more likely to be classified as such because local grocery stores carry little or no healthy food. The locations of food deserts may reflect low purchasing power in low-income neighborhoods (Alwitt and Donley 1997) or race-based discrimination (D'Rozario and Williams 2005; Moss and Tilly 2001). In addition, some urban neighborhoods are disadvantaged by a trend in food retail toward fewer, larger stores located outside of cities (Eisenhauer 2001; Dunkley, Helling, and Sawicki 2004). There is some evidence that access to supermarkets in low-income urban areas has declined over time (Larsen and Gilliland 2008).

Research on disparities in the food environment has examined proximity to or density of food outlets by area income and/or racial composition. Audit studies of food stores tend to find that, compared with other retailers, supermarkets provide access to healthy food in greater variety and of higher quality (Franco et al. 2008; Block and Kouba 2006); thus, access to supermarkets has become a commonly used criterion of the quality of the food environment. Neighborhoods with higher income levels and higher proportions of white residents tend to have greater access to supermarkets or large chain food stores, while poorer neighborhoods and those with higher proportions of black or Hispanic residents may have relatively high access to small grocery stores (Powell, Slater et al. 2007; Moore and Diez Roux 2006; Zenk et al. 2005; Morland, Wing, Diez Roux, and Poole 2002; Alwitt and Donley 1997; Morland and Filomena 2007; Block and Kouba 2006; Sloane et al. 2003; Small and McDermott 2006; Helling and Sawicki 2003; Chung and Myers 1999). A few studies consider access to convenience stores, with most finding that low-income or predominantly minority neighborhoods have more access to these stores (Sloane et al. 2003; Morland, Diez Roux, and Wing 2006).

Research relating the food environment to health outcomes posits that proximity to supermarkets and other stores selling healthy food will be associated with a healthier diet, lower body mass index (BMI, a measure of weight adjusted for height), and lower risk of overweight or obesity, while proximity to convenience stores and small grocery stores will be associated with less positive outcomes. Much research provides evidence consistent with this hypothesis. Supermarket access is associated positively with consumption of a healthy diet in a number of studies (Laraia, Siega-Riz, Kaufman, and Jones 2004; Rose and Richards 2004; Moore, Diez Roux, Nettleton, and Jacobs 2008; Morland, Wing, and Diez Roux 2002), although not all (Pearson, Russell, Campbell, and Barker 2005; Pearce, Hiscock, Blakely, and Witten 2008; Bodor et al. 2008; Timperio et al. 2008). Most studies also find that supermarket access is associated with lower BMI and lower risk of overweight or obesity (Lopez 2007; Morland, Diez Roux, and Wing 2006; Powell, Auld et al. 2007; Morland and Evenson 2009), although again there are exceptions (Wang et al. 2007). Access to convenience stores, on the other hand, is associated with a poorer diet (Jago et al. 2007; Pearce, Hiscock, Blakely, and Witten 2008; Timperio et al. 2008) and poorer weight status (Morland, Diez Roux, and Wing 2006; Morland and Evenson 2009; Grafova 2008).

Economic Geography and Food Deserts

Although economic geographers have studied the location of economic activity, to date they are not represented extensively in research on neighborhood food environments. British and Canadian geographers have given some attention to food deserts (Apparicio, Cloutier, and Shearmur 2007; Larsen and Gilliland 2008; Wrigley, Warm, and Margetts 2003), and geographers have also explored broader questions about the economic organization of food distribution, including work on alternative food networks and on food retail in the developing world (Coe and Wrigley 2007; Humphrey 2007; Sonnino and Marsden 2006). In the United States, however, the influence of geography and urban planning on food environment research has been primarily methodological, as public health researchers have adopted more sophisticated measures of distance, such as network distance and kernel density measures (Moore, Diez Roux, Nettleton, and Jacobs 2008; Rundle et al. 2009).

However, research on the food environment does engage questions on which geographers, including economic geographers, are well positioned to make a contribution. Geographers and urban planners have examined economic and political processes that influence the spatial patterning of residential location relative to commercial activity. Research on residential patterns and housing markets, including studies of gentrification and the economic value of "new urbanist" neighborhoods, informs our understanding of the forces shaping neighborhood access to food outlets (Freeman 2005; McKinnish, Walsh, and Kirk White 2010; Wyly and Hammel 1999; Song and Knaap 2003; Song and Sohn 2007). In addition, food deserts, by definition, are a matter of spatial accessibility, a topic that has received extensive treatment by geographers and urban planners, primarily in work on access to services (Handy and Niemeier 1997; Talen and Anselin 1998; Guagliardo et al. 2004). In methodologically focused work, geographers have also sought to improve the accuracy of spatial accessibility measures by taking account of factors such as facility opening hours, traffic congestion, or individual schedule constraints (Kwan 1999, 2000; Kim and Kwan 2003; Geurs and van Wee 2004; Guagliardo et al. 2004; Mobley et al. 2006; Vandenbulcke, Steenberghen, and Thomas 2009).

As the research points out, physical distance is not equivalent to "travel burden," in other words, the time cost and difficulty of movement between two locations. The relationship between physical distance and travel burden is likely to depend on both individual/household and neighborhood characteristics. Individual characteristics such as vehicle ownership or mobility impairments due to poor health or disability can have a profound impact on spatial accessibility. In addition, neighborhood features may affect the efficiency or safety of specific types of travel. For instance, infrequent bus service will increase average travel time, and unsafe traffic or crime "hot spots" may encourage pedestrians to use less direct routes or patronize more distant stores. Spatial variation in characteristics such as vehicle ownership, public transit infrastructure, crime, and traffic safety is likely to have significant implications for the validity of food environment measures based on distance. Furthermore, variation in these characteristics across settings may explain the mixed findings in studies relating the food environment to health outcomes. In the following discussion, we describe each of these characteristics briefly and discuss their implications for the spatial accessibility of food outlets.

