An Agent-Based Model of Income Inequalities in Diet in the Context of Residential Segregation

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Background: Low dietary quality is a key contributor to obesity and related illnesses, and lower income is generally associated with worse dietary profiles. The unequal geographic distribution of healthy food resources could be a key contributor to income disparities in dietary profiles.

Purpose: To explore the role that economic segregation can have in creating income differences in healthy eating and to explore policy levers that may be appropriate for countering income disparities in diet.

Methods: A simple agent-based model was used to identify segregation patterns that generate income disparities in diet. The capacity for household food preferences and relative pricing of healthy foods to overcome or exacerbate the differential was explored.

Results: Absent other factors, income differentials in diet resulted from the segregation of high-income households and healthy food stores from low-income households and unhealthy food stores. When both income groups shared a preference for healthy foods, low-income diets improved but a disparity remained. Both favorable preferences and relatively cheap healthy foods were necessary to overcome the differential generated by segregation.

Conclusions: The model underscores the challenges of fostering favorable behavior change when people and resources are residentially segregated and behaviors are motivated or constrained by multiple factors. Simulation modeling can be a useful tool for proposing and testing policies or interventions that will ultimately be implemented in a complex system where the consequences of multidimensional interactions are difficult to predict.
(Am J Prev Med 2011;40(3):303–311) © 2011 American Journal of Preventive Medicine

Introduction

Habitual intake of energy-dense nutrient-poor foods has been identified as a key contributor to obesity and related illnesses, which has led to interest in identifying public health interventions that can improve population diet quality. Moreover, an income differential in diet quality has been observed in numerous studies, illustrating that lower income is generally associated with worse dietary profile.[1,2] Thus, diet quality has been identified as a key factor in socioeconomic inequalities in obesity and diet-related illnesses.[3]

Residential segregation by income and race/ethnicity is an undisputed feature of most urban areas in the U.S.[4] Resources and services are concentrated in higher-income areas and thus are likely contributors to health disparities. Within many urban areas in the U.S., minority and low-income neighborhoods have significantly fewer venues for purchasing healthy foods as compared with high-income neighborhoods,[5–8] which can discourage healthy eating behaviors and help shape residents' preferences.[9] As a result, variation in the "food environment" by residential neighborhood has received increasing attention because of its potential contribution to inequalities in diet.[10]

An alternate explanation for inequalities in diet is that they simply reflect preferences[11,12]: high-income households prefer healthy foods and choose to live in areas with healthy food stores, whereas low-income households pre-

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0749-3797/$17.00
doi: 10.1016/j.amepre.2010.10.033

fer unhealthy foods and choose to live in areas without healthy food stores.[13] Yet another explanation for income inequalities in diet is that the high cost of healthy foods places them beyond the reach of poor households.[14]

It is plausible that income inequalities in diet originate and are perpetuated by factors associated with all these explanations. The variety of these explanations highlights that inequalities likely occur within a complex system of interrelated processes that are not well understood. Specifically, there has been little examination of the extent to which the factors associated with residential economic segregation—location and household income—influence healthy food availability and may affect income differences in healthy eating. In addition, there has been little examination of the extent to which healthy food prices and preferences can reduce disparities attributable to economic segregation.

An examination of this complex system presents challenges. First, there are no empirical data permitting a comprehensive assessment of these factors. Second, even if data were available, standard statistical approaches are incapable of incorporating multiple feedback and adaptive mechanisms between people and their environments over time.[15]

See related Commentary by Maglio and Mabry in this issue.

Simulation models are becoming recognized as useful tools that can overcome the limitations of traditional statistical approaches. In particular, agent-based models (ABMs) that run experiments in controlled environments are able to examine complex processes involving multiple dynamic interactions among people and between people and their environments over time.[15–18] In an ABM, entities respond to other entities and change their behavior.[19] These entities (aka "agents") are assigned characteristics and baseline behaviors that organize their actions and interactions. Decision-making rules specify agent capabilities to carry out particular behaviors while allowing agents to choose their behaviors in response to other agents and the environment.[17,20] ABMs are being used in a number of disciplines. Sociologists have used them to show how racial segregation can emerge from micro-level preferences in ways that cannot be easily predicted using traditional approaches.[21,22] Public health scholars recently have used ABMs in drug/alcohol health behavior research[23–25] and to explore optimal strategies for containing infectious disease transmission.[26–29] In clinical research, ABMs have been used for medical decision making and cost-effectiveness research.[30,31] ABMs can range from simple models[21] to sophisticated models that have high degrees of realism and typically make use of high-resolution empirical data.[29] (For a description of ABMs and primers in ABMs see Appendix A, available online at www.ajpm-online.net.)

