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Highlights

Public health relevance—How does this work relate to a public health issue?

- School neighborhood food environments in Michigan show widespread exposure to unhealthful food outlets, a key driver of obesogenic environments affecting children's dietary behaviors.
- The study addresses a critical evidence gap by providing the first statewide, multiscale assessment of food environments surrounding public schools in Michigan.

Public health significance—Why is this work of significance to public health?

- Reveals strong spatial clustering and inequitable distribution of fast food restaurants and convenience stores near schools, with significantly higher exposure in urban areas.
- Demonstrates the value of integrating healthfulness (mRFEI), availability, and accessibility across multiple spatial scales to better capture environmental risk.

Public health implications—What are the key implications or messages for practitioners, policy makers and/or researchers in public health?

- Findings support place-based policy interventions (e.g., zoning, outlet regulation, healthy food incentives) targeting high-exposure school neighborhoods.
- Highlights the need for multiscale, multidimensional approaches in research and planning to more accurately inform healthy food environment interventions.

Abstract

This study examines the retail food environment surrounding public schools in Michigan using a multiscale, multidimensional framework. A cross-sectional spatial analysis integrates relative healthfulness (modified Retail Food Environment Index, mRFEI), availability (outlet density), and accessibility (network-based walking time) across school districts, census tracts, block groups, and school-centered buffers. The analysis includes 3,530 public schools, 7,680 fast food restaurants, and 2,065 convenience stores. Results show pronounced spatial heterogeneity and clustering of unhealthful outlets (Nearest Neighbor Index = 0.284, $p < 0.001$), with many located near schools. Approximately 34% of schools are within a 10-minute walk of a fast food restaurant, increasing to 65% within 20 minutes. Urban schools face significantly higher exposure—2.27–2.80 times more fast food outlets and shorter walking times than rural schools ($p \leq 0.002$)—with consistent gradients across city, suburban, town, and rural contexts. Overall, school neighborhood food environments are highly structured, obesogenic, and inequitable. By integrating multiple spatial scales and dimensions, this study advances food environment research and provides policy-relevant evidence for targeted, place-based interventions to improve access to healthier food around schools.

Keywords: school neighborhood; food environment; mRFEI; multiscale spatial analysis; urban–rural disparities; accessibility; availability; unhealthful food outlets; Michigan

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1. Introduction

Poor dietary quality among children and adolescents remains a major public health concern in the United States. A substantial proportion of youth fail to meet national dietary recommendations, with inadequate consumption of fruits, vegetables, and whole grains and frequent intake of energy-dense, nutrient-poor foods [1–4]. These dietary patterns are strongly associated with adverse health outcomes, including childhood overweight and obesity, which have increased markedly over recent decades [5,6]. Despite federal efforts to improve school meal quality through programs such as the National School Lunch Program and School Breakfast Program, children's overall nutritional status remains suboptimal [7].

Children's dietary behaviors are shaped by a complex interplay of influences operating across multiple levels, consistent with socio-ecological models of health behavior [8–10]. Among these influences, the neighborhood food environment—defined by the availability, accessibility, and relative healthfulness of food outlets—plays a critical role in shaping dietary behaviors and health outcomes [11–13]. The school neighborhood food environment is particularly important, as schools and their surrounding areas constitute primary daily activity spaces where children are repeatedly exposed to food options [14,15]. In Michigan alone, more than 1.38 million children were enrolled in public schools during the 2024–2025 academic year [16], highlighting the scale at which school-centered environments may influence population-level dietary behaviors. Frequent exposure to nearby food outlets, coupled with increasing autonomy in food purchasing—particularly among adolescents—may significantly influence food preferences, consumption patterns, and diet-related health outcomes.

A growing body of research demonstrates that the spatial characteristics of school neighborhood food environments are related to children's eating habits and health outcomes [12,17,18]. Evidence consistently shows that greater availability and proximity of unhealthful food options—particularly fast food restaurants and convenience stores—near schools are associated with increased consumption of energy-dense foods and lower intake of fruits and vegetables [15,19–22]. Additionally, higher exposure to unhealthful outlets has been linked to increased body mass index and a greater prevalence of overweight and obesity among children and adolescents [14,23–25]. Importantly, emerging evidence suggests that the external food environment may moderate the effectiveness of school-based nutrition policies. Even when schools implement interventions to promote healthy eating, the presence of nearby unhealthful food outlets may undermine these efforts by providing convenient and appealing alternatives, thereby influencing student food choices beyond the school setting [26].

Methodologically, prior studies have employed a range of approaches to define and measure school neighborhood food environments. Two dominant approaches include the use of administrative units (e.g., census tracts or zip codes) and spatial buffers around schools [11,12,27]. While administrative units provide standardized geographic boundaries, they may not accurately reflect actual exposure due to the modifiable areal unit problem (MAUP) [28]. In contrast, buffer-based approaches—particularly network-based buffers—offer more behaviorally realistic representations of accessibility by accounting for street networks and pedestrian travel pathways [29,30]. Measures of food environment exposure typically include availability (e.g., counts and density of outlets) and accessibility (e.g., distance or travel time to the nearest outlet), with density and proximity being the most widely used indicators [11,12,15,31–33]. Composite indices such as the modified Retail Food Environment Index (mRFEI) have been increasingly used to quantify the relative balance of healthy and unhealthful food outlets within a given area [34–37].

Despite substantial progress, several important gaps remain in the literature. First, many studies focus on a single spatial scale, limiting understanding of how food environments operate across multiple geographic contexts. Second, relatively few studies integrate multiple dimensions of food environments—such as availability, accessibility, and relative healthfulness—within a unified analytical framework. Third, although urban–rural disparities in food environments have been widely documented, comprehensive analyses examining gradients across multiple urbanicity categories (e.g., city, suburban, town, and rural) remain limited. Finally, while there is a growing interest in evaluating food environments in Michigan [38–41], no study to date has conducted a comprehensive, statewide, multiscale analysis of school neighborhood food environments.

Addressing these gaps is essential for informing public health policy and intervention. A more comprehensive understanding of how food environments vary across spatial scales and geographic contexts can support the development of evidence-based strategies aimed at creating healthier school neighborhood environments, including land-use planning, zoning policies, and community-level interventions targeting food access.