Vehicle Ownership and Public Transit Access

Whether people travel by automobile, by public transit, or by foot has a sizeable effect on spatial accessibility. Pedestrians may travel about a kilometer (0.62 miles) in a 10- to

15-minute trip, while drivers may reach destinations that are 5 kilometers (3 miles) or more away in the same time. Research on job accessibility of low-wage workers has highlighted the importance of travel mode. Although early work on "spatial mismatch" emphasized the physical distance between inner-city workers and jobs opportunities, later research has found quite different patterns of job accessibility for those with versus those without an automobile (Kawabata and Shen 2007; Ong and Miller 2005; Grengs 2010).

Most food environment studies use neighborhood measures that approximate a walking distance, such as a census tract, zip code area, or 800- to 1,000-meter (approximately 0.5- to 0.62-mile) buffer. Shopping trips by car may extend over longer distances, however. Individuals in the Multiethnic Study of Atherosclerosis (MESA) sample—located in New York City, New York; Baltimore, Maryland; and Forsyth County, North Carolina—reported traveling a median distance of 5.6 kilometers (3.5 miles) to shop for food (Auchincloss et al. 2008). Measures based on shorter distances are a better approximation of the food environment among populations that are less mobile or in densely settled environments. Consistent with this interpretation, Auchincloss et al. (2008) analyzed data from the MESA study and found that the food environment within a mile of the home had a much stronger association with insulin resistance (a condition related to diabetes) for individuals who did not own cars and for those living in New York City, a relatively densely settled context with low rates of car ownership. In Los Angeles, despite its reputation as a car-oriented city, half the people surveyed in a recent study of family and neighborhood life traveled less than a mile to reach their usual grocery store (Inagami, Cohen, Finch, and Asch 2006).

Studies of the food environment rarely take account of travel mode. The exceptions include Rose and Richards (2004), who developed a composite index of supermarket accessibility that included car ownership as well as travel time and supermarket use, and Block and Kouba (2006), who identified geographic areas with relatively low proximity to supermarkets *and* relatively low rates of car ownership. Studies that define neighborhoods using census tracts or zip code areas do reflect a crude de facto adjustment, because these census/administrative units typically are larger in lower-density environments where vehicle ownership tends to be higher. However, more systematic adjustment for vehicle ownership would make measures of spatial accessibility more comparable across areas.

For those who lack a private automobile, the extent and frequency of public transit service may be pivotal for accessing resources (Kawabata 2003). Although people who lack a car may borrow a vehicle or take a cab to do major shopping trips, obtaining healthy provisions between these major trips is easier if the public transit network is dense and reliable. Researchers typically include measures of public transit in studies of neighborhood walkability (Hoehner et al. 2005) and of physical activity and weight status (Wener and Evans 2007; Rundle et al. 2007; Li et al. 2008). Among studies of the food environment, the most extensive effort to take account of public transit is reported in research by Larsen and Gilliland (2008). In a study of London, Ontario, they classified points within a 500-meter (0.3-mile) walk and a 10-minute (3-kilometer or 1.86-mile) bus ride to a supermarket as being accessible by bus. They concluded that among residents of the most urbanized part of London, Ontario, 35.1 percent lived within 1 kilometer (0.62 miles) of a supermarket, while 86.5 percent had accessibility by bus (Larsen and Gilliland 2008). As these results suggest, public transit can substantially expand access to retail services, including grocery stores. In locations with infrequent or unreliable transit service, however, use of public transit for shopping is likely to be time consuming and inefficient (Clifton 2004; Shaw 2006).

Neighborhood Safety

There is some evidence that fear of crime and other safety-related concerns discourage people from neighborhood walking or other forms of outdoor physical activity (Foster and Giles-Corti 2008; Harrison, Gemmell, and Heller 2007; Agrawal, Schlossberg, and Irvin 2008). Concerns about safety could prompt shoppers to take a less direct route or seek out more distant stores. In interviews with African American residents of low-income neighborhoods in Chicago, respondents identified safety concerns as an impediment to use of local food stores; the authors commented that "approaches that consider only density or residents' proximity to food outlets may not capture food resources perceived as inaccessible by community residents because of social barriers" (Odoms-Young, Zenk, and Mason 2009, S147). The effect of neighborhood safety is likely to be more pronounced for people traveling on foot or by public transit because these travel modes involve greater exposure to conditions in the neighborhood immediately surrounding the store (Shaw 2006). High crime rates near a supermarket could also lead to a vicious cycle in which crime deters customers and reduces sales revenues, making it more difficult to stock perishable foods such as fresh produce. This decision, in turn, could further reduce pedestrian traffic near the store, weakening informal social controls that might otherwise curb street crime (Sampson, Raudenbush, and Earls 1997).

Adjustment of Spatial Accessibility Measures

As the previous discussion suggests, simple physical distance may not be an adequate measure of the spatial accessibility of food outlets because individual or neighborhood characteristics may affect accessibility by modifying distance (Cutts, Darby, Boone, and Brewis 2009). As a result, measures of food deserts may be biased. As an exploratory exercise, we conducted a series of sensitivity analyses using data for New York City, comparing disparities in access to healthy food outlets before and after adjustment for vehicle ownership, public transit access, crime, and traffic safety.

On the basis of the existing evidence linking supermarkets to healthy dietary and weight patterns, our analysis focused on accessibility of supermarkets; however, one set of analyses also included fruit and vegetable markets and farmers' markets as healthy food outlets to examine the degree to which including these alternative sources of food might provide different conclusions about the accessibility of healthy food missed by using only supermarkets. Small retailers may play an important role in the food environment of densely settled neighborhoods, where the difficulty and cost of acquiring large tracts of land can make it difficult to build supermarkets.

Methods

The unit of analysis for our study is the census tract. All 2,172 populated census tracts in New York City were included in the analysis. For each tract, we constructed multiple measures of the spatial accessibility of healthy food outlets. We categorized census tracts in terms of their racial/ethnic and economic composition. All such data were drawn from the 2000 U.S. Census summary file 3. For racial and ethnic composition, we defined five categories using tract-level data from the Census of Population: majority (more than half) non-Hispanic white, majority non-Hispanic black, majority Hispanic, majority Asian or Pacific Islander, and a residual category of tracts in which no racial or ethnic group had a majority. We also compared tracts that had more than 50-percent foreign-born residents in 2000 to those that had 50-percent or less foreign-born population. To describe economic composition, we divided tracts into quartiles based on their poverty rates, defined as the proportion of residents living below the federal poverty line.