In the present study, an ABM was used to explore the role that segregation can play in shaping dietary behaviors and to suggest policy levers that may be used to counter its effects. The model incorporates interactions of where people live with healthy food resources in their community, income constraints, and healthy food preferences. It is a simple model that is not intended to provide definitive answers to the causes of or solutions to income inequalities in diet. Rather, this exploratory model can be used to explain why an observable phenomenon is occurring,[32,33] stimulate further questions about processes involved in generating income differentials in health behaviors, and identify data collection needs for future studies.

Methods

Agent-Based Model

Model objective and overview. The investigation began by examining several extreme scenarios for economic residential segregation and spatial clustering of healthy food stores. The computational model identified scenarios that revealed income differentials in diet that have been observed in previous empirical studies; thus, the model could serve as a tool for examining the ways that segregation can contribute to income disparities in diet. Simple experiments tested whether pricing and preference factors were capable of reducing income differentials in diet generated by segregation (see Experiments section). The text below provides an overview of the model. Model details are given in Appendix B (available online at www.ajpm-online.net).

Agents. Only two types of agents were included: households and food stores. Household attributes were income and food preference. Households were classified randomly into either low- or high-income (binary low=0 or high=1, with 50% of households assigned to the low-income category). This classification ignored the middle-income category in order to keep the model simple and improve interpretation. Food preferences can be thought of in a number of ways, such as preference for energy-dense nutrient-poor foods (unhealthy) versus preference for whole grains and fresh vegetables (healthy). Household food preference was assigned as a continuous score from 0 to 1 (0 is preference for unhealthy food and 1 is preference for healthy food). Preference was either randomly assigned or assigned by household income in "preference experiments" (Appendix C, available online at www.ajpm-online.net).

At baseline, stores were assigned a type of food (binary unhealthy=0 or healthy=1; at initialization, 50% of stores sell healthy foods) and average price for food at the store (either inexpensive=0 or expensive=1; 50% of stores sell inexpensive foods). Unhealthy food stores can be thought of as convenience stores, whereas healthy food stores can be thought of as fresh produce markets. Because the model measured interactions occurring dynamically

Table 1. Eight segregation scenarios derived from the cross-classification of households and food stores

Segregation of stores[a]		Segregation of households[a]					
Grid position[b]		Grid position[b]					
		Left side vs right side		Left side vs right side		Left side vs right side	
Left side vs right side		Random	Random	High-income	Low-income	Low-income	High-income
Random	Random	1		4		4[c]	
All stores	No stores	2		5		8	
Healthy stores	Unhealthy stores	3		6[d]		7[c]	
Unhealthy stores	Healthy stores	3[c]		7		6[c]	

[a]Notes for numbered cells in table:
1. Random placement of households and stores (no segregation)
2. Random placement of households; all stores on one side of grid versus no stores on other side of grid
3. Random placement of households; unhealthy stores on one side of grid versus healthy stores on other side of grid
4. High-income households on one side of grid versus low-income households on other side of grid; random placement of stores
5. High-income households and all stores on one side of grid versus low-income households and no stores on other side of grid
6. High-income households and healthy stores on one side of grid versus low-income households and unhealthy stores on other side of grid
7. High-income households and unhealthy stores on one side of grid versus low-income households and healthy stores on other side of grid
8. Low-income households and all stores on one side of grid versus high-income households and no stores on other side of grid

[b]In order to create segregated scenarios, the grid was divided in half: left side (left half) versus right side (right half).
[c]Redundant cells have the same number.
[d]Scenario 6 was selected as the index scenario ("S6", see Results section in manuscript).

over time, stores were able to change the type of food they sell, but store prices remained fixed throughout the experiment. At initialization, either price was assigned randomly or food price was linked to healthy food.