Therefore, the aim of this study is to conduct a multiscale spatial analysis of the retail food environment around public schools in Michigan. Specifically, this study: (1) evaluates the relative healthfulness of food environments using mRFEI across school districts, census tracts, and block groups; (2) assesses the availability and accessibility of unhealthful food outlets—defined as fast food restaurants and convenience stores—using multiple network-based walking-time buffers (10-, 15-, and 20-minute thresholds); and (3) examines variation across urbanicity categories, including city, suburban, town, and rural settings. By integrating multiple spatial scales and dimensions of food environments, this study provides a comprehensive assessment of school neighborhood food environments and offers evidence to inform policies aimed at improving children's nutritional environments.

2. Materials and Methods

2.1. Study Design and Study Area

This study is a cross-sectional spatial analysis examining the retail food environment surrounding public schools in Michigan, USA. The study area includes all public schools and their surrounding neighborhoods across diverse geographic contexts ranging from highly urbanized to remote rural settings. The analysis included 3,530 public schools across 541 school districts, encompassing 1,792 census tracts (hereafter "school tracts") and 2,303 census block groups ("school block groups") where schools are located. A total of 7,680 fast food restaurants and 2,065 convenience stores were included in the analysis.

A multiscale spatial analytical framework was employed to capture variation in food environments across multiple geographic levels. Analyses were conducted at four spatial scales: (1) school districts, (2) school tracts, (3) school block groups, and (4) school-centered network-based walking-time buffers. This multilevel design addresses the modifiable areal unit problem (MAUP) and enables a more robust assessment of spatial disparities in food environments [28].

The analytical workflow consisted of two complementary components: (1) area-based analysis of the relative healthfulness of food environments using the modified Retail Food Environment Index (mRFEI), and (2) school-level analysis of exposure and accessibility to unhealthful food outlets. This integrated approach aligns with recent food environment research emphasizing multiscale and multidimensional analysis [15].

2.2. Data Sources and Food Outlet Classification

Public school locations and school district boundaries were obtained from the National Center for Education Statistics (NCES) Education Demographic and Geographic Estimates (EDGE) program [42] Food outlet data were derived from Esri Business Analyst [43], supplemented with farmers markets, on-farm markets, and food hubs from the USDA Local Food Directory [44].

Food outlets were classified using North American Industry Classification System (NAICS) codes into healthy and unhealthful categories. Healthy food retailers included supermarkets, grocery stores, warehouse clubs, specialty food retailers, and USDA-listed local food sources, while unhealthful outlets included fast food restaurants and convenience stores. This classification approach is widely used in food environment research [34,45].

2.3. Multiscale Analysis of Food Environment Healthfulness

The modified Retail Food Environment Index (mRFEI) was used to quantify the relative availability of healthy versus unhealthful food outlets [34]. The mRFEI represents the proportion of healthy food retailers relative to the total number of food retailers within a defined area and is expressed as a percentage: mRFEI = (Healthy Food Retailers / Total Food Retailers) × 100. Values range from 0 (no healthy food retailers) to 100 (all food retailers are classified as healthy), with higher values indicating a healthier retail food environment. mRFEI scores were calculated at three spatial scales: school districts, school tracts, and school block groups.

Spatial clustering of mRFEI values at the school district level was assessed using the Getis–Ord Gi* statistic. A fixed distance threshold of 50 km was used to define spatial relationships between districts. Statistically significant clusters of high values (hot spots) and low values (cold spots) were identified based on *z*-scores and *p*-values [46].

To assess within-district variability in food environment healthfulness, the coefficient of variation (CV) was calculated using block group–level mRFEI scores aggregated to the district level: $CV = (\sigma / \mu) \times 100$, where σ represents the standard deviation and μ represents the mean mRFEI. Higher CV values indicate greater heterogeneity in the distribution of healthy and unhealthful food outlets within districts, reflecting potential intra-district inequalities. All mRFEI-related outputs were mapped to visualize spatial patterns across Michigan.

2.4. School-Level Spatial Analysis

Spatial relationships between public schools and unhealthful food outlets were examined through a series of complementary analyses. School locations were first overlaid with fast food restaurants and convenience stores to visualize co-location patterns. The spatial distribution of unhealthful food outlets was further evaluated using Nearest Neighbor Analysis (NNA) to determine whether outlets were clustered, randomly distributed, or dispersed [47].

To assess school exposure to unhealthful food outlets, network-based walking-time service areas of 10 and 20 minutes were generated around each unhealthful outlet (hereafter "walkable service areas"). Schools located within these service areas were identified through spatial joins. Network-based buffers were used because they more accurately represent realistic accessibility and pedestrian travel behavior [27]. Walking-time thresholds were based on commonly used benchmarks in school neighborhood research [30].

Availability of unhealthful food outlets near schools was assessed using network-based buffers of 10, 15, and 20 minutes constructed around each school (hereafter "walkable school zones"). Counts of fast food restaurants and convenience stores within each buffer were calculated. The use of multiple buffer thresholds enables a multiscale assessment of food outlet density and reduces bias associated with single-buffer approaches.

Accessibility was further assessed by calculating the network-based walking time from each school to the nearest unhealthful food outlet, capturing the minimum effort required to access these food options. This proximity-based measure complements availability-based metrics and is widely used in food environment research [12].

Schools were stratified using the NCES school locale classification system into urban–rural and four-category classifications (city, suburban, town, and rural), a framework commonly used in school neighborhood environment research [30].

2.5. Statistical Analysis

Differences in accessibility were assessed using Welch's *t*-tests and Welch's ANOVA, followed by Games–Howell post hoc tests. Statistical significance was set at $p < 0.05$, and effect sizes were reported using Cohen's *d* and partial eta squared (ηp^2).

Differences in outlet availability were analyzed using negative binomial regression models to account for overdispersion in count data. Results are reported as incidence rate ratios (IRRs) with 95% confidence intervals.

All spatial analyses were conducted using ArcGIS Pro [48], and statistical analyses were performed using IBM SPSS Statistics [49].