Data on supermarkets came from a 2005 data set purchased from Dun & Bradstreet, a leading vendor of business data. These data include the location of the establishment, the business name, number of employees, annual sales, and the Standard Industrial Classification (SIC) code. We categorized as supermarkets all grocery stores (SIC code 5411) that were not coded as convenience stores and that had annual sales of at least $2 million, a threshold used by the U.S. Department of Agriculture and widely employed in research on the neighborhood food environment (Morland, Diez Roux, and Wing 2006; Wang, Gonzalez, Ritchie, and Winkleby 2006; Harris, Kaufman, Martinez, and Price 2002). For stores that had missing data on annual sales, we categorized as supermarkets all those with 17 or more employees. We selected this threshold based on an inspection of data for stores with nonmissing sales data; mean annual sales exceeded $2 million among stores with 17 employees but did not for stores with 16 or fewer employees. Dun & Bradstreet also provided more detailed SIC codes that further classify the type of store using extended 6- and 8-digit classifications. We classified supermarkets based on annual sales (or employment) rather than on the 6- and 8-digit SIC codes for supermarkets provided by Dun & Bradstreet, because many establishments in our data set were missing these 6- and 8-digit codes, and review of the data indicated that many national and regional chain supermarkets were not identified as such by these codes.

Vehicle Ownership and Public Transit Access

We carried out two kinds of analyses to examine the implications of transportation resources on measured disparities in food environments. The first concerned vehicle ownership. In neighborhoods with higher rates of vehicle ownership, a larger proportion of the residents can readily travel farther to shop for food, making distant supermarkets more accessible. We assumed that supermarkets within about 800 meters (0.5 mile) were accessible to households without a vehicle; the median walking trip in the United States is about 1 kilometer (0.62 mile) (Pucher and Renne 2003), and an 800-meter standard is sometimes used in studies of pedestrian accessibility of food stores (Algert, Agrawal, and Lewis 2006). We assumed that supermarkets within 1,600 meters (1 mile) were accessible to households with a vehicle. While the industry standard is 3 miles, we selected a shorter distance because traffic congestion often impedes automobile travel in dense urban settings like New York City and also because additional driving may be required to find on-street parking (Transportation Alternatives 2007). For this analysis, we measured distances using the street network (the network distance) from the population-weighted tract center point to food outlets. Our adjusted measure of supermarket access is an average of the supermarket counts for 800 meters and 1,600 meters, weighted by the tract proportion of households that own a vehicle. We compared this measure with the unadjusted count of supermarkets within 800 meters to illustrate the implications of adjusting for vehicle ownership.

To consider the effects of adjusting for public transit access, we first identified supermarkets that had a bus or subway stop within 400 meters (0.25 mile); we categorized these supermarkets as bus or subway accessible. In this and subsequent analyses, to simplify the GIS methods, we employed straight-line distances and radial buffers. Bus and subway stop locations were obtained from the Metropolitan Transit Authority through Community Cartography, a local data vendor. We intersected these supermarkets with a 1,600-meter radial buffer measured from the population-weighted center point of the tract, yielding a count of transit-accessible supermarkets within 1,600 meters from each tract centroid. We also identified tracts with and without a bus or subway stop within 400 meters of the centroid. Using these measures, we categorized each tract into one of four categories. Tracts that we identified as having pedestrian access had at least one supermarket within 800 meters (network distance) of the center point of the tract. For tracts without pedestrian access, those with subway access contained at least one subway stop within 400 meters of the centroid and had a subway-accessible supermarket within 1,600 meters. For tracts without pedestrian or subway access, those with bus access contained at least one bus stop within 400 meters of the centroid and had a bus-accessible supermarket within 1,600 meters. The remaining tracts were classified as having neither pedestrian nor transit access.

Neighborhood Safety

Using indicators of crime and traffic hazards, we constructed measures of neighborhood safety near supermarkets. We assumed that hazardous conditions were more likely to deter use of a supermarket if they occurred within close proximity; thus, we assigned each supermarket the crime or traffic safety values of the area within a 400-meter (5-minute walk) radial buffer around the supermarket. We used data on homicides to represent the risk of serious crime. We obtained point data on homicides that occurred in 2003 to 2005 from a public *New York Times* website (http://www.nytimes.com/packages/html/nyregion/20060428_HOMICIDE_MAP.html). We estimated a kernel density grid for homicide point locations, combining data for all three years. The kernel density technique uses point data (in this case, homicides) to estimate a continuous density surface using a three-dimensional floating function that visits an arbitrary set of points overlaid on the study area. In kernel density estimation, distances are measured from each point on the map to each point feature that falls within a predefined distance or bandwidth (an 800-meter distance was used for this analysis, meaning that all homicides within 800 meters of a point were used to calculate the homicide density at that point). The contribution of each homicide to the local density value at a given point is based on that point's distance from the location of the homicide. After calculating the kernel density surface, we calculated the average homicide density in the 400-meter buffer around each supermarket.

Using a similar approach, we measured traffic hazards with data on the locations of automobile accidents resulting in pedestrian injuries or fatalities. These data were obtained for 2002 to 2005 through a Freedom of Information Letter submitted to the New York City Department of Transportation by a local nonprofit organization, Transportation Alternatives. We estimated a kernel density grid for accident point locations and calculated the average density of accidents in the 400-meter buffer around each supermarket. As a second measure of traffic hazards, we used data on the presence of expressways, which represent barriers or hazards to pedestrians. Nonpedestrian roadways were represented using data from the New York City Department of City Planning's LION streets database. A nonpedestrian indicator in the database was used to pull out the expressways, on/off ramps, and other roadways designated by the New York City Department of Education as nonpedestrian in determining walking routes for public school students. We estimated a kernel density grid for nonpedestrian roadway locations and calculated the average density in the 400-meter buffer around each supermarket.