Space. The model was built on a 50×50 grid. Segregation scenarios were tested by dividing the grid in half (left side, right side, see Table 1). The space was toroidal (continuous space projection) to eliminate boundary considerations.[34] Each cell in the grid contained one household, and households remained at a fixed location during an experiment. At baseline, stores filled 2% of the grid cells (thus, each store shared its cell with a household).

Household behavior. At each time step, each household selected a store to shop from and shopped for food (a time step could be thought of as about every 2–3 days corresponding to food shopping frequency in empirical studies[35,36]). The behavioral economics[37] literature was used to determine how households chose which store to shop at. Households ranked stores on four dimensions: price of food at the store, distance to the store, the household's habitual behavior, and the household's preference for healthy foods. Each household used a utility function to assign each store a score, to which random noise was added to represent bounded rationality.[38] (See Appendix C, available online at www.ajpm-online.net, for the justification of the dimensions and details of the utility function.)

Store behavior. A key advantage of an ABM is its ability to incorporate feedback behaviors. Very simple rules allowed stores to change location and food type in order to examine how diet differentials varied when stores responded to customer demand and households had opportunities to re-evaluate where to shop. Primary models used a "move-out/move-in" scenario, where stores with the fewest customers had an opportunity to close, the location remained vacant for a time, and then a new store moved in. Base experiments assigned a 10% chance that the new store would change the type of food it sold; thus, most new stores sold the same type of food as the previous store but some stores changed their food type. Sensitivity was tested for lower and higher rates of change.

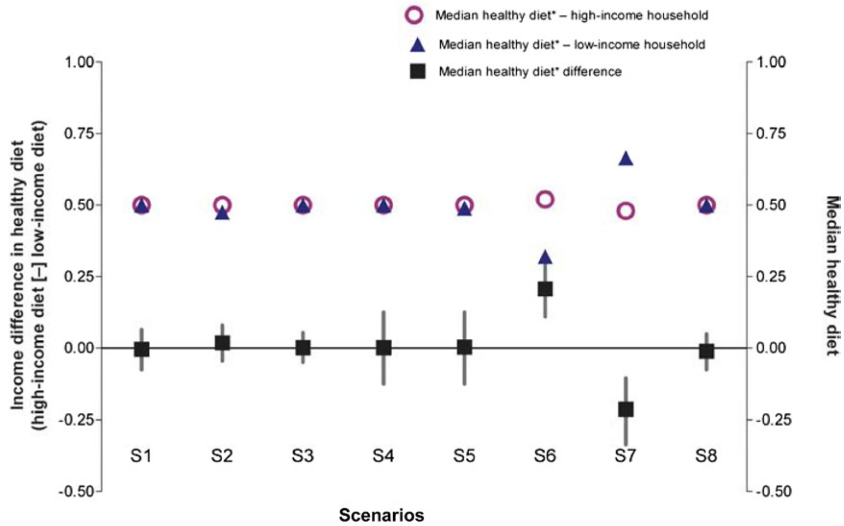
Outcome Measure/Summaries

The primary outcome measure was the income differential in diet (diet of high-income households minus diet of low-income households). Absolute diet values for high- and low-income households were secondary outcomes. A simplifying assumption was used to derive each household's diet: If the household shopped at a healthy food store, they ate healthier food and had a better diet. Diet was summarized as the average proportion of times the household shopped at a healthy food store (diet of 0.5 meant they shopped at healthy food stores half of the time, diet values close to zero meant they infrequently shopped at healthy food stores).

Uncertainty and randomness was built into the model (e.g., agent location and attribute assignment) because store behaviors and households' selection of where to shop cannot always be explained by rational choice. Stochasticity was incorporated to represent variability in agents' state and behaviors that are due to factors and processes that were not explicitly modeled (e.g., highly variable conditions and behaviors that are too complicated to be explicitly modeled, or for which mechanisms are not known).[16] For example, uncertainty and randomness was built into agent initialization (e.g., agent location and attribute assignment) as well as store behaviors and households' selection of which store to go to. Experiments were run until there were no longer rapid transitions and changes were slowed. Each experiment was run 60 times to obtain the distribution of outcomes and then summarized as the median and the 5th–95th percentile values. Experimental results were summarized by averaging diet for the final 20% of the run of the model.