3. Results

3.1. Multiscale Patterns of Food Environment Healthfulness (mRFEI)

The spatial distribution of modified Retail Food Environment Index (mRFEI) scores across Michigan demonstrates substantial geographic variability in the healthfulness of school neighborhood food environments. At the school district level, mRFEI values ranged from 0 (i.e., no healthy food retailers) to 100 (i.e., all food retailers are classified as healthy), with most districts falling within moderate ranges, indicating a mixture of healthy and unhealthful food outlets (Figure 1). Higher mRFEI values were more prevalent in western Michigan, the northern Lower Peninsula, and parts of the Upper Peninsula, whereas lower values were concentrated in the central and southeastern Lower Peninsula, particularly in metropolitan regions.

A small number of districts contained no food retailers, representing cases of extremely limited food availability. Overall, the distribution of mRFEI values indicates considerable spatial heterogeneity in food environment healthfulness across the state.

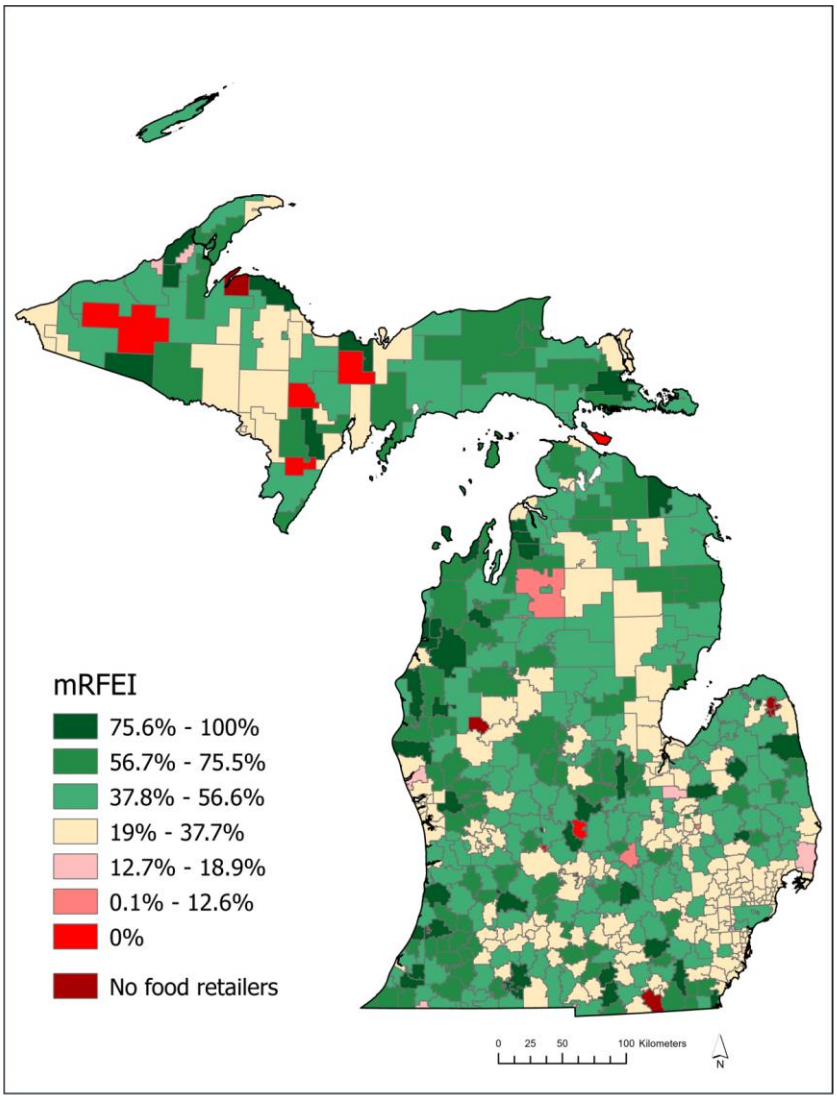

Figure 1. The modified Retail Food Environment Index (mRFEI) scores by school districts in Michigan.

Hot spot analysis identified statistically significant clustering of mRFEI values (Figure 2). Cold spots (low mRFEI values) were more numerous and spatially concentrated than hot spots, with the most prominent cluster located in Southeast Michigan. In contrast, hot spots were fewer and more dispersed, with the largest cluster observed in Northwest Michigan.