We examined the difference in the number of supermarkets before and after adjustments based on the density values for homicides, traffic accidents, and expressways. The unadjusted supermarket counts included all supermarkets within 800 meters. Adjusted counts excluded supermarkets with crime or traffic hazard densities (i.e., expressways and traffic accidents) in the top quintile. This threshold is admittedly arbitrary; it is intended simply to illustrate the effect on food environment measures of this type of adjustment.

Alternative Sources of Healthy Food

Although supermarkets have received the most attention as sources of healthy food, other kinds of food retailers also provide access to fresh produce, an important element of a healthy diet. To examine the effects of including other retailers in food environment measures, we constructed a "healthy food" outlet measure that included supermarkets, fruit and vegetable markets, and farmers' markets. Geocoded measures of fruit and vegetable markets (SIC code 5431) were drawn from the same 2005 Dun & Bradstreet data that we used for supermarkets. Farmers' market measures were constructed from data downloaded from the New York City Coalition Against Hunger (NYCCAH), which collected the data from the Council on the Environment of New York City and the New York State Department of Agriculture and Markets. Data included the names and addresses of all known farmers' markets in New York City as of 2006. We used the kernel density technique in ArcGIS (version 9.3) to estimate a continuous density surface of establishments per square kilometer using an 800-meter search radius. We averaged the kernel density values from the density surface within the tract boundaries and compared the kernel density of supermarkets with the kernel density of the three healthy food outlet types (supermarkets, fruit and vegetable markets, and farmers' markets) taken together.

Results

New York City contains many densely settled neighborhoods that are characterized by mixed land use; in such neighborhoods, which are particularly prevalent in Manhattan and the innermost sections of Brooklyn, Queens, and the Bronx, the density of healthy food outlets is relatively high. Figure 1 displays a kernel density measure of healthy food outlets that combines data on supermarkets, fruit and vegetable markets, and farmers' markets. Based on this measure, the areas of the city with the lowest access to healthy food are those in Staten Island and the outer edges of Queens, Brooklyn, and the Bronx. As discussed above, however, physical distance may not adequately reflect travel burden. The following sensitivity analyses illustrate the effects of adjusting for the neighborhood characteristics we described above. We also examined the effects of including smaller retailers such as fruit and vegetable markets in measures of healthy food access. Measured disparities by neighborhood race/ethnic, immigrant, or poverty composition vary depending on the measure employed; our focus here is on the effects of adjustment for vehicle ownership, transit access, and neighborhood safety.

Vehicle Ownership and Public Transit Access

Access to a vehicle has significant implications for the number of food outlets that a household can reach. Households without vehicles are disproportionately low income; food environment measures that do not adjust for the variation in vehicle ownership are likely to understate disparities by income in access to healthy food. To illustrate the effect of adjusting for cross-neighborhood variation in vehicle ownership, we weighted measures of accessibility to healthy food by the rate of vehicle ownership in each tract, using a measure from the 2000 U.S. Census of the proportion of occupied housing units with at least one vehicle available.

As Table 1 shows, about half of all New York City households own at least one vehicle, and this proportion varies by neighborhood composition. In 2000, predominantly Hispanic neighborhoods had the lowest average rates of vehicle ownership, while predominantly white neighborhoods had the highest rates. Poor neighborhoods tended to have lower vehicle ownership rates, while predominantly immigrant and nonimmigrant neighborhoods had roughly the same vehicle ownership rates. The third and fourth