Experiments

Spatial segregation. Eight segregation scenarios were selected and at initialization there were no income differentials in diet. Scenarios where income differentials in diet emerged were used as examples of how segregation can contribute to income disparities in diet. Scenarios were derived from the cross-classification of crude segregation patterns for households and food stores (Table 1). Scenario 1 had no segregation (households and stores were placed randomly on the grid). All other scenarios had at least one aspect of segregation (segregation of households by income and/or segregation of healthy food stores). In the initial models, preference and price were invariant across income and healthy food store.



S1. Random placement of households and stores (no segregation)
S2. Random placement of households; all stores on one side of grid vs no stores on other side of grid
S3. Random placement of households; unhealthy stores on one side of grid vs healthy stores on other side of grid
S4. High-income households on one side of grid vs low-income households on other side of grid; random placement of stores
S5. High-income households and all stores on one side of grid vs low-income households and no stores on other side of grid
S6. High-income households and healthy stores on one side of grid vs low-income households and unhealthy stores on other side of grid
S7. High-income households and unhealthy stores on one side of grid vs low-income households and healthy stores on other side of grid
S8. Low-income households and all stores on one side of grid vs high-income households and no stores on other side of grid

* Diet was derived from the average proportion of times the household shopped at a healthy food store

Figure 1. Income differences (with 5th–95th percentiles) healthy diet and median healthy diet under various segregation scenarios

Healthy food preferences and the relative price of healthy food. Using the segregation scenario(s) where income differentials in diet emerged, a series of experiments were run in order to identify under which experimental conditions healthy food prices and preferences could overcome or exacerbate the effects of segregation on the diet differential. What follows describes the manipulations of price and preference (also see rationale for these experiments in the Introduction). High-income household preferences were fixed to prefer healthy foods. For low-income households, preference for unhealthy foods was assigned in one experiment and a preference for healthy food was assigned in another experiment. Healthy foods alternately were made relatively expensive and cheap compared to unhealthy foods. Finally, a combination of preference and price was modeled and experiments were re-run.

Validity

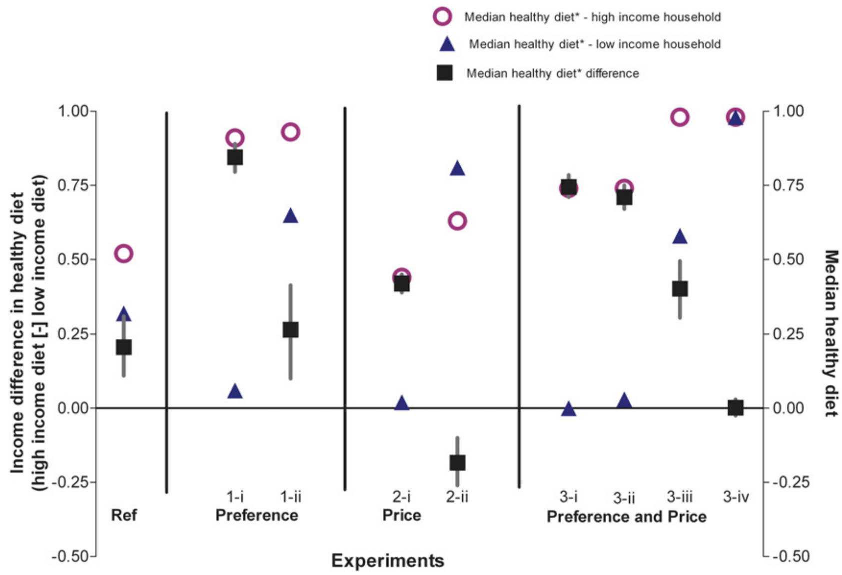
Observational studies and survey data from government and industry sources were used to guide agent decision-making rules for generating plausible behaviors. Agent behaviors were tested against available data to reflect intuitive and known behaviors, such as high-income households spending more on food[39,40] and traveling at least as far or farther than low-income households.[41,42] Household size as well as household and store density also were incorporated into the model. Sensitivities to alternate weighting and scoring for the utility function and size and household/store density of the grid were examined.

Results

Experiments

Spatial segregation. Figure 1 shows the income differential in diet and absolute diet levels under various segregation scenarios. These initial scenarios assumed no income differences in healthy food preferences, and assumed no price differences by type of food store. The expected income differential in diet was generated by only one scenario: scenario 6, the segregation of high-income households and healthy food stores from low-income households and unhealthy food stores (hereafter referred to as "S6"; Table 1). The other scenarios showed either no differential, or differentials that contradicted the empirically observed diet disparity (S7 was reverse expectation).