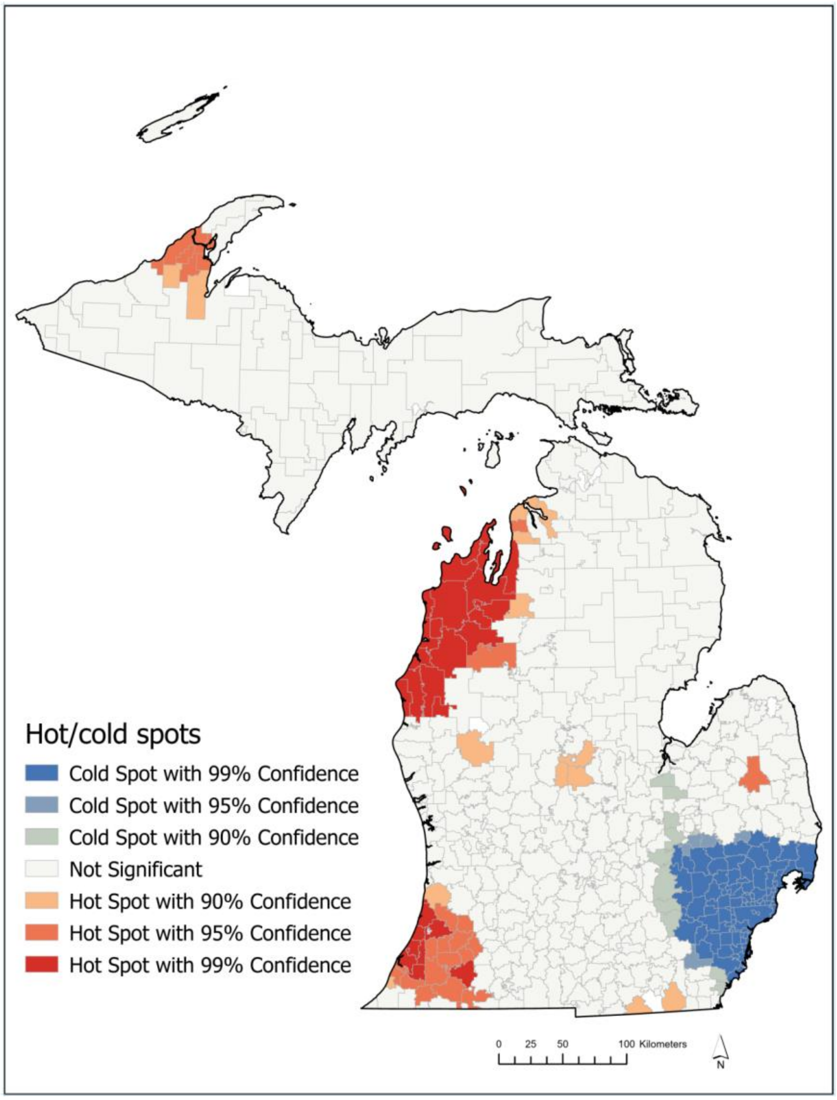

Figure 2. Hot spots and cold spots of mRFEI scores at the school district level (Getis-Ord Gi*) in Michigan.

Substantial intra-district variability was observed in mRFEI values (Figure A1). The coefficient of variation (CV) ranged from 0% to 245%, with most districts exhibiting moderate variability (50%–100%). Lower variability was more common in northern and rural regions, whereas higher variability was concentrated in central and southeastern Michigan.

At finer spatial scales, the food environment exhibited increased fragmentation. At the census tract level, moderate mRFEI values predominated, with clusters of low values in urban cores—particularly in Southeast Michigan—and remote rural areas (Figure A2). Some school tracts contained no food retailers altogether. This pattern became more pronounced at the block group level, where low and zero mRFEI values were more spatially concentrated in urbanized regions (Figure 3), while areas without food retailers were more prevalent in rural parts of northern and central Michigan and the Upper Peninsula.

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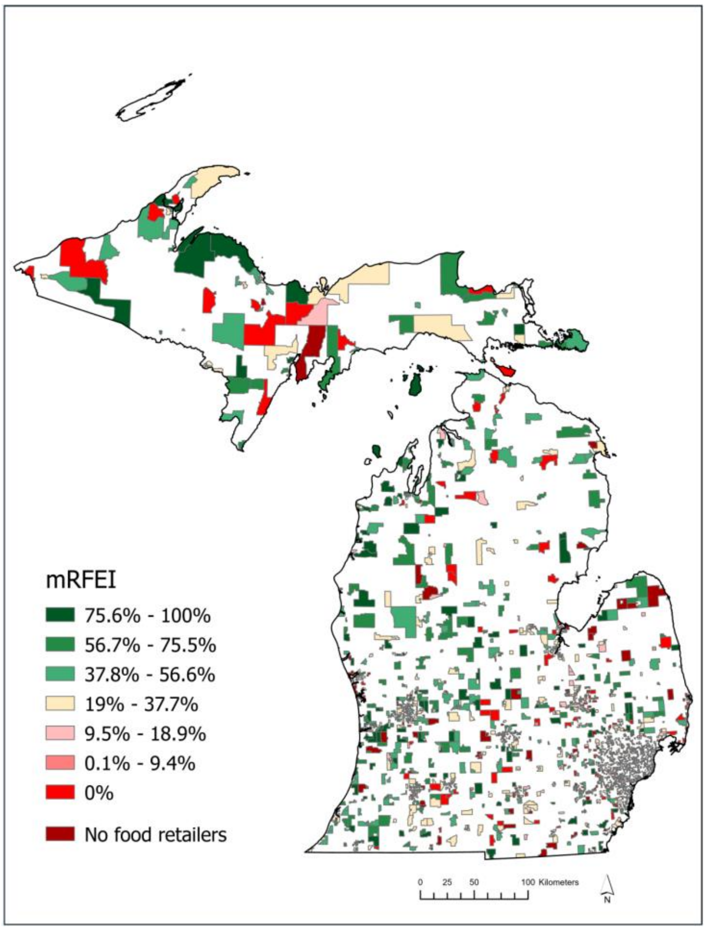

Figure 3. The modified Retail Food Environment Index (mRFEI) scores by census block groups where Michigan public schools are located.

3.2. Spatial Clustering of Unhealthful Food Outlets

Fast food restaurants and convenience stores exhibited strong spatial clustering across Michigan, with the highest densities located in the southern Lower Peninsula, particularly in urban areas and along major transportation corridors. In contrast, northern and rural regions showed substantially lower outlet densities (Figure 4).

Spatial overlay analysis indicated a clear correspondence between public school locations and clusters of unhealthful food outlets. Many schools in urbanized regions were located within or adjacent to dense concentrations of fast food restaurants and convenience stores. This co-location pattern was more pronounced for fast food restaurants, which were more numerous and spatially extensive than convenience stores.

Nearest Neighbor Analysis confirmed that unhealthful food outlets were significantly clustered (Table A1). The Nearest Neighbor Index (NNI) indicated strong clustering for all unhealthful outlets combined (NNI = 0.284, $p < 0.001$), with fast food restaurants exhibiting the most pronounced clustering (NNI = 0.248) and convenience stores showing moderate clustering (NNI = 0.575).