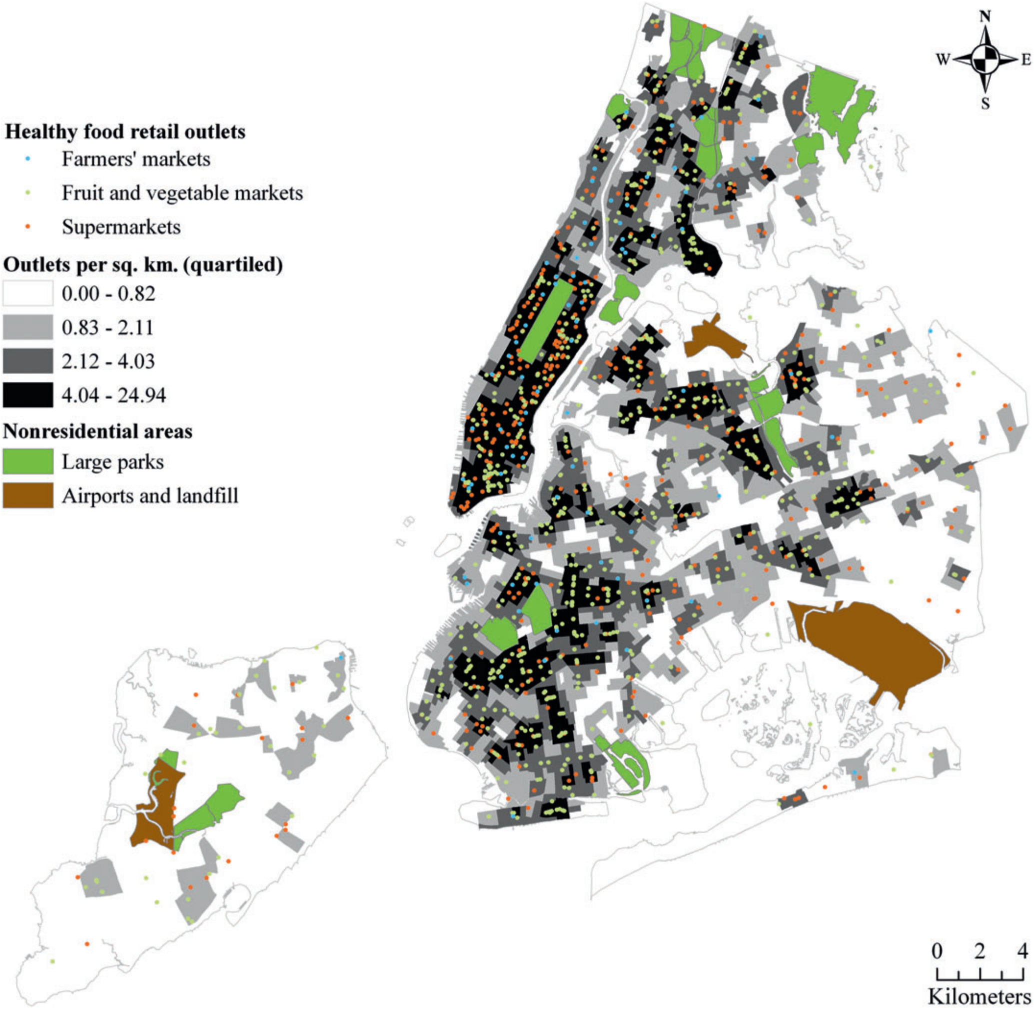

Figure 1. Density of healthy food retail outlets by census tract.

columns in Table 1 show, respectively, the unadjusted and adjusted counts of accessible supermarkets. The fifth column displays the absolute difference between adjusted and unadjusted measures. Here and in subsequent tables, we examined the statistical significance of differences in accessibility measures, comparing predominantly race/ethnic minority tracts to predominantly white tracts, predominantly foreign-born neighborhoods to predominantly native-born neighborhoods, and higher poverty quartiles to the lowest-poverty quartile. Boldface numbers indicate that these differences were statistically significant at the $p < 0.05$ level.

Overall, the mean number of accessible supermarkets increased from 1.3 to 2.8 when we assumed that vehicle-owning households could travel up to 1,600 meters to shop for food. Compared with the average in white neighborhoods, the mean number of accessible supermarkets increased more in Asian neighborhoods and less in black and Hispanic neighborhoods. Although predominantly immigrant neighborhoods had slightly lower rates of car ownership, adjusting for vehicle ownership widened the difference in supermarket access between these neighborhoods and those neighborhoods with lower immigrant

Table 1

Count of Accessible Supermarkets Adjusted for Rate of Vehicle Ownership, by Tract Composition

	Tracts	Percentage with Vehicle	Unadjusted	Adjusted[a]	Difference
All New York City tracts	2,172	0.496	1.335	2.763	1.428
By racial/ethnic composition					
Majority white	814	0.581	1.677	3.345	1.668
Majority black	526	0.485	0.753*	1.835*	1.082
Majority Hispanic	388	0.309	1.165*	2.137*	0.972
Majority Asian	41	0.478	3.200*	5.568*	2.368
Other	403	0.521	1.380*	3.116	1.736
By percent foreign-born					
Majority native-born	1,744	0.498	1.260	2.566	1.306
Majority foreign-born	428	0.487	1.643*	3.566*	1.923
By percent poverty					
First quartile (low poverty)	543	0.679	1.494	3.129	1.635
Second quartile	543	0.587	1.390	3.067	1.677
Third quartile	543	0.441	1.302	2.856	1.554
Fourth quartile (high poverty)	543	0.277	1.155*	2.000*	0.845

[a] Counts of supermarkets adjusted for vehicle ownership are averages of the supermarket count within 800 meters and the supermarket count within 1,600 meters, weighted by the proportion of housing units in the tract with at least one vehicle available. Network distances are used in both cases.

* Indicates statistically significant ($p < 0.05$) differences in accessibility between the reference category (majority white, majority native-born, and the first quartile of percent poverty) and the remaining categories.

representation; this difference between immigrant and nonimmigrant neighborhoods appears to reflect a concentration of immigrant neighborhoods in medium-density areas of Queens, where supermarkets are not as prevalent as in Manhattan but are generally located within a mile. Nonimmigrant neighborhoods with high rates of car ownership tended to be in lower-density areas on the outskirts of the city, where some neighborhoods did not have any supermarkets at all within a mile. Last, high-poverty neighborhoods benefited less than other neighborhoods from the adjustment for vehicle ownership.

Table 2 presents results for the public transit analysis. With an extensive public transit network, New York City provides good transit access to food outlets. Using our simple typology of accessibility, more than 3 out of 5 census tracts had a pedestrian-accessible supermarket (within 800 meters or about a 10-minute walk). An additional 9.7 percent had a subway-accessible supermarket, 25.5 percent had bus access only, and a total of 96.3 percent of tracts had either pedestrian or transit access to a supermarket. Predominantly black neighborhoods, as well as neighborhoods with lower proportions of immigrant or poor residents, benefited most from the adjustment for public transit. It is worth noting, however, that one-third of the city's predominantly black neighborhoods and one-third of its low-poverty neighborhoods had only bus access to supermarkets. Likewise, taking public transit into account improved measures of supermarket accessibility more for high-poverty neighborhoods than for low-poverty neighborhoods. The census tracts most likely to lack walking and transit access to supermarkets were predominantly white and low-poverty, reflecting the composition of neighborhoods on the outskirts of the city.

Neighborhood Safety

High crime in the neighborhoods surrounding food outlets may deter consumers, especially those traveling on foot or by public transit, because these travel modes involve

Table 2

Percentage of Tracts with Accessible Supermarket, by Travel Mode and Tract Composition

	Tracts	Accessible by Walking[a]	Accessible by Subway[b]	Accessible by Bus (Only)[c]	Accessible by Walking or Transit[d]
All New York City tracts	2,172	61.1	9.7	25.5	96.3
By racial/ethnic composition					
Majority white	814	59.7	6.1	27.4	93.2
Majority black	526	51.0*	12.2	34.6	97.7*
Majority Hispanic	388	69.9*	16.2	13.1	99.2*
Majority Asian	41	87.8*	2.4	9.8	100.0
Other	403	66.0*	8.2	23.3	97.5*
By percent foreign-born					
Majority native-born	1,744	57.7	10.2	27.7	95.5
Majority foreign-born	428	75.0*	7.9	16.6	99.5*
By percent poverty					
First quartile (low poverty)	543	49.7	2.4	38.5	90.6
Second quartile	543	63.4*	6.4	28.2	98.0*
Third quartile	543	64.8*	13.3	19.5	97.6*
Fourth quartile (high poverty)	543	66.5*	16.8	15.8	99.1*