Healthy food preferences and the relative price of healthy food. Figure 2 shows how the diet differential seen in the index case (S6) changed when (separately) differences in food preferences by income and differences in price between healthy and unhealthy stores were incorporated into the model. Differentials in diet generally followed anticipated patterns when (at initialization)



Ref, The referent experiment, index scenario 6 (S6 from Figure 1). No income differences in preference or prices; healthy food preference and price of food are randomly assigned.

1-i High income prefers healthy food, low income prefers unhealthy food
1-ii High income prefers healthy food, low income prefers healthy food

2-i Healthy food stores are expensive; unhealthy food stores cheap
2-ii Healthy food stores are cheap; unhealthy food stores expensive

3-i High income prefers (expensive) healthy food, low income prefers (cheap) unhealthy food
3-ii High income prefers (expensive) healthy food, low income prefers (expensive) healthy food
3-iii High income prefers (cheap) healthy food, low income prefers (expensive) unhealthy food
3-iv High income prefers (cheap) healthy food, low income prefers (cheap) healthy food

* Diet was derived from the average proportion of times the household shopped at a healthy food store

Figure 2. Income differences (with 5th–95th percentiles) in healthy diet and median healthy diet for index scenario S6 (ref) and experiments that incorporate differences in food preferences by income and differences in price between healthy and unhealthy food stores ref, referent experiment (S6)

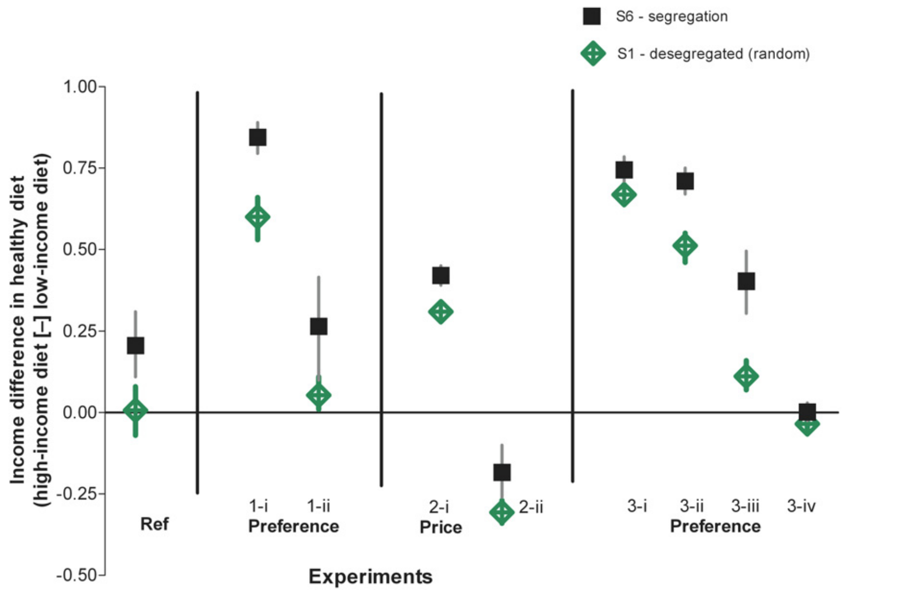
food store segregation reflected residents' preferences (Figure 2; compare S6 to 1-i and 2-i) and less predictable patterns when food store segregation did not support residents' preferences. Absent *price* differentials, low-income household healthy food preferences had little influence on whether unhealthy food stores closed in their neighborhood (1-ii). However, absent *preference* differences, once healthy foods were made relatively inexpensive (2-ii) expensive neighborhood stores did not do well in the low-income area. When expensive neighborhood stores closed, inexpensive healthy stores were able to move into the low-income neighborhood. In this way, the segregation of healthy food resources broke down and the income differential in diet was reversed.