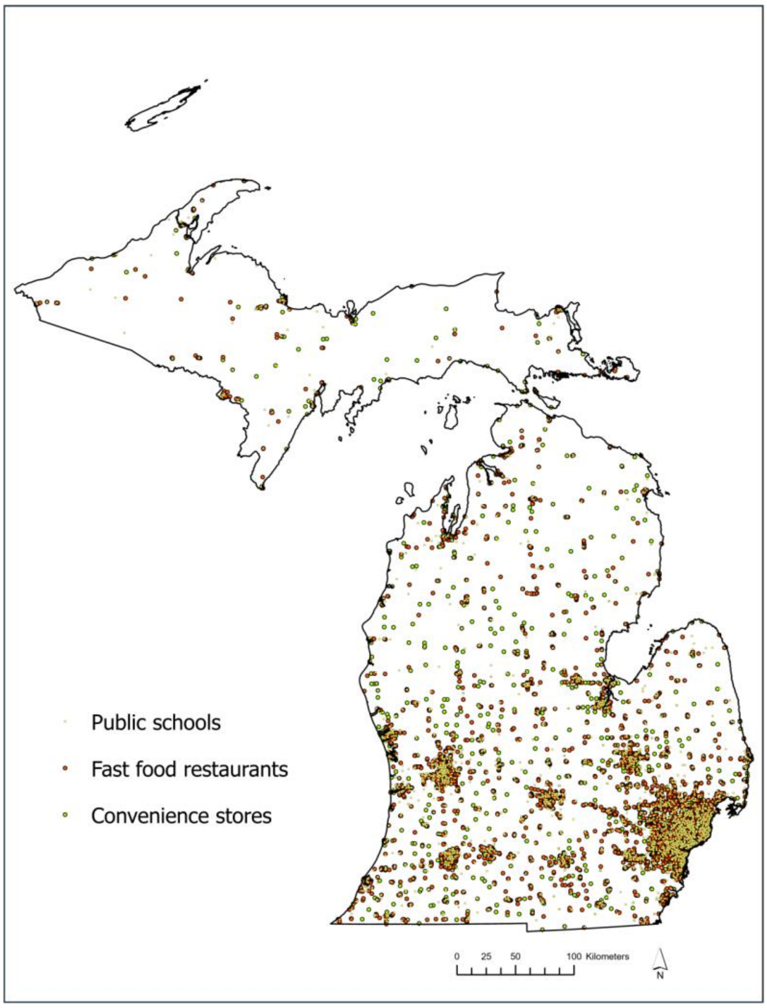

Figure 4. Co-location patterns of public schools and unhealthful food outlets in Michigan.

3.3. Exposure Within Walkable School Environments

Network-based analyses demonstrated substantial exposure of Michigan public schools to unhealthful food outlets within walkable distances (Table A2). Approximately 34% of schools were located within a 10-minute walk of a fast food restaurant, increasing to approximately 65% within a 20-minute walk. For convenience stores, approximately 22% of schools were within a 10-minute walk, increasing to more than 51% within a 20-minute walk.

The distribution of unhealthful food outlets within walkable school zones showed a clear distance-dependent pattern (Table A3). Approximately one-third of unhealthful food outlets were located within 10-minute walking distances of schools, more than half within 15 minutes, and over two-thirds within 20 minutes. Across all buffer distances, fast food restaurants consistently outnumbered convenience stores.

3.4. Urbanicity-Based Disparities in Availability and Accessibility

Consistent urban–rural gradients were observed in both availability and accessibility of unhealthful food outlets.

Availability analyses (Tables 1 and 2) indicated that urban schools were surrounded by substantially higher densities of both fast food restaurants and convenience stores than rural schools. Negative binomial regression models showed that urban schools had between 2.27 and 2.80 times as many fast food outlets and 1.25 to 1.87 times as many convenience stores within 10–20 minute walking buffers ($p \leq 0.002$; 95% confidence intervals entirely above 1). These differences increased with buffer distance.

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Across four urbanicity categories, outlet density followed consistent gradients. At 10- and 15-minute buffer distances, the pattern was City > Town > Suburban > Rural, while at the 20-minute distance it shifted slightly to City > Suburban > Town > Rural. These differences were statistically significant across all models ($p < 0.001$). Across all categories and distances, fast food outlets were more numerous than convenience stores.

Table 1. Urban–rural differences in outlet density (counts).*.

Outlet Type	Buffer	IRR (Urban vs Rural)	95% CI	*p*
Fast food restaurants	10 min	2.27	2.05–2.51	<.001
	15 min	2.45	2.25–2.66	<.001
	20 min	2.80	2.59–3.03	<.001
Convenience stores	10 min	1.25	1.08–1.43	.002
	15 min	1.56	1.39–1.74	<.001
	20 min	1.87	1.69–2.06	<.001

* IRR = incidence rate ratio; values >1 indicate higher outlet density in urban vs. rural schools. Urbanicity is defined using the U.S. Department of Education locale classification. Models were estimated using negative binomial regression. 95% CIs >1 indicate statistical significance. *p*-values are from likelihood ratio tests.

Table 2. Differences in outlet density (counts) across urbanicity categories.*.

Outlet Type	Buffer	City IRR	Suburban IRR	*Town IRR*	*p*	Significant Comparisons
Fast food restaurants	10 min	4.83	2.77	2.93	<.001	City > Town, Suburban > Rural
	15 min	5.47	3.41	3.44	<.001	City > Town, Suburban > Rural
	20 min	7.05	4.33	4.13	<.001	City > Suburban, Town > Rural
Convenience stores	10 min	1.79	1.07	1.25	<.001	City > Town, Suburban > Rural
	15 min	2.31	1.39	1.41	<.001	City > Town, Suburban > Rural
	20 min	3.04	1.74	1.67	<.001	City > Suburban, Town > Rural

* IRR = incidence rate ratio; rural is the reference category. Values >1 indicate higher outlet density relative to rural schools. Urbanicity categories follow the U.S. Department of Education locale classification. Negative binomial models were used. Pairwise comparisons are Bonferroni-adjusted; only significant results ($p < 0.05$) are shown.

Accessibility analyses (Tables 3 and 4) showed that urban schools had significantly shorter walking times to the nearest unhealthful food outlet than rural schools. Mean walking times to the nearest fast food restaurant were 15.0 minutes for urban schools and 38.5 minutes for rural schools ($t = -16.64$, $p < 0.001$, $d = 0.68$). For convenience stores, mean walking times were 21.2 minutes for urban schools and 48.9 minutes for rural schools ($t = -16.29$, $p < 0.001$, $d = 0.66$).

Across four urbanicity categories, differences in walking time were statistically significant for both fast food ($F = 164.11$, $p < 0.001$, $\eta p^2 = 0.171$) and convenience stores ($F = 166.24$, $p < 0.001$, $\eta p^2 = 0.128$). Post hoc comparisons indicated systematic gradients in walking time, with City < Town < Suburban < Rural for fast food and City < Suburban < Town < Rural for convenience stores (all $p < 0.05$).

Rural areas exhibited greater variability in walking times, with standard deviations reaching approximately 60–70 minutes, indicating more heterogeneous access compared with urban areas.

Table 3. Urban–rural differences in walking time (minutes) to the nearest unhealthful food outlet.*.