[a] Tracts with walking-accessible supermarkets have at least one supermarket within 800 meters.
[b] Tracts with subway-accessible supermarkets do not have walking-accessible supermarkets but have at least one supermarket within 1,600 meters and subway stops within 400 meters of the supermarket and tract centroid.
[c] Tracts with bus-accessible supermarkets do not have walking- or subway-accessible supermarkets, but have at least one supermarket within 1,600 meters and bus stops within 400 meters of the supermarket and tract centroid.
[d] The proportion of tracts with at least one supermarket that meets our criteria for accessibility by walking, subway, or bus.
* Indicates statistically significant ($p < 0.05$) differences in accessibility between the reference category (majority white, majority native-born, and the first quartile of percent poverty) and the remaining categories.

greater exposure to conditions in the immediate neighborhood of the food outlet. Our analysis examined supermarkets only, using counts of stores within an 800-meter radial buffer drawn around the tract population-weighted centroid. (Unadjusted supermarket counts are higher in the figures reported in Tables 3 and 4 than in Table 1 due to the use of radial buffers, which cover a larger area.) For purposes of this analysis, we assumed that supermarkets in the highest quintile of homicide density simply became unavailable to consumers. This is obviously not literally true; supermarkets with no customers would soon go out of business. It is plausible, however, that poor safety conditions nearby might reduce use of supermarkets in that neighborhood. Consumers might avoid these markets at night or shop there only when they are unable to travel to stores in safer neighborhoods. The unadjusted counts reported in Table 3 include all supermarkets within 800 meters of the tract center point (weighted by population). For the adjusted measure, we excluded high-crime supermarkets (those in the highest quintile for homicide density in the immediate neighborhoods). The last column presents the difference between adjusted and unadjusted measures. Rather than using a more traditional regression approach that "controls" for the presence of crime while predicting the count of supermarkets, we compared supermarket counts after eliminating supermarkets in the most dangerous neighborhoods to highlight disparities in supermarket access caused by assuming that unsafe supermarkets become inaccessible for some or all of the population.

Across all tracts, excluding stores in high-crime areas reduced the mean number of accessible supermarkets from 2.0 to 1.6. The impact of this adjustment was most severe

Table 3

Count of Accessible Supermarkets Adjusted for Homicide Rates, by Tract Composition

	Tracts	Unadjusted	Adjusted[a]	Difference
All New York City tracts	2,172	2.050	1.643	–0.407
By racial/ethnic composition				
Majority white	814	2.558	2.425	–0.133
Majority black	526	1.240*	0.606*	–0.634
Majority Hispanic	388	1.786*	0.995*	–0.791
Majority Asian	41	4.415*	3.537*	–0.878
Other	403	2.094*	1.849*	–0.245
By percent foreign-born				
Majority native-born	1,744	1.955	1.518	–0.437
Majority foreign-born	428	2.435*	2.152*	–0.283
By percent poverty				
First quartile (low poverty)	543	2.284	2.184	–0.100
Second quartile	543	2.110	1.941	–0.169
Third quartile	543	2.017	1.648*	–0.369
Fourth quartile (high poverty)	543	1.788*	0.799*	–0.989

[a] Counts of supermarkets adjusted for homicide density exclude supermarkets in the highest quintile of average kernel density values for homicides within 400 meters of the supermarket. Radial buffers (based on straight-line distances) are used.

* Indicates statistically significant ($p < 0.05$) differences in accessibility between the reference category (majority white, majority native-born, and the first quartile of percent poverty) and the remaining categories.

in the poorest neighborhoods. By our definition, the number of accessible supermarkets in the poorest tracts dropped from 1.8 to 0.8 after we imposed our criterion for crime safety. Excluding stores in high-crime areas also had a large impact on neighborhoods with higher proportions of black, Hispanic, and Asian residents. Overall, unsurprisingly, adjustment for crime rates widened income and race/ethnic disparities in measures of food environments.

Hazardous traffic conditions may also make food outlets unattractive to pedestrians. We constructed two indicators of pedestrian safety within the 400-meter buffers around supermarkets, one based on the density of pedestrian-automobile accidents and the other based on the density of expressways. Column 2 in Table 4 shows the same unadjusted mean counts of supermarkets included in Table 3. The third column shows the adjusted counts for which stores in the highest quintile of accident density were removed, and the fourth column reports the difference between these adjusted figures and the unadjusted measures in column 2. Likewise, the fifth column reports mean counts of supermarkets in which stores in the highest quintile of expressway density were removed, and the sixth column shows the difference between the adjusted and unadjusted measures.

Supermarkets with high densities of traffic accidents tended to be located near neighborhoods that were majority white or majority Asian, had low poverty rates, and had fewer foreign-born residents. As a result, adjusting for the density of accidents tended to reduce or even reverse disparities in supermarket access by race/ethnicity and poverty. Supermarkets with a high density of expressways nearby tended to be located near white, Hispanic, or Asian neighborhoods, and in lower-poverty neighborhoods. In general, adjusting supermarket accessibility for expressway density reduced disparities in access between white or Asian and other neighborhoods, as well as between high-poverty and low-poverty neighborhoods.