The simultaneous addition of healthy food preferences and price to the segregation index scenario showed more complex behaviors, particularly when preferences for type of food and price were not aligned. When low-income households preferred healthy foods but unhealthy foods were cheaper and nearby (3-ii), unhealthy food stores prospered in the low-income area and low-income diets remained unhealthy (this held for alternate weighting schemes; Appendix D, available online at www.ajpm-online.net). Healthy food stores, which were expensive for this scenario, could not attract enough customers so did not thrive in low-income areas. (This accounts for surprising results that the diet differential was even *worse* than in experiments in which both high- and low-income households preferred healthy food [1-ii] and in which healthy food stores were expensive but unhealthy food stores were cheap [2-i].) Absent strong preferences, price and location interact to perpetuate an income differential in diet. When preferences were activated and low-income households preferred unhealthy nearby food but it was expensive (the corollary of relatively cheap healthy food), they chose unhealthy food less, low-income diets improved, and the diet differential was smaller (Figure 2, contrast 1-i and 3-iii). Nevertheless, within a segregated context, under most weighting schemes a diet differential remained (3-iii) and it consistently disappeared only when low-income households had *both* a preference for healthy food and healthy food was relatively cheap (3-iv). (For an alternate weighting scheme, see Appendix E, available online at www.ajpm-online.net.)

Figure 3 shows differences in the estimated diet differential between two extreme spatial scenarios: desegregated (random) and segregated (S6). This illustrates another way of exploring under which experimental conditions segregation adds to or subtracts from differentials in diet. In almost all experiments, spatial segregation increased the magnitude of the income differential in diet. However, when the type of food that low-income households preferred was the least expensive food (3-i and 3-iv), segregation had very little if any additional effect on the differential. Price incentives thus appear to magnify preferences and substantially reduce the effects of segregation.

Exploring store changes. Scenarios with low rates of change in stores produced estimates of the income differential in diet that were generally consistent with the index scenario (see Appendix F, available online at www.ajpm-online.net, for details and results). However, higher probabilities of food store changes over time completely dissolved the structure of segregation as more and more new stores opened and changed the type of food they sold. In this way, high rates of change in stores (changing availability and food type) led to improvements in low-income diets and worsening of high-income diet (because not all stores were healthy)—such that diet differences eventually fell to zero.

Scenarios in which stores competed for customers and were able to be highly dynamic and easily change their offerings permitted favorable resources to move into resource-poor "food deserts" and enhanced opportunities for low-income diets to improve.[43]



Ref, The referent experiment, index scenario 6 (S6 from Figure 1). No income differences in preference or prices; healthy food preference and price of food are randomly assigned.
1-i High income prefers healthy food, low income prefers unhealthy food
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3-i High income prefers (expensive) healthy food, low income prefers (cheap) unhealthy food
3-ii High income prefers (expensive) healthy food, low income prefers (expensive) healthy food
3-iii High income prefers (cheap) healthy food, low income prefers (expensive) unhealthy food
3-iv High income prefers (cheap) healthy food, low income prefers (cheap) healthy food

Figure 3. Income differences (with 5th–95th percentiles) in healthy diet for the desegregated (random) and segregated (index scenario 6) scenarios
ref, referent experiment (S6)

Validity

The model presented was a simple, abstract model that was not intended to be highly realistic or quantitatively calibrated to data. As a tool for explaining observable phenomena and stimulating questions, this model had reasonable face validity. Qualitative patterns of the income differential in diet were largely insensitive to alternate parameterizations within a reasonable bracketed range. (Appendix E, available online at www.ajpm-online.net, provides a detailed explanation.)

Discussion

The present study's highly stylized model enhanced insight into how spatial segregation can exacerbate structural factors contributing to inequalities in diet. Experiments showed that, absent other factors, an income differential in diet could be generated by the type of segregation of high-income households and healthy food stores from low-income households and unhealthy food stores that has been observed in numerous empirical studies.[5–8] The current study's experiments highlight the possibility that healthy food resources may become better integrated into low-income areas if healthy foods are favorably priced and healthy food preferences are encouraged.