Outlet Type	Urban (Mean ± SD, *n* = 2095)	Rural (Mean ± SD, *n* = 1435)	*t* (*df*)	*p*	Cohen's *d*
Fast food restaurants	15.0 ± 10.3	38.5 ± 52.7	-16.64 (*df* = 1509.3)	<.001	-.68
Convenience stores	21.2 ± 15.1	48.9 ± 63.2	-16.29 (*df* = 1546.3)	<.001	-.66

* Values are mean walking time (minutes ± SD); lower values indicate greater accessibility. Urbanicity (urban vs. rural) is defined using the U.S. Department of Education locale classification. Welch's *t*-test was used. Cohen's *d* represents the standardized mean difference.

Table 4. Differences in walking time (minutes) to the nearest unhealthful food outlet across urbanicity categories.*.

Outlet Type	City (Mean ± SD, *n* = 792)	Suburban (Mean ± SD, *n* = 1303)	Town (Mean ± SD, *n* = 419)	Rural (Mean ± SD, *n* = 1016)	Welch's *F* (df_1, df_2)	*p*	ηp^2	Significant Pairwise Differences (Games–Howell)
Fast food restaurants	11.8 ± 7.1	16.9 ± 11.4	15.3 ± 10.9	48.1 ± 59.7	164.11 (3, 1455.2)	<.001	.171	City < Town < Suburban < Rural
Convenience stores	16.4 ± 9.7	24.2 ± 16.9	30.9 ± 37.7	56.4 ± 69.7	166.24 (3, 1330.4)	<.001	.128	City < Suburban < Town < Rural

* Values are mean walking time (minutes ± SD); lower values indicate greater accessibility. Urbanicity categories (city, suburban, town, rural) follow the U.S. Department of Education locale classification. Welch's ANOVA with Games–Howell post hoc tests was used. Reported pairwise differences are significant at $p < 0.05$. ηp^2 denotes effect size.

3.5. Summary of Key Findings

Across all analyses, the retail food environment surrounding public schools in Michigan exhibited pronounced spatial variation. Unhealthful food outlets were strongly clustered and frequently located near schools, particularly in urban areas. Network-based analyses indicated substantial exposure to unhealthful food outlets within walkable distances, with exposure increasing as buffer distance expanded.

Clear and consistent urban–rural gradients were observed across all measures. Urban schools were characterized by both higher densities of unhealthful food outlets and shorter distances to the nearest outlet, whereas rural schools had lower outlet densities but longer and more variable travel times.

4. Discussion

This study provides a holistic, nuanced assessment of the nutritional landscape surrounding public schools in Michigan. Across all analyses, a consistent pattern emerges: school neighborhood food environments are highly uneven, spatially structured, and characterized by substantial exposure to unhealthful food outlets. Evidence from multiple measures—relative healthfulness (mRFEI), outlet density, proximity, and spatial clustering—converges to indicate that many Michigan public schools are situated within environments where unhealthful food options are both abundant and readily accessible.

By integrating multiple spatial scales and dimensions of exposure, this study extends prior research and demonstrates that food environments surrounding schools are not only heterogeneous but systematically structured in ways that shape the intensity and immediacy of exposure.

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4.1. Multiscale Inequities in Food Environment Healthfulness

A central contribution of this study is the demonstration of pronounced spatial inequities in food environment healthfulness across multiple geographic scales. The clustering of low mRFEI values in southeastern Michigan, particularly in metropolitan regions, indicates persistent regional disparities in the relative balance of healthy and unhealthful food outlets. In contrast, higher mRFEI values observed in western and northern regions are more spatially dispersed and less regionally dominant.

At finer spatial scales, substantial intra-district variability further highlights localized inequities. The wide range of coefficient of variation (CV) values indicates that school districts often contain neighborhoods with markedly different food environments. These findings underscore the importance of multiscale analysis, as reliance on aggregated administrative units alone may obscure meaningful within-area disparities.

Together, these results indicate that food environment inequities operate simultaneously across regional and local scales, reinforcing the need for analytical approaches that capture both. These findings are consistent with prior research documenting spatial inequalities in food environments across geographic contexts [50].

4.2. Convergence of Exposure: Availability, Accessibility, and Clustering

The findings reveal a strong convergence across multiple dimensions of food environment exposure. Density analyses indicate that unhealthful food outlets are highly concentrated around schools, particularly in urban areas, with fast food restaurants consistently more prevalent than convenience stores. Accessibility analyses show that a substantial proportion of schools are located within short walking distances of these outlets, indicating that exposure is not only widespread but behaviorally relevant. In addition, spatial clustering analyses confirm that these outlets are not randomly distributed but are concentrated in specific areas.

This convergence suggests that many schools are embedded within environments where unhealthful food outlets are numerous, nearby, and spatially clustered. Such configurations intensify environmental exposure and increase the likelihood of repeated interaction with these food sources during daily school-related activities. This pattern aligns with prior studies demonstrating that combined measures of availability and accessibility provide a more comprehensive understanding of food environment exposure than single measures alone [12].

4.3. Urban–Rural Dual Burden of Food Environments

A key finding of this study is the identification of a dual burden of food environment inequity operating through distinct mechanisms in urban and rural contexts. In urban areas, high outlet density and strong clustering create conditions characterized by concentrated exposure to unhealthful food options. The results indicate that urban schools not only have significantly higher numbers of nearby outlets but also shorter walking times to these outlets, reflecting both intensity and immediacy of exposure.

In contrast, rural areas exhibit a different form of spatial disadvantage. Lower outlet density and, in some cases, the absence of nearby food retailers reflect limited overall availability. At the same time, greater variability in walking times indicates more heterogeneous and less predictable access. This combination of scarcity and spatial dispersion suggests that food environments surrounding rural schools are characterized by constraints on access rather than excess exposure.

These findings indicate that inequities in school neighborhood food environments are not uniform but instead reflect distinct structural conditions across the urban–rural continuum. Addressing these disparities requires differentiated approaches that account for the underlying mechanisms shaping food access in each context. These results are consistent with existing literature documenting urban–rural disparities in food access and availability [35].

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4.4. Urbanicity Gradients and Scale-Dependent Exposure

The study further demonstrates that food environment exposure follows clear and systematic gradients across urbanicity categories. Consistent patterns observed across both availability and accessibility measures indicate that city environments represent the highest levels of exposure, followed by suburban and town contexts, with rural areas exhibiting the lowest overall exposure.