Table 4

Count of Accessible Supermarkets Adjusted for Expressway Density and Accident Density, by Tract Composition

			Accident Density		Expressway Density	
	Tracts	Unadjusted	Adjusted[a]	Difference	Adjusted[b]	Difference
All New York City tracts	2,172	2.050	1.644	–0.406	1.645	–0.405
By racial/ethnic composition						
Majority white	814	2.558	1.668	–0.890	2.021	–0.537
Majority black	526	1.240*	1.238*	–0.002	1.106*	–0.134
Majority Hispanic	388	1.786*	1.711	–0.075	1.289*	–0.497
Majority Asian	41	4.415*	2.780*	–1.635	3.902*	–0.513
Other	403	2.094*	1.945*	–0.149	1.700*	–0.394
By percent foreign-born						
Majority native-born	1,744	1.955	1.497	–0.458	1.538	–0.417
Majority foreign-born	428	2.435*	2.245*	–0.190	2.079*	–0.356
By percent poverty						
First quartile (low poverty)	543	2.284	1.349	–0.935	1.772	–0.512
Second quartile	543	2.110	1.738*	–0.372	1.744	–0.366
Third quartile	543	2.017	1.849*	–0.168	1.648	–0.369
Fourth quartile (high poverty)	543	1.788*	1.641*	–0.147	1.414*	–0.374

[a] Counts of supermarkets adjusted for accident density exclude supermarkets in the highest quintile of average kernel density values for automobile accidents resulting in pedestrian injuries or fatalities within 400 meters of the supermarket. Radial buffers (based on straight-line distances) are used.
[b] Counts of supermarkets adjusted for expressway density exclude supermarkets in the highest quintile of average kernel density values for nonpedestrian roadways within 400 meters of the supermarket.
* Indicates statistically significant ($p < 0.05$) differences in accessibility between the reference category (majority white, majority native-born, and the first quartile of percent poverty) and the remaining categories.

Alternative Sources of Healthy Food

Although most of our analyses focus on supermarket accessibility, smaller outlets such as fruit and vegetable markets and farmers' markets may also be important sources of healthy food. Small outlets such as these can be particularly important in densely settled urban neighborhoods, where it can be difficult to assemble the land required for a supermarket. Smaller retailers clearly play an important role in access to healthy food in New York City. Across all tracts, only 36.1 percent of the accessible healthy food outlets were supermarkets, while 57.3 percent were fruit and vegetable markets, and 6.6 percent were farmers' markets.

Table 5 compares kernel density measures for supermarkets with those for all three types of healthy food outlets combined. The mean density of all healthy food outlets is almost three times the density of supermarkets alone. Fruit and vegetable markets and farmers' markets increased access to healthy food most in predominantly Hispanic, Asian, and immigrant neighborhoods, with the least effect in predominantly black neighborhoods. These smaller markets also increased access to healthy food more in higher-poverty than lower-poverty neighborhoods. Although use of farmers' markets is often associated with affluent and well-educated consumers, farmers' markets actually played a more important role in the food environment of the highest-poverty neighborhoods, where they represented 10 percent of accessible healthy food outlets (results not shown).

Limitations

Limitations of this study include the use of 800 meters as a walkable distance to the supermarket; for people who are in poor health or have limited mobility for other reasons,

Table 5

Mean Kernel Density of Supermarkets, Fruit and Vegetable Markets, and Farmers' Markets by Tract Composition

	Tracts	Density of Supermarkets	Density of Healthy Food Outlets[a]	Difference
All New York City tracts	2,172	1.038	2.873	1.835
By racial/ethnic composition				
Majority white	814	1.309	3.192	1.883
Majority black	526	0.609*	1.944*	1.335
Majority Hispanic	388	0.912*	3.195	2.283
Majority Asian	41	2.373*	6.752*	4.379
Other	403	1.036*	2.739*	1.703
By percent foreign-born				
Majority native-born	1,744	0.987	2.629	1.642
Majority foreign-born	428	1.248*	3.868*	2.620
By percent poverty				
First quartile (low poverty)	543	1.164	2.356	1.192
Second quartile	543	1.067	2.619	1.552
Third quartile	543	1.019	3.278*	2.259
Fourth quartile (high poverty)	543	0.902*	3.240*	2.338

[a] Healthy food outlets include supermarkets, fruit and vegetable markets, and farmers' markets.
* Indicates statistically significant ($p < 0.05$) differences in accessibility between the reference category (majority white, majority native-born, and the first quartile of percent poverty) and the remaining categories.

a smaller distance is likely to be more appropriate. In addition, this study relies primarily on business microdata from Dun & Bradstreet. While this database is widely used in studies of the food environment (Powell, Slater et al. 2007; Zick et al. 2009), such commercial databases commonly involve some degree of error (Boone, Gordon-Larsen, Stewart, and Popkin 2008; Kowaleski-Jones et al. 2009); however, there is little or no systematic bias in where error occurs in commercial databases (Bader, Ailshire, Morenoff, and House forthcoming). The scale of New York City made a comprehensive "ground truthing" effort infeasible. Distances are measured from population-weighted tract centroids; while this procedure reduces the likelihood of spatial error, there may be instances in which the centroid is a poor indicator for the location of population living in the tract because of the tract's large size or an unusual spatial distribution of population. Last, the study is based in New York City; results may not be generalizable to places with quite different patterns of population density or land-use mix, or where patterns of residential location by race and ethnicity or income differ from those in New York City. Replication in other locales will help establish the generality of the patterns we observed.

Conclusion

Research on food deserts has brought new attention to questions of spatial accessibility. Although most studies of food deserts use physical distance to evaluate accessibility, research in geography and public health highlights ways that accessibility may be affected by parameters having to do with personal mobility (vehicle ownership), as well as environmental facilitators and barriers to travel (public transit service, poor safety). As an exploratory exercise, we carried out a series of sensitivity analyses to examine how supermarket accessibility measures are affected by simple adjustments for vehicle ownership, public transit, and neighborhood safety.

We find that failing to adjust supermarket accessibility measures for vehicle ownership is likely to mask food environment disparities between advantaged and disadvantaged communities because of differences in vehicle ownership rates. A simple adjustment for vehicle ownership added 1.6 accessible supermarkets in low-poverty tracts and only 0.8 in high-poverty tracts. Failure to adjust for vehicle ownership is also likely to understate food accessibility in suburban or lower-density neighborhoods relative to urban areas, where fewer residents drive and where travel is more often impeded by traffic congestion.