There has been considerable debate on the contributing factors to income inequalities in diets, particularly the role that differential spatial access to healthy foods plays in creating these inequalities. It is often assumed that people are spatially segregated by income, preferences for healthy foods vary by income (e.g., high-income individuals prefer healthy foods and low-income individuals prefer unhealthy foods), and the providers of healthy foods locate where consumer demand is strongest.[11–13,44] This assumption means that if low-income households can shift their preferences toward healthier foods then segregation of healthy food resources will be reduced and the income differential in diet will disappear.[45] Results from the current study's simple models did not support this assumption. Given current residential segregation patterns, when low-income households possessed the same strong healthy food preferences as high-income households, the diet differential remained (Scenario 1-ii). Favorable preferences for healthy foods and favorable prices (i.e., healthy foods priced cheaper than unhealthy foods) both had to be present to improve diet and eliminate the diet differential.

These findings point to three potential policy interventions that might lessen the diet differential. First, policymakers could use subsidies to make healthy food cheaper than unhealthy food. Second, public health education should do more to shift low-income individuals' preferences to favor healthy foods, including working to counter commercial efforts that promote the sale of unhealthy foods. Third, because the model suggests that the relative differential in diet was reduced when stores in low-income areas switched to selling healthier foods, stores in low-income areas could be provided financial incentives to stock healthy foods. One promising real-world strategy that combines pricing incentives and desegregation of food stores is the new requirement that WIC-certified stores (many of which are in low-income neighborhoods) sell whole grains, fruits, and vegetables in order to be certified.[46]

Increasing the cost of unhealthy foods is attracting interest for its potential to reduce unhealthy food intake (such as imposing a tax on unhealthy food[47,48]). Shifting relative pricing of healthy versus unhealthy foods has received less attention but would appear to be a promising strategy because the public health community likely will need to employ incentives as well as disincentives to induce favorable dietary changes. Nevertheless, the current study's results serve as a reminder to the public health community to pursue multiple tactics in order to shift normative preferences in a favorable direction. Even when healthy food was cheaper than unhealthy food, the diet differential remained when low-income households were far from healthy food stores and preferred unhealthy food. Although price incentives for healthy foods and increasing access to these foods are two reasonable tactics, public health messaging likely will also need to be employed. Effective tactics may vary depending on how substantially unfavorable preferences are being shaped by unhealthy food marketing.

One of the fundamental challenges for all modeling, particularly ABMs, is making models simple enough to yield useful insights yet complex enough not to misrepresent what is occurring in the real world.[17] Audiences accustomed to traditional empirical studies may have low tolerance for abstract computational models. Models that draw heavily on detailed empirical data may promote acceptance of these powerful tools. However, these data are often unavailable. Existing data/reports had little direct correspondence to the parameterization and algorithm building that the present study's model required. For example, information was largely absent regarding influences of income on food store selection and why stores decide to stock healthy foods or change their product mix. Absent detailed empirical support, it is argued that models are still useful for explaining observable phenomena, stimulating further questions, and identifying collectable data required to build more sophisticated models. All models by definition rest on simplifying assumptions: statistical assumptions in statistical models and input parameters and algorithm specification in ABMs. The intent of the current study was not to present a full representation of the processes that create income differentials in diet but to explore specific interactions between key processes hypothesized in the literature and comparatively evaluate results using different scenarios.[49] Computational models do not replace empirical models but they can be used to complement them. As the research and practice communities continue to highlight the limitations of traditional models for framing and answering certain types of questions, growing interest is anticipated in systems science and nontraditional tools for exploring complex phenomenon.[50]

Conclusion

Income inequalities in diet originate and are perpetuated by a complex system of interrelated processes that are not well understood. The present study examined the extent to which the effects of residential economic segregation on healthy food availability affect income differences in healthy eating. Residential segregation, relative pricing of healthy foods, and dietary preferences appear to influence the diet differential and highlight the combination of conditions likely required to reduce diet inequalities.

This simple model is a preliminary step in understanding these complexities and is currently insufficient to generate detailed policy recommendations. As data collection proceeds and improves, it will be possible to further refine the model to better inform the debate on how to reduce inequalities in healthy behaviors such as diet. Nevertheless, even the current study's simple model points to the utility of ABMs as a complement to empirical and statistical analyses. By explicitly modeling dynamic processes, this approach may inform our understanding of how health disparities emerge and can be reduced in economically segregated environments.

The authors thank Wallace V. Genser, PhD, for reviewing and editing the manuscript.

This research was supported by the University of Michigan's Robert Wood Johnson, Health and Society Scholars Program.

No financial disclosures were reported by the authors of this paper.

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Appendix

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.amepre.2010.10.033.