Importantly, the magnitude of these differences increases with spatial scale. As buffer distances expand from 10 to 20 minutes, disparities in outlet density become more pronounced, indicating that exposure differences accumulate across broader activity spaces. This scale-dependent pattern underscores the importance of using multiple spatial thresholds when assessing school neighborhood food environments, as single-distance measures may underestimate the extent of exposure [30].

The findings also reveal spatial nuance within intermediate urbanicity categories. The relative positioning of suburban and town contexts varies across distances, indicating that these environments do not follow a uniform pattern. In contrast, rural areas consistently exhibit lower density but greater variability in accessibility, reinforcing their distinct spatial characteristics.

4.5. Policy and Public Health Implications

The findings of this study have several important implications for public health policy and intervention. First, the multiscale nature of exposure indicates that strategies limited to immediate school surroundings may be insufficient. Interventions should consider broader neighborhood contexts that reflect the full range of students' daily activity spaces.

Second, the spatial clustering of unhealthful food outlets indicates that targeted, place-based strategies may be particularly effective. Zoning policies that regulate the density of fast food outlets near schools, incentives for healthy food retailers, and integration of food environment considerations into land-use planning may help reshape local food landscapes. Similar approaches have been recommended in prior research on built environment and food environment interventions [51].

Third, the identification of distinct urban and rural patterns highlights the need for context-specific approaches. In urban areas, efforts should focus on reducing exposure to unhealthful outlets and improving the relative availability of healthier options. In rural areas, strategies may prioritize increasing overall food access through infrastructure development, transportation solutions, and alternative food distribution systems such as mobile markets.

Finally, the findings emphasize the limitations of school-based nutrition interventions when implemented in isolation. External food environments may counteract improvements made within schools, underscoring the need for integrated approaches that combine environmental, policy, and educational strategies.

4.6. Strengths and Limitations

This study makes several methodological and substantive contributions. The multiscale spatial framework, integrating administrative units with network-based buffers, enhances the robustness of findings and addresses limitations associated with single-scale analyses. The integration of multiple dimensions of food environments—relative healthfulness, availability, accessibility, and spatial structure— provides a more comprehensive assessment than approaches relying on a single metric. In addition, the use of network-based walking-time buffers improves the behavioral relevance of accessibility measures.

The study also benefits from statewide coverage, allowing for the identification of broad spatial patterns while capturing localized variation through fine-scale analysis. The explicit focus on school-centered food environments further strengthens the relevance of findings for public health policy.

Several limitations should be considered. Although multiple spatial scales were used, the analysis remains subject to the modifiable areal unit problem. GIS-based measures represent potential rather than actual exposure and do not capture individual behavior or activity patterns. The use of secondary commercial datasets may introduce inaccuracies due to omissions or misclassification of food outlets. The binary classification of outlets into "healthy" and "unhealthful" simplifies complex nutritional realities. Finally, other dimensions of food access, such as affordability and in-school food environments, were not examined.

4.7. Future Research Directions

Future research should extend this work by incorporating longitudinal designs to assess changes in school neighborhood food environments over time and their relationship to diet-related health outcomes. Integrating individual-level data on dietary behavior and mobility patterns would improve understanding of how environmental exposure translates into actual consumption. Additional research is also needed to evaluate the effectiveness of policy interventions aimed at modifying school neighborhood food environments. Expanding similar multiscale analyses to other states or regions would further enhance the generalizability of findings.

5. Conclusions

This study provides a comprehensive, multiscale assessment of the retail food environment around public schools in Michigan by integrating measures of relative healthfulness, availability, accessibility, and spatial structure. The findings demonstrate that school neighborhood food environments are highly uneven, spatially structured, and predominantly obesogenic. Across all measures, clear and consistent urbanicity gradients emerge, with urban areas characterized by high densities, close proximity, and strong clustering of unhealthful food outlets, and rural areas characterized by lower availability but greater spatial isolation. Together, these patterns reveal a dual burden of food environment inequity operating through distinct mechanisms across the urban–rural continuum.

This study contributes to the literature by advancing a multiscale and multidimensional analytical framework that captures both regional disparities and localized variation in food environments. By integrating multiple spatial scales and exposure measures within a school-centered context, the findings demonstrate that no single metric or geographic unit is sufficient to characterize the complexity of food environments. The convergence of high availability, accessibility, and clustering of unhealthful food outlets—particularly around urban schools—highlights the extent to which environmental conditions may shape students' dietary behaviors and reinforce obesogenic exposures.

From a public health perspective, these findings underscore the need for coordinated, place-based strategies that extend beyond the immediate school environment. In urban areas, policy approaches may include zoning regulations to limit the concentration of fast food outlets near schools and incentives to increase access to healthier food options. In rural areas, strategies should focus on improving overall food supply. More broadly, the results highlight the limitations of school-based interventions when external food environments remain unchanged, emphasizing the importance of integrated, cross-sectoral approaches.

Although this study focuses on Michigan, the observed multiscale patterns and urban–rural disparities are likely relevant to other regions with similar spatial and socioeconomic characteristics. These spatial patterns have important implications for children's dietary behaviors and long-term health outcomes. The findings reinforce the importance of incorporating multiscalar perspectives in food environment research and public health planning. Ultimately, improving school neighborhood food environments will require addressing both the structural and spatial dimensions of food access to support healthier dietary behaviors and reduce long-term health risks among children.

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Data Availability Statement: The data used in this study are available from publicly accessible sources and commercial providers. Access to commercial data is subject to licensing restrictions. Derived data are available from the corresponding author upon reasonable request.