Given New York City's extensive public transit system, only 3.7 percent of tracts did not meet our criteria for supermarket access by walking, subway, or bus. Adjustment for public transit access had the largest impact on predominantly black neighborhoods, predominantly native-born neighborhoods, and low-poverty neighborhoods. Notably, one-third of all predominantly black census tracts and one-third of the lowest-poverty tracts lacked walking or subway access to supermarkets but met our criteria for bus access. While carless residents of such neighborhoods are able to reach a supermarket, their shopping trips are likely to be lengthy and inefficient. Adjusting food environment measures for public transit access is unimportant in most areas, but would be important in studies of areas served by public transit systems.

Adjustments for neighborhood safety had mixed effects. Adjusting for crime tended to widen disparities in access to supermarkets by neighborhood race/ethnicity and income, because minority and low-income neighborhoods had higher homicide rates. Adjusting for traffic safety, on the other hand, narrowed or even reversed economic and racial/ethnic differences in access to supermarkets. Adjusting for crime and traffic hazards is more likely to be important in studies of urban contexts, where the prevalence of travel by public transit or on foot exposes shoppers to more hazards in the neighborhoods they traverse.

Including fruit and vegetable markets and farmers' markets, as well as supermarkets, had a sizeable effect on measures of access to healthy food, increasing densities of healthy foods particularly in Hispanic and Asian neighborhoods, immigrant neighborhoods, and high-poverty neighborhoods. While the density of supermarkets is highest in low-poverty neighborhoods, the density of healthy food outlets was highest in high-poverty neighborhoods. As these results suggest, smaller retailers can play an important role in neighborhoods where conventional supermarkets may not be viable for economic or regulatory (zoning) reasons; measures of food environments or food deserts that include only supermarkets may underestimate the availability of healthy foods in low-income urban areas. At the same time, however, one should keep in mind that neither fruit and vegetable markets nor farmers' markets carry the full range of products available at a supermarket and that most farmers' markets are open only once or twice a week and do not operate year-round. More nuanced measures of food environments are needed to represent the contribution made by smaller retailers and markets without treating them as equivalent to supermarkets.

This study illustrates relatively simple ways of adjusting food environment measures for neighborhood characteristics such as vehicle ownership, public transit access, and neighborhood safety. These methods can readily be applied in other locations and in other kinds of spatial accessibility studies. As we found, these adjustments have a sizeable impact on estimates of accessibility to healthy food, although in different directions: adjusting for crime and vehicle ownership tended to widen measured disparities in accessibility, while adjusting for traffic safety and the availability of smaller retailers tended to reduce measured disparities, and adjusting for transit access had mixed effects. It is worth noting that in all but one comparison, New York City's predominantly black neighborhoods had the lowest access to healthy food regardless of adjustment.

Although our findings are specific to the environment of New York City, the distinctive urban geography of New York City offers some useful lessons on food environments in diverse and high-density urban environments. First, because of New York City's extensive public transportation system, few New Yorkers live in neighborhoods with no walking or transit access to healthy food outlets. Second, defining access only by distance or transit availability is likely to hide neighborhood conditions such as crime risk that affect accessibility to healthy foods. New York City neighborhoods served only by buses include some of the most dangerous areas in the city. The fact that low-income and racial/ethnic minority residents are more likely to be affected by violence highlights the implications of class and racial residential segregation for health disparities in New York City. A final point is the importance of alternatives to supermarkets, such as fruit and vegetable stands and farmers' markets. Because of the density of development and the high price of real estate in New York, it is difficult and costly to assemble the floor space for a full-scale supermarket. Therefore, smaller-scale alternatives play an important role in the food environment of New York City, as well as in other densely populated cities.

An important next step is to understand the combined effects of these measures. Exploring these risks jointly requires understanding risk perception among local residents (including what kinds of risks are more or less salient and how accurately people perceive the risks of different types of hazards), as well as understanding how residents take action to mitigate risks (for instance, traveling during the daytime or getting a ride from a friend to reduce the risk of crime, or taking alternative routes to avoid busy streets). Although we know that people alter their behavior in response to perceived risk, we do not know how and how much they respond, how responses vary across people, or how well objective data such as crime rates match perceived risk. Although our work employed arbitrary parameters, future research could use empirical evidence about risk perception and travel behavior to inform parameters about the influence of neighborhood conditions on consumer behavior. Such evidence would help us understand the combined influence of crime, traffic hazards, and other diverse neighborhood conditions.

Because the location of economic activity is a central question for the field, economic geography is well positioned to make a contribution to research on the food environment. Insights from research on spatial accessibility can improve the conceptualization and measurement of "food deserts." More broadly, research in geography can embed the food environment in theoretically grounded accounts of economic activity and urban form, taking into account factors such as housing markets, segregation, gentrification, land-use policy, economic development, and the structure of food distribution networks.

While our work suggests questions for geographic research on spatial accessibility, it also informs public health research. As discussed above, measures of "food deserts" may be biased if they fail to take account of individual or neighborhood characteristics that influence accessibility. As a result, descriptive studies of the location of food deserts may either understate or overstate disparities in access to healthy food. Adjusted measures like the ones described in this article may improve the validity of such descriptive assessment, which is a matter of growing interest in public health (Powell, Slater et al. 2007; Moore, Diez Roux, and Brines 2008; Cutts, Darby, Boone, and Brewis 2009).

In addition, our work can inform public health research that relates neighborhood characteristics to health outcomes such as diet, obesity, and diabetes. Previous studies have included measures of vehicle ownership, public transportation, and neighborhood safety in analyses relating the food environment to obesity or BMI. For instance, Inagami, Cohen, Finch, and Asch (2006) considered both car ownership and distance to grocery store as independent predictors of BMI, and several studies have examined the independent associations of food environment measures and crime with body size (Burdette and

Whitaker 2004; Grafova, Freedman, Kumar, and Rogowski 2008). While this work assumes that transportation or safety shape BMI through their influence on physical activity, transportation or safety may also affect BMI by shaping access to healthy food and thereby diet. Measures of accessibility to food outlets that are adjusted for barriers related to transportation or safety will enable better understanding of the multiple causal pathways through which neighborhood conditions influence health.

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