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Abbreviations

CDC	Centers for Disease Control and Prevention
CEPI	Michigan Center for Educational Performance and Information
CV	Coefficient of variation
EDGE	Education Demographic and Geographic Estimates
Esri	Environmental Systems Research Institute
MAUP	The Modifiable Areal Unit Problem
mRFEI	The modified Retail Food Environment Index
NAICS	North American Industry Classification System
NCES	National Center for Education Statistics
NNA	Nearest Neighbor Analysis
NNI	Nearest Neighbor Index
USDA	U.S. Department of Agriculture

Appendix A

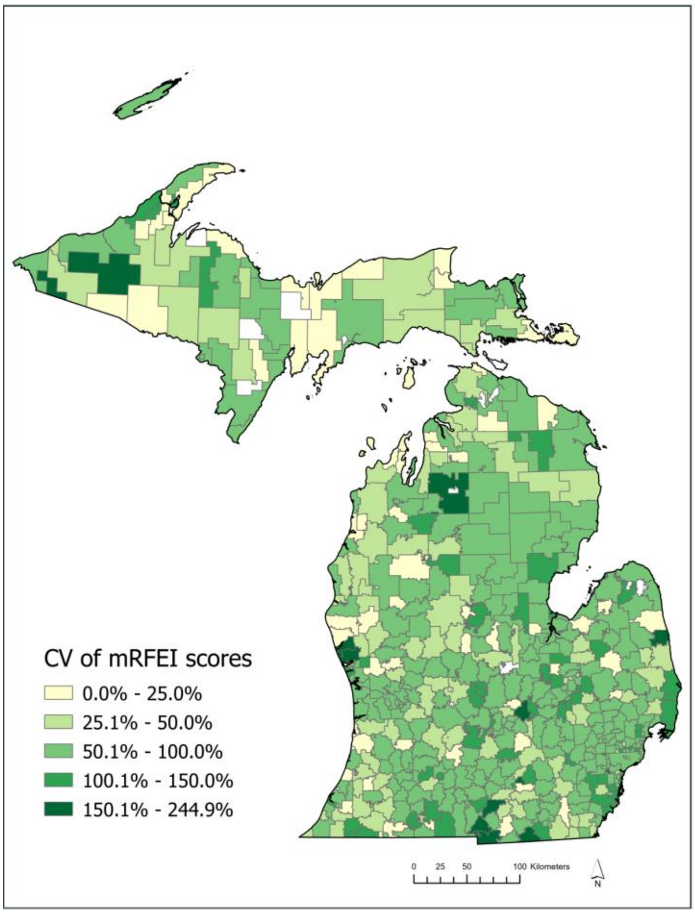

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Figure A1. The coefficient of variation (CV) of the modified Retail Food Environment Index (mRFEI) scores by school districts in Michigan.

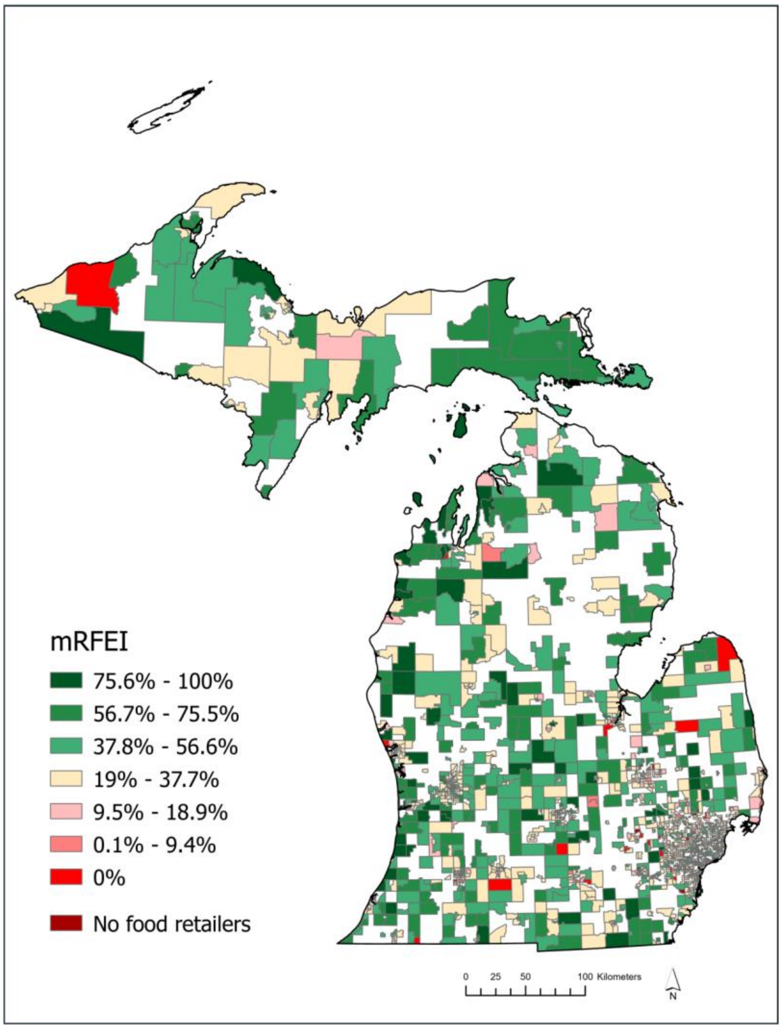

Figure A2. The modified Retail Food Environment Index (mRFEI) scores by census tracts where Michigan public schools are located.

Table A1. Average nearest neighbor summary statistics for unhealthful food outlets.

Outlet Type	NNI *	*z*-Score	*p*-Value	Observed Mean Distance (meters)	Expected Mean Distance (meters)
Unhealthful outlets combined (*N* = 9745)	0.284	-135.19	<.001	557.9	1963.6
Fast food restaurants (*N* = 7680)	0.248	-126.04	<.001	549.0	2211.9
Convenience stores (*N* = 2065)	0.575	-36.98	<.001	2450.9	4265.6

* NNI: Nearest Neighbor Index.

Table A2. Schools (*N* = 3530) located within 10- and 20-minute walk of unhealthful food outlets.

Outlet Type	Within 10 minutes		Within 20 minutes	
	# of Schools	%	# of Schools	%
Fast food restaurants	1201	34.0%	2287	64.8%

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Convenience stores	766	21.7%	1819	51.5%

Table A3. Unhealthful food outlets located within 10-, 15-, and 20-minute walk of schools.

Outlet Type	Within 10 minutes		Within 15 minutes		Within 20 minutes	
	# of Outlets	%	# of Outlets	%	# of Outlets	%
Fast food restaurants (N = 7680)	2466	32.1%	4228	55.1%	5472	71.3%
Convenience stores (N = 2065)	704	34.1%	1092	52.9%	1348	65.3%

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